RESEARCH CAREERS IN ATOMIC ENERGY

at Harwell, Winfrith Amersham and Wantage

Research Careers in Atomic Energy

An account of the work of the Research Group of the United Kingdom Atomic Energy Authority

RESEARCH GROUP
UNITED KINGDOM ATOMIC ENERGY AUTHORITY

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Introduction

One of the most spectacular developments in the last generation has been the discovery of the basic facts of nuclear fission and their application to practical purposes, which has led to the growth of a new major industry. The first use was a military one but for some years now the emphasis has turned towards applying atomic energy to peaceful uses. In the United Kingdom particular attention has been paid to the generation of electric power from nuclear fission and a programme is well under way by which about 5,000 MW of nuclear electrical generating capacity will be built by 1968.

The Research Group concentrates upon the fundamental scientific aspects of the work. The Group includes a number of establishments, the biggest of which is the Atomic Energy Research Establishment, Harwell. At Harwell the chemical, metallurgical, and nuclear physics problems of nuclear power are studied; a very large part of the work turns upon the behaviour and properties of matter in the environment of a reactor, especially the interaction between the matter and neutrons or other radiation, so that the Establishment is concerned principally with the materials of nuclear energy. The Atomic Energy Establishment at Winfrith, Dorset (the second largest establishment of the Group) on the other hand is concerned principally with reactor systems as a whole. Four large research reactors are used as sources of neutrons and radiation for much fundamental and technical research. These two aspects of the work are closely inter-related; technical development waits upon scientific advance and new fundamental knowledge often emerges from research begun for technical ends. To give some examples, the technical importance of radiation damage in metallic fuels has led to new knowledge about the physics of metals; in chemistry, the study of effects of radiation upon the reaction between carbon and carbon dioxide at high temperatures has given interesting new information in the field of solid-gas reactions. In physics, measurements, with high accuracy and covering a wide range of energies, of neutron interactions with both nuclei and nucleons have been valuable to nuclear physicists and to reactor designers alike. Fundamental research has always been recognised at Harwell as of primary importance and as a matter of policy about a fifth of the Establishment's effort has been devoted to it.

Besides its reactors the Establishment has several particle accelerators, including a 180 MeV synchro-cyclotron, a 12 MeV tandem electrostatic accelerator, and a 5 MeV electrostatic generator. Research into the principles underlying, and the development

and construction of, advanced types of accelerator has been done at the Establishment from its inception until the end of 1960, when the work was transferred, together with the team doing it, to the Rutherford High Energy Laboratory of the National Institute for Research in Nuclear Science. The Institute is an independent body, having its own charter, which works in close co-operation with the Authority and the universities. The Rutherford Laboratory is at Harwell adjacent to A.E.R.E.; it has a 50 MeV proton linear accelerator in operation and a 7,000 MeV (7 GeV) proton synchrotron, known as Nimrod, is being built. Both machines were designed by the former Accelerator Division of A.E.R.E.

Another fascinating field of fundamental research is the study of controlled thermonuclear reactions. From this work it is hoped that ultimately it will prove possible to use fusion reactions to yield power on an industrial scale. At present, however, the fundamental physics of plasma, the high-temperature highly ionised gases in which the thermonuclear reactions will take place, are so little understood that a large programme of research, involving machines of a considerable size, will be necessary for some years. This programme has been started in the Controlled Thermonuclear Reactions Division at Harwell and, as there is little scope for further expansion at the Harwell establishment, a separate new one is being built at Culham to continue and extend the work. Certain work in this field now being done at Aldermaston will also be moved to the new establishment.

The Atomic Energy Establishment, Winfrith, has been set up as the Authority's principal centre for research into the physics and basic engineering technology of nuclear reactor systems, particularly of power-producing reactors. In collaboration with the consortia which are building nuclear power stations, this establishment is studying the physics of graphite-moderated gas-cooled reactors. It is concerned also with the physics of the advanced gas-cooled reactor, which is expected to succeed the types now going into service, and with the engineering physics of boiling-water and organic-moderated systems. A study team from the British Shipbuilding Research Association at Winfrith is examining the possibilities and problems of nuclear propulsion for merchant ships.

Winfrith is the headquarters of the DRAGON project, an international undertaking sponsored by O.E.E.C., which is carrying out research and development on the high-temperature gas-cooled reactor. In this system the heat released in a fuel mixture of uranium, thorium and graphite, clad in impermeable graphite, is removed at high temperature by helium. A 20 MW experimental reactor is being built by the project. A wide programme of experimental research on high-temperature reactor systems is being carried out at A.E.E. in parallel with, and often in direct support of, the DRAGON project.

From its earliest days Harwell has been responsible for the production of radioactive isotopes and their applications, especially in industry. This work has placed the United Kingdom in a leading position as the world's largest exporter of radioactive isotopes. Recently the production side of this programme has been re-organised and is now the responsibility of the Radiochemical Centre at Amersham, also an establishment of the Research Group. The development of applications is the responsibility of the Isotope Research Division at the Wantage Research Laboratory. This work includes the study of the use of massive sources of radiation in industry for such purposes as sterilising medical supplies, preserving food, and initiating or accelerating chemical processes for the production of new materials such as plastics.

In addition to the reactors, accelerators, active laboratories, and other special pieces of equipment, the facilities at Harwell include that other essential of good research, a major scientific library. Recently moved to a new building, the library has a collection of over 20,000 volumes of books and periodicals in all branches of science and engineering, with smaller collections at sub-libraries in the divisions. In addition there is a vigorous information service, to answer specific questions and provide more general lists of references, and a translation service, capable of giving spot translations from all major languages including Russian and Japanese. The Establishments at Winfrith and Amersham have separate libraries which work closely with the Harwell library.

Work of the kind outlined has been going on for twelve years but is far from complete. Indeed it is not too much to say that this is the beginning of a new chapter. If it were possible to look back on the present position from a generation ahead it would probably be seen as the beginning of an era in which impressive new developments were first visualised and were brought into effective operation. The purpose of this booklet is to describe the tasks facing the Research Group of the Atomic Energy Authority and the opportunities which it offers to those who make a career in it.

1

The origins of the United Kingdom Atomic Energy Authority and the place of the Research Group in it

The most convenient starting point for describing the evolution of the Atomic Energy Authority is found in the announcements made in 1938-9 of the basic facts about the fission of the uranium nucleus. These discoveries, which were made in universities in Europe, were at once confirmed and extended by nuclear physicists in the United Kingdom and the United States. It was immediately understood that a self-sustaining fission reaction would release a million times as much energy as any chemical reaction; this could be made to produce an explosion of immense proportions or, if brought under control, to act as a new fuel of unprecedented concentration. History decreed that the first endeavours to use the enormous energies of fission should be for military purposes, and it was some years before attention was turned to peaceful applications.

In 1945 it was announced by the Prime Minister that the Government had decided 'to set up a research and experimental establishment covering all aspects of the use of atomic energy'. The responsibility for atomic energy was transferred from the Department of Scientific and Industrial Research to the Ministry of Supply and Dr. J. D. (later Sir John) Cockcroft was appointed Director of the new Establishment in January 1946. The building of A.E.R.E. started early in 1946 on the site of what had previously been a permanent Royal Air Force station at Harwell in Berkshire. In the same year the Radiochemical Centre at Amersham, which was engaged in processing natural radioactive materials, came under public ownership and was affiliated to Harwell.

Many of the staff who had been employed on atomic research during the war were appointed to the new establishment and they were supplemented by some of the men who had worked on radar; additional workers were rapidly recruited in almost every branch of pure and applied science. From the first, the work at Harwell has been closely connected with the fundamental research being done in the universities. Progressively more and more topics have been released from the secret list and the interchange of ideas has been steadily encouraged. Now about ninety per cent of the research work can be published and Harwell has become well known for its work in all fields of nuclear and related sciences. The establishment has also had a strong link with medical work through the Medical Research Council's Radiobiological Research Unit.

Very soon after the announcement of the setting-up of the research establishment the Prime Minister announced the decision to set up a Department of Atomic Energy within the Ministry of Supply, and an atomic energy production organisation to produce fissile material in sufficient quantities to 'enable us to take advantage rapidly of technical developments as they occur, and to develop our programme for the use of atomic energy as circumstances may require'. The headquarters of this organisation was set up at Risley in Lancashire. In addition research on atomic weapons began at Ministry of Supply establishments.

In July 1954, the United Kingdom Atomic Energy Authority was set up by Act of Parliament, to take over from the Ministry of Supply the responsibility for atomic energy work in the United Kingdom. The general organisation was retained unchanged, the three divisions being known as the Research, Industrial and Weapons Groups respectively; early in 1959 the Industrial Group was sub-divided into the separate Development and Engineering Group and the Production Group. During this year also, much work was transferred from Harwell to establishments in Wantage and Winfrith: notwithstanding this the total number of staff at Harwell itself has risen from 500 in 1946 to 6,000: of these more than twenty-five per cent are graduates or hold equivalent qualifications.

Thus in the short space of fifteen years the relatively small establishments of the Ministry have grown into the Atomic Energy Authority with its four groups dealing with Research, Weapons, Development and Engineering, and Production and a total payroll of 38,500 persons. In the same way the Research Group, which for ten years was predominantly at Harwell, has recently opened a second full-scale establishment at Winfrith in Dorset and has started to build a third which will deal with controlled thermonuclear fusion at Culham about eight miles from Harwell.

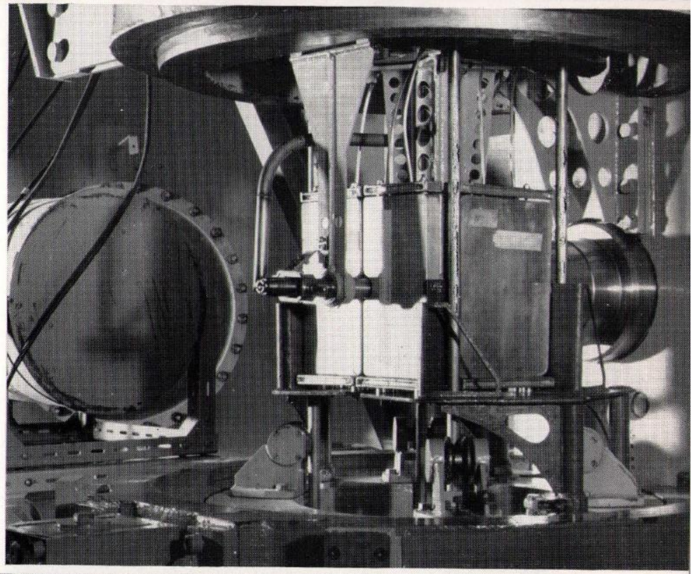
THE HARWELL NEUTRON PROJECT

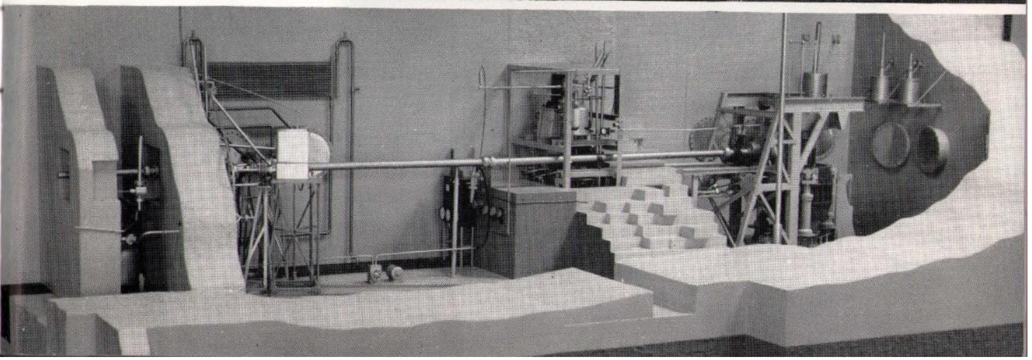
The Harwell Neutron Project consists of an extremely powerful pulsed neutron source consisting of an electron linear accelerator in conjunction with a multiplying target assembly

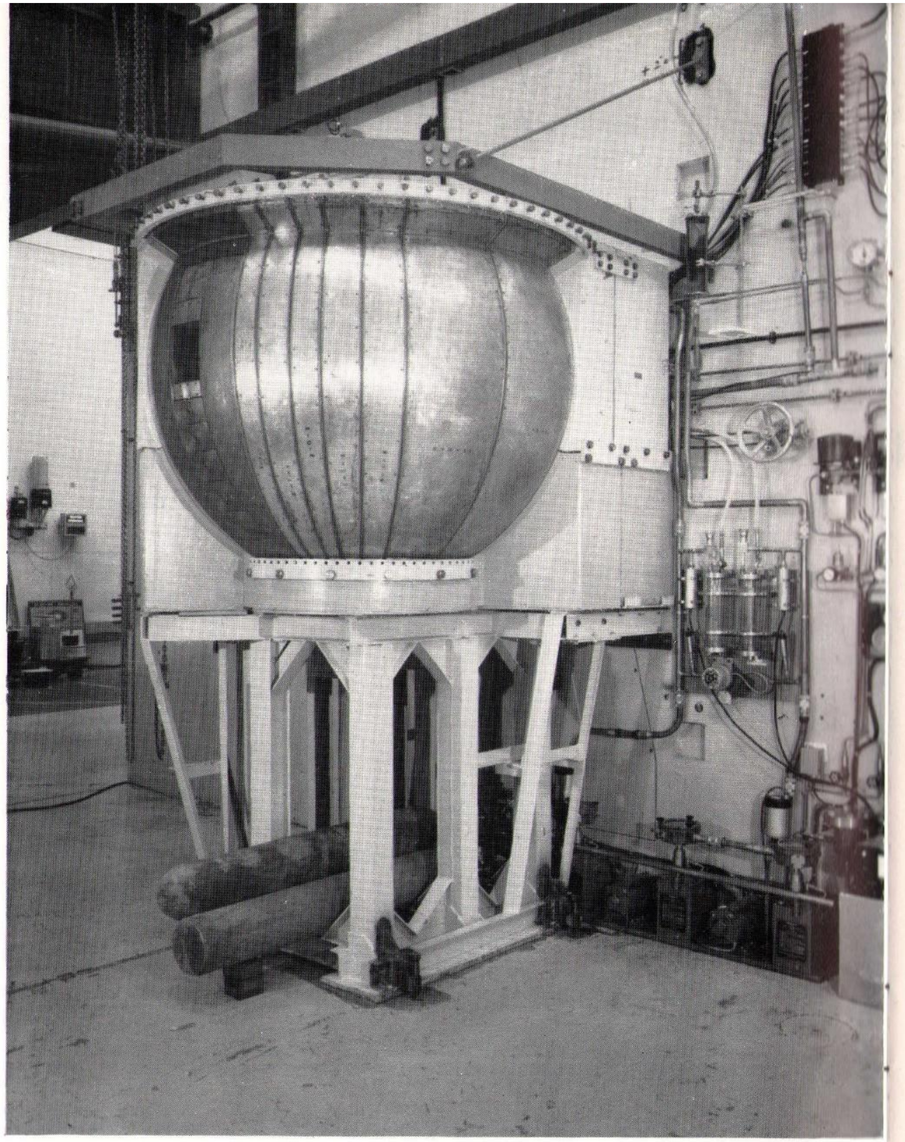
(*Above*) General view

(*Right*) Neutron booster with lead shield open

(*Below*) Model of target cells







The twin-rotor mechanical neutron-velocity selector
for solid state physics research: Harwell

2

The work of the Research Group: Harwell

Although the greater part of the work of the Research Group is concerned with the technology of reactors and the processes associated with them, a fifth of the effort is devoted to work which will establish and broaden knowledge about the bases of the sciences from which technology is developed. The selection of these fields of research calls for foresight and judgment which will anticipate, and so make unnecessary, *ad hoc* investigations which are costly both in money and time. It follows that the staff engaged in this fundamental work have the closest relations with one another and with the staff in other establishments or divisions with which they co-operate. While, therefore, the notes which follow deal separately with each division, it must be remembered that there are considerable areas in which their interests coincide and where very close collaboration takes place.

The Theoretical Physics Division

Much of the fundamental physics work of the Research Group is carried out by this Division which has a staff of nearly eighty and is divided into four groups. Three of these are engaged on theoretical physics and employ nearly equal numbers of mathematicians and physicists, the majority of whom have Ph.D. degrees or equivalent experience. The fourth group is the largest and is the main computing organisation of the Establishment; it employs mainly graduate mathematicians. The following paragraphs describe the work done by each group.

The interests of the Nuclear and Field Theory Group include low-energy nuclear structure studies and interpretation of reaction rates, meson field theory and nucleon-nucleon force studies, many-body studies of nuclear matter and, to an increasing amount, field theory and very-high-energy nuclear physics.

The Solid State Theory Group has extremely wide interests, including magnetic and neutron diffraction properties of transition metals, their alloys and their salts, the electronic structure of transuranic elements, the phonon spectra of crystals and models of liquids, the thermalisation of neutrons, the plastic properties of crystals and the effect of radiation damage on solids. The main emphasis of the work is quantum mechanical.

The Plasma Theory Group is concerned with the properties of plasmas of completely ionised hydrogen (and its isotopes) at high temperatures, which are not well understood. The prospects of fusion reactors rest on the improvement of this understanding, and work is being carried out on magneto-hydrodynamics, ionisation rates and cross-sections, stability of current channels carrying 10^6 amperes, and the processes of formation and confinement of plasmas with temperatures in excess of 10^6 degrees centigrade. Recent computation of the pinch effect in fast operating systems have shown excellent agreement with experiment, demonstrating that magneto-hydrodynamic considerations evaluated in detail may lead to well-defined design information.

The Computing Group serves the whole Establishment. Most of its work is carried out on high-speed electronic digital computers; there is a Ferranti Mercury machine at Harwell and use can be made of an IBM 704 at Risley and of the IBM 7090 at A.W.R.E. Aldermaston. The work includes some processing and reduction of data, but mainly involves the solution of large-scale mathematical problems. For example, the solution of coupled sets of Laplace's equations or diffusion equations in one, two, or three dimensions of irregular geometry, or the solution of particle trajectories in complex magnetic fields, or the deduction of complicated crystal structures for X-ray or neutron diffraction data are all undertaken by this group. Monte Carlo methods as well as more conventional numerical methods are used, and there is a lively interest in numerical analysis.

Recent work on the many-body problem has led to the publication of several papers, from each of the nuclear, solid state and plasma theory groups. In all of these fields collective effects of many particles modify greatly the properties of any one particle in the medium, and the formal analysis of this problem has now gone some way. A symposium held at A.E.R.E. on this topic attracted many university staff and stimulated the recent book on the subject by D. ter Haar of Oxford University. A similar symposium on magneto-hydrodynamics in 1959 was stimulating to the many university representatives who came; it concluded with a small international conference on the subject of magneto-hydrodynamic instability, a subject of great importance to fusion reactions and one in which the Research Group has made a major contribution to the world's knowledge.

The Nuclear Physics Division

This Division has two main functions. Firstly it carries out fundamental research into nuclear structure and processes: this activity adds to the store of basic knowledge and ensures that a pool of experienced nuclear physicists working at the frontiers of the subject are available for consultation by the other Divisions having more particular interests. Secondly, using the advanced techniques so developed, the Division undertakes many measurements which either have a direct application to the applied interests of the Research Group or are required for theoretical studies of future systems.

The Neutron Physics Group has been working on the measurement of nuclear data important to reactor work using time-of-flight methods. This involves the use of pulsed neutron sources (linear electron accelerators) or neutron choppers (with a reactor as a source) to measure total, fission, scattering or capture cross sections of fuels, moderators, structural materials and fission product poisons, as a function of neutron energy. A new pulsed source designed to give shorter more intense bursts of neutrons has recently been brought into operation. High energy electrons are produced in a travelling wave linear accelerator and fall on a mercury target to produce X-rays. The X-rays then produce neutrons by photodisintegration reactions and a further increase in the neutron intensity is obtained by surrounding the mercury target with a subcritical assembly of uranium-235 in which fission multiplication takes place. Using the new device both reactor data and data of importance to basic nuclear theory are being studied.

The High Voltage Group has been working on both fast neutron interactions and basic nuclear structure. A 600 keV Cockcroft-Walton, a 5 MeV Van de Graaff and a 12 MeV tandem accelerator are used for this work. The latter is a new variety of accelerator recently brought into operation.

In the field of higher particle energies, the following instruments permit first class research to be carried out:

A 150 MeV proton synchrocyclotron is used for fundamental studies of nucleon-nucleon interactions.

A team from the Division is working with the 50 MeV proton linear accelerator studying higher energy charged particle reactions.

Another group is engaged in the design of experimental beam handling arrangements for the 7 GeV proton synchrotron NIMROD.

One of the most important pieces of information required for the calculation of reactors concerns the scattering law of neutrons in condensed systems such as the moderator materials, water or graphite. Measurements are now made on such materials with the most advanced neutron spectrometers, supplemented by basic research into the processes underlying the energy interchanges between neutrons below 1 eV energy and a crystal lattice or a liquid. Another group is determining directly neutron spectra emitted by representative small lattice structures using suitable time-of-flight methods. Such work is carried out with either a pulsed neutron source such as a linear accelerator, or a reactor such as LIDO.

The Controlled Thermonuclear Reactions Division

The ultimate aim of the work being done in this Division is the production of useful quantities of electrical power from the fusion of light elements (probably the isotopes of hydrogen). The only practical method of doing this appears to be to heat a gas to temperatures of about 10^8 degrees. At these temperatures the gas is fully ionised.

The key work of the Division is in the field of plasma physics, the study of the behaviour of ionised gases in the presence of magnetic fields. Much of the work is concerned with methods of heating and confining plasmas, and with the stability of various configurations of confined plasma.

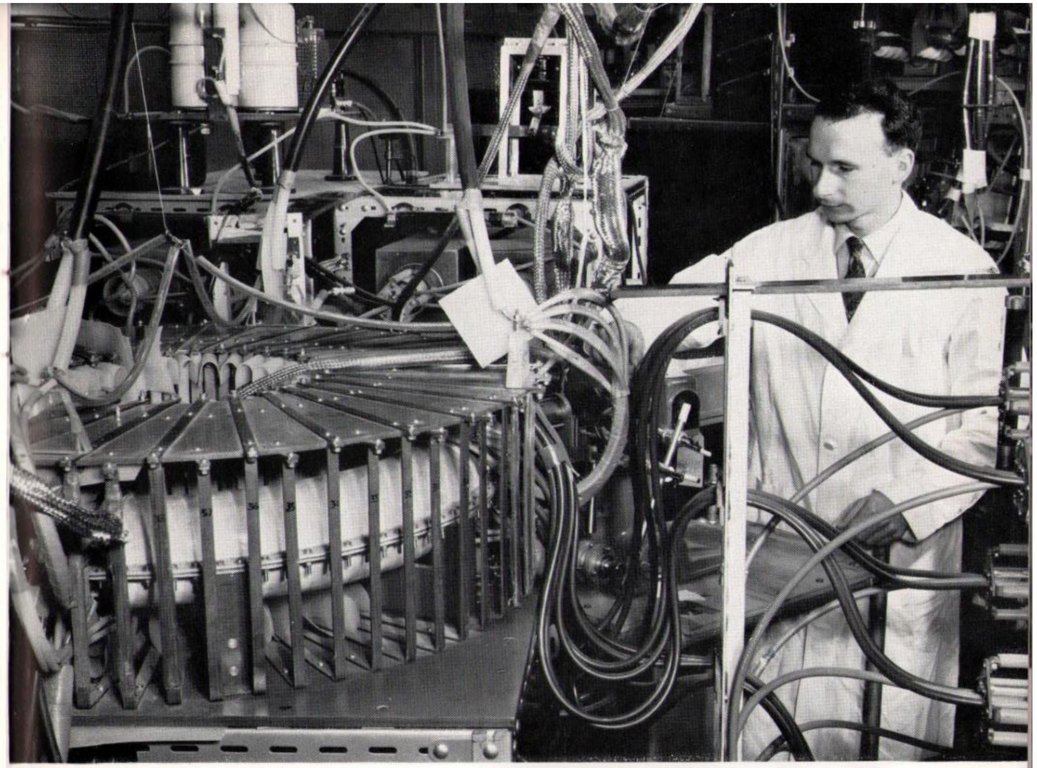
Most of this work is being done in the field of the 'pinched' discharge, in which the plasma is both heated and confined by the passage through it of a large current. The plasma is confined as a result of the interaction of the current with the magnetic field which it produces.

Substantial effort is being devoted to the development of techniques for obtaining as complete a picture as possible of the physical conditions existing in the plasma, i.e. for determining the variation in space and time of such properties as the temperature, density, electric and magnetic fields, resistivity, impurity content, and degree of ionisation. The techniques used include spectroscopy in the visible, vacuum ultra-violet, infra-red and X-ray regions, microwave techniques, magnetic and Langmuir probe measurements, examination of the electrical characteristics of discharges, and measurements of the numbers and energies of neutrons and protons produced in the discharge. Cross-section measurements are being made in which the probability of various multiple ionisations by energetic electrons is determined.

Among the electrical engineering problems being investigated are the production and control of pulsed currents in the megampere range (the currents rising from zero to megamperes in a few microseconds), energy storage and switching.

Subsidiary work being done includes the development of vacuum techniques, the investigation of the behaviour of various materials in the vicinity of hot plasmas, and methods of preventing the formation of arcs between the plasma and the walls of the containing vessel.

The largest 'pinch' device so far built is ZETA, a ring-shaped apparatus in which deuterium gas is heated to high temperatures. The gas, initially weakly ionised, forms the single secondary turn of a transformer: when an electric charge stored in a condenser



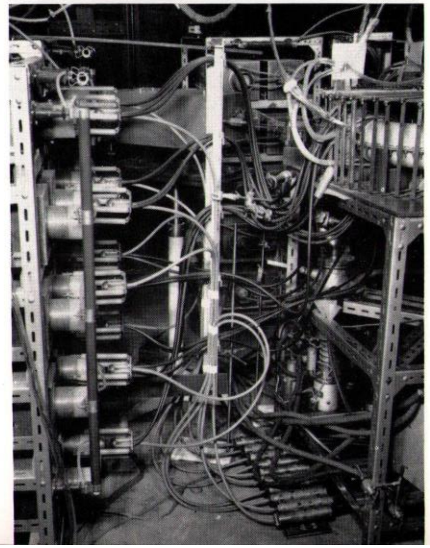
'SPIDER'

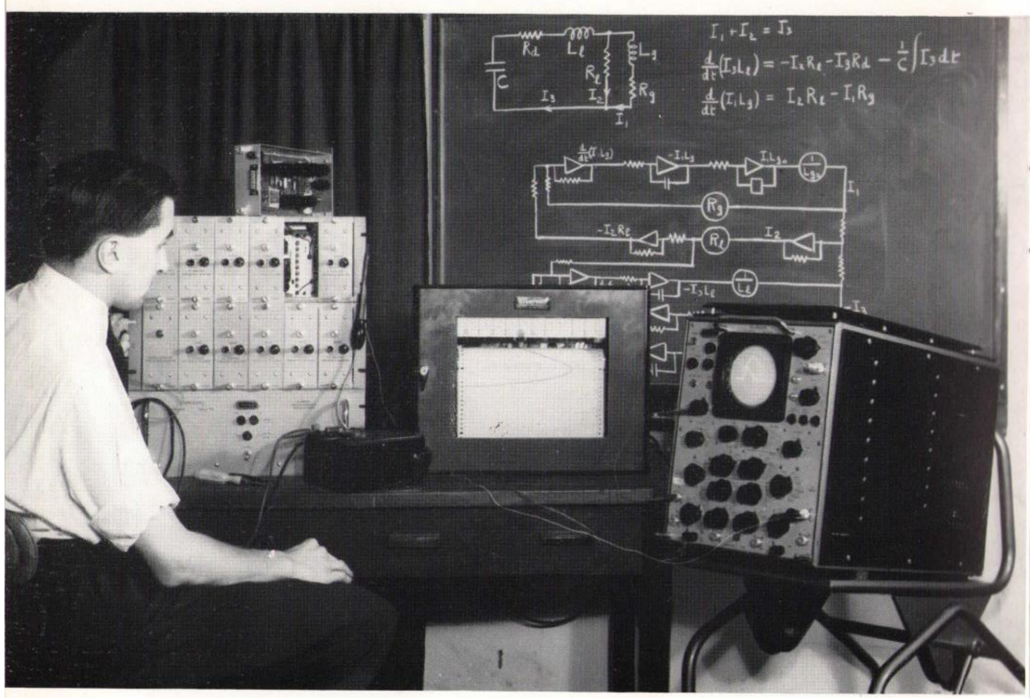
The fast toroidal pinch experiment

This experiment has shown that it is possible to set up an approximation to the simple stabilised pinch configuration in the confinement geometry of a torus; also, that when the skin current collapses rapidly a cylindrically imploding hydromagnetic shock is produced. The results obtained are of interest for stability and shock-heating studies

(*Above*) Part of the torus primary, enclosed in the axial field coil. An adjustment is being made to the spectrometer for time-resolved spectroscopy of the light from the discharge

(*Right*) The capacitor bank. On the left are the spark gaps attached to one bank of capacitors and the cables to the torus; at the bottom centre the trigger capacitor tubes, and bottom right the trigger cables radiating from the master gap which is just off the picture. In the centre background there is a remote-drive magnetic probe unit





Analogue computation work associated with fusion machine design:
Electronics Division, Harwell

bank is discharged through the primary of this transformer, a large pulse of current (up to about a million amperes) is induced in the gas, causing it to be heated to temperatures in the region of a million degrees.

It has been shown that although photographs of the discharge and measurements of the changing magnetic field within it both suggest that the current channel is confined by its own magnetic field and kept away from the walls of the torus, there is an excessive loss of energy to the torus walls during the current pulse. The exact mechanism by which this energy is being lost is not fully understood but there is evidence that energetic particles are being continually lost to the torus walls. The main object of the present experimental programme is to build up a complete picture of the important physical processes in the ZETA discharge, and to find the reasons for the energy and particle loss.

Parallel with this work, small-scale equipment is being used to study more specific aspects of plasma physics. Examples are: studies of the propagation of magneto-hydrodynamic waves in plasmas; studies of stability in various modifications of the pinch geometry; and studies of plasma confinement in different configurations of magnetic field, such as the so-called cusp-geometry. Experiments are also being carried out on the injection and trapping of energetic particles as a means of building up a high temperature plasma.

Although many problems in fusion research may be solved by small or medium-scale experiments, some can only be attacked by very large, and hence very costly, experimental assemblies. These involve complex technological problems, both in the high-energy power supplies and switchgear, and in the experimental apparatus itself. There is a strong technological team in the Division working on phase problems.

Thus the work in the Division covers the whole range of laboratory plasma physics studies, from large and powerful devices involving teams of research workers, to modest one-man experiments. At the present stage, original research work in basic plasma physics is quite as valuable as direct attacks on the magnetic containment problem.

The Authority is building a new laboratory for this work at Culham, a few miles from Harwell. The Director of this Laboratory will be Mr. J. B. Adams, at present Director-General of the C.E.R.N. Laboratories in Geneva. The new laboratory will provide more room than is available at Harwell, more modern and flexible laboratory accommodation and complete freedom from security restrictions. When completed, within the next few years, the Culham Laboratory will become the centre of the Authority's controlled thermonuclear reactions work, at present carried out both at Harwell and at Aldermaston.

The Direct Conversion Group

As has been explained in the introduction, the bulk of the work of the former Accelerator Division at Harwell, has been transferred to the Rutherford High Energy Laboratory, belonging to the National Institute for Research in Nuclear Science. The Direct Conversion Group will, however, remain a part of the Atomic Energy Research Establishment at Harwell.

The group is concerned with methods of direct production of electricity from heat particularly in relationship to reactors and the nuclear power programme. The main emphasis is on the physics and engineering of the various conversion devices, solid state converters, thermionic diodes and various forms of magneto-hydrodynamic converters in which plasma physics is involved. Contact is maintained with other relevant developments such as fuel cells and storage devices, and some analysis of complete systems is carried out to establish technical and economic feasibility.

The Electronics Division

Most of the research and development carried out in the Research Group involves the detection and measurement of nuclear particles and radiations. Electronic techniques provide almost the only means of performing this and are needed also for many other functions, so it is hardly surprising that electronic instruments and systems are much in evidence. They are vital for controlling nuclear reactors and for studying their behaviour, for protecting workers against excessive exposure to nuclear radiations, and for research work in the chemical and metallurgical fields. In nuclear physics research, the equipment for many experiments consists basically of large and complicated electronic systems.

Nuclear experiments using the new high-energy particle accelerators are capable of providing information at a great rate; in order to make the best use of the time of these expensive machines this information must be analysed and recorded very rapidly by specialised electronic data-handling systems and special-purpose electronic computers. Work on controlled thermonuclear reactions depends on the use of advanced electronic techniques for the detection, measurement, recording and analysis of a wide variety of physical quantities.

Moving forward the frontiers of knowledge in these fields of research depends so often on electronic techniques that there is a constant need to refine them and to introduce new ones. The Electronics Division has the task of studying and developing electronic techniques likely to be of value in the research and development carried out at Harwell and applying these techniques effectively. This involves close contact with, and often participation in, very many of the Research Group projects, so as to be able to understand clearly the problems involved and to contribute effectively to their solution.

Important contributions have been made at Harwell to the application of transistors and special magnetic devices, to the theory and practice of controlling nuclear reactors, to the study of very-high-speed pulse circuits and to the development of nuclear radiation detectors using gas discharges and scintillating crystals, to mention only a few examples. In addition a great deal of electronic instrument development work is carried out in close collaboration with the electronic industry.

Work in this field calls for a training in either physics or electrical engineering and there is a great advantage in having at least some knowledge of both.

The Health Physics Division

A basic problem in all atomic energy work is to ensure that no one suffers any injury due to radioactive substances or ionising radiations. The Health Physics Division at Harwell provides an advisory and measurement service for safeguarding those at Harwell who work with a unique range of reactors, high energy particle accelerators, radiochemical laboratories and equipment for handling thousands and tens of thousands of curies. Thereby it gets to know at firsthand practical health physics problems and needs. Fundamental knowledge on the hazards of radiation is limited; therefore, side by side with its service function, the Health Physics Division carries out research in the physical sciences of selected topics in this interesting, though difficult, field. Several of the topics for new and profitable lines of research stem from the close association of the health physicsist with operational problems. Current research includes radiation dosimetry of all types of radiation, the measurement of radioactivity in the human body, the behaviour of air-borne radioactive particles, and the uptake and fate of radioactive substances on silt and clay.

The measurement of radiation dose ranges from basic studies of the physics of the interaction of radiation with matter to the design, in conjunction with the Electronics Division, of new instruments for the measurement of radioactivity and radiation levels. Among current interests are the measurement of gamma ray and neutron dose at different depths in 'phantoms' or body simulators; the determination of neutron dose (or neutron flux and energy) over a wide range of energies; methods of radiation spectrometry (such as gamma spectrometry) applied to the analysis of radioactive contamination and the use of computers to analyse the spectra; special counting techniques for samples of low activity emitting radiations of very low energy; measurement of specific radionuclides in air and rain (particularly fall-out from weapons tests), and the correlation of these results with meteorological theories; and the design of a new compact photographic dosimeter for personnel monitoring that is capable of recording as much information as possible concerning the energy of the beta particles, gamma rays and neutrons producing the dose, as well as registering the dose received.

The most interesting aspects of the measurement of radioactivity in the human body are two fold; on the one hand there is the development of new techniques for measuring radiation from radionuclides within the human body, and interpreting the results, and on the other hand there is the application of a particular technique to the study of the behaviour of radioactive materials in the body. The development of techniques includes the study of the energy spectrum of the radiation emitted from bulky sources of radioactive materials, and its variation with gamma-ray energy, with distribution in an absorbing medium, and with the size of the medium. There is also the study of the directional properties of various types of collimators at different gamma-ray energies, so that small amounts of radioactivity may be localised *in vivo*. An important problem is the study of the nature of the background counting rate of various types of counters, especially those using as detectors crystals of thallium-activated sodium iodide. The techniques developed may be used to determine the retention-time pattern for radioactive substances which gain access to the body either accidentally in minor laboratory incidents, or under controlled conditions, that is by injection or orally. In the latter case there is close collaboration with the Medical Research Council's Radiobiological Research Unit at Harwell. The information which can be gained from such studies is directly applicable to the assessment of maximum permissible concentrations in air and water of the radionuclides concerned.

The Aerosol Group of the Health Physics Division carries out research on the important class of problems concerned with the physics and chemistry of small airborne particles of radioactive substances. Fundamental knowledge of the behaviour of these small particles is important in the design of effective systems to remove radioactivity from air and in the calculation of rate deposition and range of travel of radioactivity released to the atmosphere. The meteorological aspects of this subject are studied both in the field and in the laboratory. Cloud chamber techniques are used to investigate the mechanism by which small particles become attached to cloud droplets, and a small wind tunnel is used to study the deposition of aerosol particles on surfaces. By attaching radioactive nuclides to them, the movement of sub-microscopic aerosol particles can be followed. The application of aerosol studies to practical problems in the Atomic Energy Authority is also pursued. In one series of such experiments, radioactive iodine vapour was released into the containment shell of a reactor at Harwell and studies made of the behaviour of the activity regarding its adsorption on condensation nuclei in the air as well as on the reactor and the walls of the containment shell; and also with respect to the behaviour of the filtration plant through which the exhaust air from the reactor shell is released.

The Public Health Section of the Operations Group has the main task of carrying out radiochemical analyses of samples of soil, herbage and milk from around Harwell to ensure that their radioactive content is not seriously increased as a result of work carried out at the establishment. Research is also carried out on the safe disposal of radioactive liquid wastes in rivers. The work includes both field and laboratory investigations into

the biological and physical uptake of specific radioisotopes. The field studies on the fate of radioisotopes as they are carried downstream are carried out on the Thames, into which limited amounts of liquid radioactive effluent are discharged from Harwell under controlled conditions. Caesium-137, one of the principal radioisotopes in effluent from Harwell, is a particular case which is being studied and giving results of great scientific interest.

The Solid State Physics Division

A new Physics Division has recently been created at Harwell to carry out fundamental research into the structure and behaviour of solids, making particular use of the special facilities provided by the research reactors. This work has been carried on for a considerable period already, originally under the Metallurgy and the General Physics Divisions, and, more recently, in the Metallurgy Division.

The aim of the work is to increase our understanding of the behaviour of solids under all kinds of physical conditions (including the situation in a reactor where the material is irradiated by energetic particles). Many solids have highly complex physical properties, the understanding of which has had not only intrinsic scientific value, but has also produced materials and devices which have had a revolutionary effect on industry and technology. The functioning mechanism in these devices is the crystallographic structure of the substance, and the working parts are the individual atoms themselves. This understanding has come about as the result of fundamental research into the properties of crystalline matter, and the furtherance of such research at Harwell is the main activity of the Solid State Physics Division.

The work is carried out under four main headings, neutron crystallography, inelastic neutron scattering, physical properties of metals and alloys, and, in the future, radiation damage. These are outlined in more detail below.

Elastic scattering of thermal neutrons by a crystal is predominantly Bragg scattering from the regularly aligned nuclei. In many materials a considerable contribution is made by scattering from the aligned magnetic moments of electrons. Investigation of the patterns of these magnetic moments in ferro- and antiferromagnets is central to the study of magnetism and is leading to a greater understanding of the electronic constitution of the transition metals and their compounds. Work of this kind is mainly carried out on spectrometers with crystal monochromators, of which there are several in the Division.

Inelastic neutron scattering allows the excited states of crystals to be studied, such as phonon vibrational states, magnetic spin wave states and electron band states. These studies have already been extremely rewarding, and have supplemented and confirmed many theoretical ideas on the thermodynamically important excited states of crystals. The work involves good energy resolution and one of the instruments used is the mechanical velocity selector shown in the plate opposite page 9.

The study of physical properties of metals and alloys includes work on many transition metal alloy systems, using many techniques including electronic specific heat measurements at liquid helium temperatures, nuclear magnetic resonance and line breadth measurements, optical properties, high precision gamma-ray absorption spectrometry (the Mössbauer effect), magnetic susceptibilities, and diffusion properties. One of the aims of this work is also an increase in our understanding of the transition metals.

Readers familiar with semiconductor physics will know that recent investigations have shown the great value of using superpure materials in solid state investigations. Though superpure materials are of no direct engineering application in themselves, they allow special atomic mechanisms in solids to be studied in simplified circumstances, and are therefore an important requirement of the work. Part of the supporting effort of the Division will be devoted to preparing such specimens.

The Metallurgy Division

Since 1946 interest in the newer metals has been stimulated by the atomic energy programmes for which it was necessary to develop quickly the science and technology of uranium, thorium and plutonium as fissile and fertile materials; magnesium, zirconium, beryllium, vanadium, niobium and special stainless steels as canning materials; cadmium, and to a lesser extent hafnium and the rare earth metals, as control materials.

There are general features of similarity between these metals. The extraction processes are all relatively complicated compared with those of the more readily available metals. All these metals are reactive and in many cases their physical properties, notably their ductility, are highly sensitive to small concentrations of soluble impurities such as hydrogen, oxygen, and nitrogen.

As a result of the emphasis on purity, significant improvements have had to be made in the development of fabrication techniques. Examples which spring to mind are vacuum melting and casting, melting both in inert gases and in vacuo, and specialised welding techniques.

For some metals such as thorium and niobium, the high melting points and chemical reactivity have necessitated the development of powder metallurgy techniques and advances have been made in hydrostatic pressing and high temperature vacuum sintering techniques. Similar developments are necessary with beryllium but for the different reason that with this metal there is general brittleness of the large-grained as-cast material. The physical metallurgy of uranium and plutonium is complicated by their existence in several allotropic modifications, and their alloying behaviour does not conform to the patterns followed by the simpler metals.

In contrast to these points of similarity, neutron irradiation of fuel and canning materials has brought entirely new features to metallurgical studies. Dealing first with

uranium, the most important and most interesting features are in its behaviour under irradiation as a reactor fuel. Fission of the uranium 235 atoms takes place releasing large amounts of energy; thus when natural uranium (containing 0.7 per cent uranium 235) is irradiated in BEPO for a year about one atom in 7,000 undergoes fission and the energy produced is sufficient to melt all the material in a 'thermal spike' 10^4 atoms in length and 100 atoms radius. In each fission about 25,000 atoms are displaced by knock-on collisions, so that every atom in a bar of uranium is knocked out of place a few times a year under these conditions. Furthermore the fission products are chemically different and about ten per cent of the new atoms are the rare gases krypton and xenon.

Three broad effects are associated with fission:

(*a*) Interstitial atoms and vacancies are formed by neutron bombardment and bombardment by fission fragments.

(*b*) Small regions of high temperature lead to local increases in volume around the 'thermal spike' due to thermal expansion. This introduces internal stress systems associated with plastic deformation.

(*c*) An increase in the number of atoms present may cause a large decrease in density if bubbles of the inert gases are nucleated.

The magnitude of all these effects will of course increase as we move to power reactors with higher neutron fluxes and heat ratings.

Alpha uranium is anisotropic and this anisotropy can also play a part in the behaviour under irradiation. The stresses set up in the region of the thermal spike lead to anisotropic deformation, causing a change in shape of a crystal which can be related to its crystallographic orientation. The nett result of the heating and cooling processes during a fission event is that a crystal changes shape on irradiation, tending to grow in a particular direction. This phenomenon, known as irradiation growth, can be minimised by obtaining a randomly oriented fine-grained structure; one way in which this can be achieved is by rapidly cooling through the α/β transformation (β quenching) of uranium.

A second phenomenon encountered in the irradiation of uranium is at high burn-up, when swelling occurs. Swelling is the term used to describe the marked decreases in density observed in some samples irradiated in the higher temperature ranges (above 450 degrees C) and is associated with the nucleation of the fission gases. The latter is a complicated process and may be affected by thermal fluctuations during the irradiation and by other factors.

This is a very condensed account of the phenomena encountered in investigating uranium as a reactor fuel. While natural uranium has been adopted as the fuel for the large gas-cooled nuclear stations now being built, and is expected to give satisfactory performance, for future advanced gas-cooled reactors a fuel of higher irradiation life is required. There has been a change in emphasis therefore towards ceramic fuels, as exemplified by uranium dioxide and uranium carbide, with particular attention being concentrated on the former. Uranium dioxide is known to pose fewer irradiation problems than the metal but suffers from the disadvantages of being a brittle material and possessing a much lower thermal conductivity than the metal.

For advanced gas-cooled reactors operating at higher temperatures than the present stations under construction (600 degrees C compared with 450 degrees C), uranium dioxide has been chosen as the fuel and there are two alternative canning materials, beryllium and stainless steel. Beryllium is a relatively new metal and research is proceeding on its physical metallurgy and fabrication. Under irradiation, helium is produced in beryllium by nuclear reactions and the nucleation of the helium gas atoms into bubbles, and the subsequent effects on the mechanical properties of the beryllium are being investigated. Stainless steel is better known to metallurgists but problems arise from the high neutron absorption of stainless steel which makes it necessary to use very thin cans. The steels therefore must have very low inclusion contents and they must possess high-temperature creep resistance.

A further field of vital interest in metallurgy and ceramics is plutonium utilisation. Plutonium will be a by-product of the large nuclear stations and in the 1960's will be available for enriching natural fuel. Pure plutonium has six allotropic forms and the transformation temperatures have been determined by thermal analysis and dilatometry and by measurements of electrical resistivity and magnetic susceptibility. Considerable interest has been attached to the negative coefficients of expansion of two of the plutonium allotropes (the delta and delta-prime phases). This behaviour is unique among pure metals having isotropic crystal structures and poses theoretical problems.

Since plutonium will be used as enrichment, and not in the pure form, attention has been concentrated on plutonium alloys, cermets (mixtures of refractory plutonium compounds in metallic phases) and plutonium ceramics. There is thus a broad area of research and development necessary in this field, particularly in investigating the irradiation behaviour of these novel fuels.

The Metallurgy Division consists of eight groups devoted to carrying out basic research on these problems and developing the basic technology of the materials discussed above.

There are three irradiation groups, working on metallic fuel irradiation, ceramic fuel irradiation and basic irradiation studies respectively, with extensive facilities for experimental work in the DIDO and PLUTO research reactors and the carrying out of post-irradiation examination.

There are also groups engaged on ceramics, fabrication development, plutonium metallurgy, physical metallurgy, and corrosion, the major part of the research being concentrated on the materials discussed previously.

As will be seen, the Metallurgy Division is concerned with a wide range of investigations, which involve many fields of science. Not only metallurgists, but physicists and chemists in considerable numbers, are employed. The Division is equipped with the most modern apparatus, including powerful electron microscopes, the latest equipment for X-ray diffraction and X-ray fluorescence analysis, advanced neutron diffraction equip-

ment, an ion accelerator, a micro-beam analyser, remote-handling facilities for radioactive materials, apparatus for the accurate measurement of physical and mechanical properties, and modern equipment for testing materials in a variety of ways.

The Chemistry Division

Chemistry plays a vital role in atomic energy, and several fields of fundamental chemical research have been stimulated as a direct result of the needs of the nuclear programme. The Chemistry Division is one of the original Harwell divisions, and is the largest scientific division in the Research Group with fourteen groups organised into four branches. In addition to the laboratories at Harwell there are also outstations of the Analytical Chemistry Branch at Woolwich and Chatham where much specialised research into analytical methods and the provision of specialised analytical services are undertaken.

The work is of two kinds, studies directed towards certain definite requirements in the atomic energy programme, and long-term fundamental work of interest in the field of atomic science, some of it directly related to projects of the first kind. Certain service requirements are also fulfilled, such as the provision of specialised analytical services and the production of electromagnetically separated isotopes.

The work is largely of a physical or inorganic nature, apart from that of a small specialist organic group, and great emphasis is placed on radio-chemistry and radiochemical methods. The Division occupies a leading position in many fields of chemical research, and much of its work is published in the form of reports and papers to scientific journals. In the past twelve years 1,120 reports and over 700 papers and review articles have appeared. Staff are encouraged to present their work at scientific meetings at home and abroad where this is appropriate.

The groups of the Division are as follows: Analytical Chemistry, Chemical Processing, Electromagnetic Separator, Fission Chemistry, Fission Product Technology, Actinide Radiochemistry, Mass Spectrometry, Organic, Pile Radiation Chemistry, Preparative, Radiation Chemistry, Reactor Chemistry, Solid State Chemistry, and Spectroscopy. The work is so diversified, however, that it is best considered in relation to two important aspects of the nuclear programme: the fuel cycle, beginning with uranium ore and proceeding through the preparation and processing of the fuel to the final waste material, and the design, construction, and operation of reactors.

The range of problems in these two fields is so great that they are best set out in note form. The third group of notes "Fields of Basic Research" lists the areas where long-range fundamental work is required in support of such a programme. In practice the work is seldom broken down in so clear a fashion; there is continuing interplay between basic and applied work, and between different fields of investigation, while the relative importance of different topics will vary according to circumstances.

1. THE FUEL CYCLE

Ore: Analytical determination of low-grade sources to aid prospecting.

Extraction and purification: Methods of extraction by conventional and new techniques such as solvent extraction and ion exchange. Analytical methods for process and quality control.

Preparation of fuel: Production and properties of metallic and ceramic fuels. Analytical methods for determining impurities and alloying materials.

Irradiation in reactor: Radiation damage to fuels and to reactor materials. Fission product build-up on long irradiation. Escape of fission products from defective fuel elements.

Processing of irradiated fuel: Extraction processes based on solvent extraction, ion-exchange, and other techniques. High-temperature processes based on slagging and on molten metal extraction. Behaviour of fission products in the extraction process.

Storage and disposal of wastes: Recovery of specific fission products from highly active waste solutions. Conversion of highly active wastes to non-leachable glasses. Chemical and ion-exchange treatment of low-activity wastes.

2. REACTOR DESIGN AND OPERATION

Fuel: New fuels, their preparation and properties, e.g. ceramic fuels for high-temperature reactors.
Radiation damage and the loss of fission products from damaged fuels and from defective cans.

Reactions between fuel and coolant gases under irradiation.

Moderator: New moderator materials, preparation and properties, e.g., beryllia.

Analytical control of impurities in moderator materials.

Coolant: Removal of fission products from a contaminated coolant circuit (gaseous or liquid).

Radiation effects in organic coolant-moderators.

General: Moderator-coolant reactions under irradiation in gas-cooled reactors, e.g. graphite $+O_2$, CO_2, N_2, H_2, He, etc.

Corrosion problems in water-cooled reactors.

Transport of corrosion products and of escaped activity in water circuits.

Safety problems of a chemical nature related to reactor operation.

Chemical reactions under reactor irradiation, and the possibility of chemical synthesis in nuclear reactors by fission recoil effects.

The production of separated isotopes and of highly pure chemical species for cross-section studies to determine absorption and scattering properties of reactor components, reactivity changes in fuels, and the safety of reactor systems.

3. FIELDS OF BASIC RESEARCH

Analytical research: New techniques in conventional analysis. Improved polarographic techniques; mass spectrometry. Radioactivation analysis and isotope dilution methods applied to trace analysis and to geochemical research. Nuclear magnetic resonance and electron paramagnetic resonance techniques.

Extraction processes: New solvents and improved methods of solvent extraction. Chelating agents and specific ion-exchange resins for recovery processes. Thermodynamics of solvent extraction. High-temperature extraction processes.

Ion exchange: Kinetics and equilibria; natural ion-exchange materials and new synthetic ion-exchangers. Electrodeionization studies with permselective membranes.

Solid state chemistry: Chemistry of the oxides and other refractory compounds of the heavy elements. High-temperature equilibria and selected crystallographic studies. Gas-solid equilibria and kinetics. Radiation damage studies based on broadening of X-ray line profiles.

Radiochemistry and nuclear chemistry: Studies of the fission process and of the chemical behaviour of systems undergoing fission. Fission yields and the formation of transuranic elements by multiple neutron capture.

Inorganic chemistry: Chemistry of the heavy elements, e.g. Po, Pa, U, Np, Pu, Am.

Chemistry of other metals, e.g. Be, Ru, Zr, Nb.

Radiation chemistry: Irradiation effects in selected organic systems. Gas-solid reactions under the influence of ionizing radiation. Calorimetric measurement of absorbed energy. Chemical reactions induced by fission recoil.

Physical chemistry: Electrochemical studies. Effect of radiation on gases adsorbed on solids. Activity coefficients in aqueous solutions at high temperatures.

Spectroscopy: Spectra of the heavy elements. Term analysis of U and Pu emission spectra. Infra-red studies on $HF\text{-}UF_6$ systems.

The Chemical Engineering Division

The work of the Division falls into two classes, that concerned with operations and that concerned with processes. The latter for example includes processes for the production of graphite and heavy water, for the separation of irradiated fuel, and the disposal of fission products. The former includes the study of fluidisation and certain fields of heat transfer. The distinction is not clear cut since process technology may demand special attention to a particular operation, while the study of an operation may be influenced by process requirements arising during its course. Thus all groups of the Division do both classes of work to a greater or lesser degree.

The scale of the work varies from the bench to sizeable pilot plants. Full scale work is generally done elsewhere, for example in the Authority's Production Group or in the Development and Engineering Group, and members of the Division are frequently associated with such work. By no means all the work is experimental. The choice of a process and the design of plant depend not only on technical but also on economic factors, so that design studies and economic appraisal are important aspects of the chemical engineer's work and often control the direction of the research.

The following examples chosen from current work illustrate the wide range of problems dealt with by the Division.

The large power reactors now being built in this country are of the gas (carbon dioxide) cooled graphite moderated type, but there is considerable interest in cooling by boiling water. A particularly interesting system is that in which the coolant is a two-phase mixture of steam and water—the 'wet' steam or spray cooling region in which high heat transfer coefficients can be obtained and high heat fluxes used. Research is therefore being conducted on heat transfer under these conditions and also on the hydrodynamics of the system with the object of defining the effects of the various parameters. Heat transfer experiments have been carried out at pressures up to about 100 p.s.i., and equipment is now being commissioned which will enable experiments to be made up to 1,500 p.s.i. Programmes have been prepared for the Mercury Computer, which enable the experimental readings to be rapidly translated into heat transfer coefficients, etc., thereby saving much laborious and time consuming hand calculations.

Fluidisation is a technique employed for example in some of the processes for the production of uranium tetrafluoride from ore concentrates; it has also been proposed for certain types of nuclear reactor. In order the better to understand the mechanics of the operation and to improve methods of scale-up, basic work is in progress particularly on the hydrodynamics of gas and particle flow. One part of this work is concerned with bubble formation, and experiments are being carried out in fluidised beds of various sizes and also with hydraulic models. Some understanding of the reasons for the stability of bubbles has already been obtained, but the reasons for the formation of such bubbles are still sought.

Fission product wastes present a long term problem, and ultimate storage in solids instead of liquids is the goal. The most promising process incorporates the wastes into a glass, by evaporation and fusion with glass forming materials such as borax and silica. Inactive operation of the process at about full scale has demonstrated its feasibility; and in conjunction with tracer work on a smaller scale, and laboratory work on glass composition, the stability of selected glasses to leaching and to radiation have been established. There are problems concerned with the volatile fission products still under study, but the success of the work so far justifies going to much higher levels of radioactivity as the next stage of pilot plant development. A pilot plant for operation at up to 1,000 curies is now in hand and should be ready for commissioning about the end of 1961. This work includes a wide range of chemical engineering topics; among them, heat transfer both in the furnaces and in the glass itself, since the radiation-induced heating sets limits to the size of the block, gas filtration and absorption.

The processing of irradiated fuel elements sooner or later introduces the problems of 'criticality', the hazard of an uncontrolled nuclear reaction. The best way of eliminating the hazard is to use equipment of such dimensions that a critical condition can never never arise—'eversafe geometry'. This implies a multiplicity of small units rather than one large one, so that there is a premium on obtaining the maximum throughput in such units. Increase in throughput can be sought in several ways, e.g., improved efficiency of contacting equipment in solvent extraction, higher flow rates in continuous plant, and process changes to enable higher concentrations to be used. Generally some combination of these is the optimum. One group of the Division is therefore engaged on experimental work whose goal is the design of equipment of eversafe geometry and high capacity.

Graphite is the most widely used moderator in British reactors but its use in the more highly rated reactors of the high temperature type imposes new demands on the graphite technologist. Some of these demands may be met by variations on current processes or by the use of different raw materials. Others however may require a completely new approach. There is a considerable element of empiricism in graphite technology, and one object of the Graphite Group of the Division is to rationalise this. The main current interest however is to use whatever understanding there is in an effort to produce improved types of graphite, especially those of low permeability and of higher density. Considerable success has been achieved by modification of current processes but the goal is far from reached. However these improved types are being used in reactor experiments. New methods are also under examination; one at least has produced attractive material on the small scale.

Of course, the final test of a graphite is its behaviour under irradiation, and its compatibility with the coolant; this work therefore brings the chemical engineer into close collaboration with physicists and chemists—indeed this collaboration with other disciplines is characteristic of the work of the Chemical Engineering Division.

This account would not be complete if it did not mention another aspect of the

Division's work in providing a consulting service on chemical engineering problems. A good example of this sort of work is the design of the coolant clean-up circuit for the DRAGON reactor, where members of the Division are collaborating very closely with the design office in drawing up the flowsheet and in specifying the plant required, a rewarding application of knowledge gained in previous projects in the gas cleaning and cryogenic fields.

The Isotope Research Division: Wantage

The Isotope Research Division consists of four main research groups: the Chemistry Group, Physics Group, Technological Irradiation Group and Technical Group; and the Isotope School. The Isotope Division Experimental and Advisory Service is operated jointly by the Physics and Chemistry Groups and the newly formed Industrial Liaison Team is formed by detachments from all Groups. The Division which is mainly concentrated at the Wantage Research Laboratory, ten miles from Harwell, has a small group at Harwell to make special irradiations and to do research directly connected with reactors.

The Chemistry Group

This Group is working on some of the chemical aspects of use of radio isotopes in industry and medicine, including investigations into the preparation of isotopes and radioactive compounds by new methods and techniques. As the interests of the Group are many, it contains a wider selection of scientific discipline than is usual in a Group of this size.

Radioactive tracers offer many advantages in analytical chemistry. The technique of radioactivation analysis is a most powerful method for use in trace element analysis (for quantities of 10^{-6} gm. or less). Modern industry is becoming increasingly interested in very pure materials and a service is operated to carry out such analyses. In addition many other analytical applications are always under consideration.

In the Nuclear Chemistry section, studies have been made of various secondary nuclear reactions in the reactors available at Harwell, of the excitation of fluorescent X-rays by radioisotopes, and of the reactions and yields in cyclotron targets, etc.

In Physical Chemistry, the technique of autoradiography is being developed and applied to problems in metallurgy, electrodeposition and surface exchange reactions.

Other work involves the use of co-ordination compounds in the study of ground water tracing and the labelling of industrial materials such as oils. The problems currently occupying the organic chemists are those of labelling organic compounds with tritium. They are investigating and comparing the phenomena that occur when the various labelling techniques, of which there are many, are used on different classes of compounds.

Medical interest has always been high in the study of the effects and distribution of radioisotopes in animals. The efforts of the Isotope Research Division in this field

have been concentrated on the use of colloids and emulsions. The work involves the preparation of radioactive colloids of various elements, investigations into their stability *in vitro* under various conditions, followed by laboratory trials on the distribution of the injection in experimental animals. Fuller chemical assessment is obtained by the hospitals who are collaborating in this work.

The Physics Group: Laboratory and Field Experimental Service

The Physics Group at present carries the main load of the Experimental and Advisory Service, handling about 2,000 technical enquiries a year. This service tackles practical problems, largely from industry, by radioactive techniques and requires experiments both in the laboratory and in the field.

Basic investigations are made into the properties of radiations and the advantages and the limitations of various measuring techniques are assessed. The performance of Geiger and scintillation counters and of ionisation chambers under special conditions is examined and the operation of new forms of detectors including semiconductors is explored.

Many thickness and density gauges using the absorption and scattering of radiations have been designed. The general principles of design and performance of these instruments are now established, and commercial firms deal with routine enquiries, but new investigations, particularly into the use of *bremsstrahlung* and other secondary radiations, are in progress.

A special section deals with the application of radioactive tracers to geophysical and hydrological problems, with special reference to the silting of rivers, coastal erosion and movements of water underground.

Another section specialises in metallurgical applications especially with the powerful techniques of autoradiography.

The Technological Irradiation Group

This group investigates possible industrial uses for the large amounts of radioactive materials obtainable directly or indirectly from the nuclear power programme. The main sources of radioactivity are cobalt-60, produced directly in reactors, and caesium-137, obtainable in increasing quantities as a fission product. Millions of curies a year are available.

The Technological Irradiation Group examines the basic problems in the fields of radiation biology, chemistry and physics for the exploitation of these large sources. In studies of sterilisation by radiation, the present emphasis is on the sterilisation of medical and surgical materials. The sensitivity of bacteria to irradiation is investigated both fundamentally and technologically.

Studies are being carried out on the various biochemical changes which take place when food stuffs are irradiated. In addition, extensive animal feeding trials are in progress to investigate possible physiological changes which might result from the consumption of irradiated food.

Investigations are being made into the effect of radiation on insect pests in stored products. The main effort is on a study of lethal and reproductive sterilisation effects with the purpose of evaluating doses for commercial treatment.

In inducing mutations in plants, radiation allows greater possibilities of breeding strains that are disease resistant, more fruitful or more amenable to cross-breeding. Investigations are being made into various sensitising agents which increase the sensitivity of plants towards radiation, and hence, may increase the mutation rate.

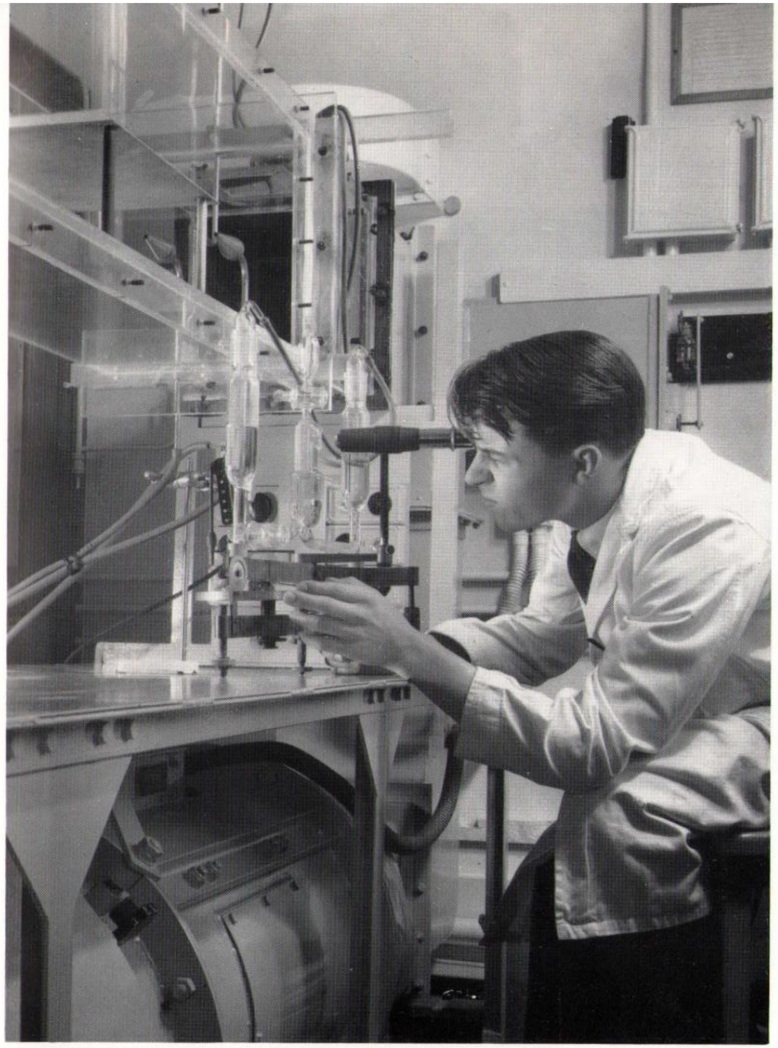
In chemistry, work has been concentrated on a study of chain processes, the three main topics being polymerisation, halogenation and oxidation. A study is being made of various aspects of graft polymerisation. Attempts are being made to reduce the solubility of silicone rubbers and also to modify the surface properties of fibres, and investigations are also being made into the possibility of using this process for the vulcanisation of various rubbers. The oxidation of hydrocarbons is being investigated, so far at atmospheric pressure only, but it is intended that high-pressure work shall be carried out. In halogenation, a subject that has attracted considerable interest recently is the effects of radiation on catalysts. Work at Wantage is being carried out using, for example, zinc oxide, irradiation of which produces changes in electrical and magnetic properties of fundamental importance.

The physics section of the Technological Irradiation Group is mainly engaged in design studies for industrial irradiation units, and in economic studies to ensure the maximum efficiency of utilisation of radiation. In addition, the physics section is responsible for operating the many large radiation sources available at Wantage Research Laboratory and for development work in dosimetry.

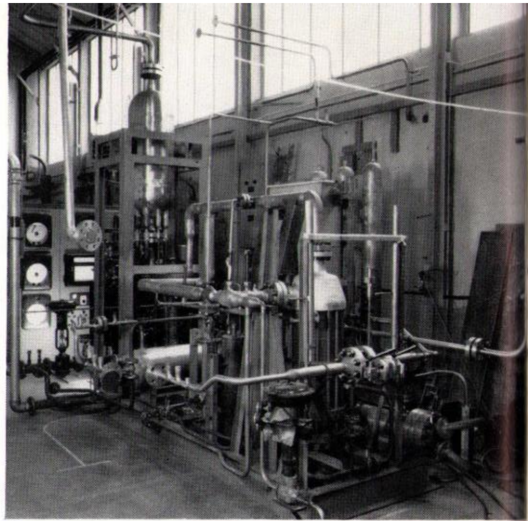
The Technical Group

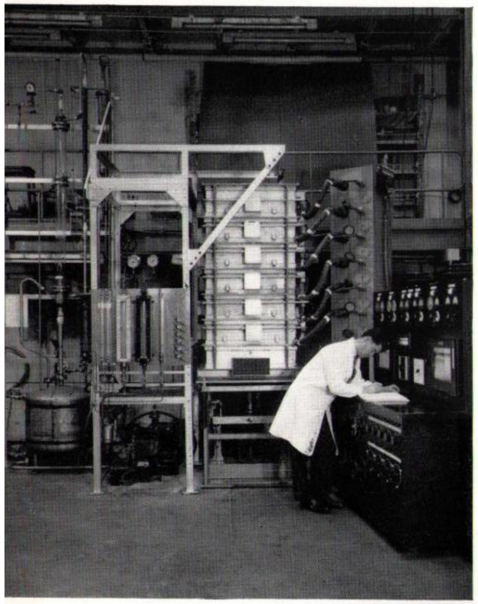
This group serves the requirements of the Division and other users, at Harwell and elsewhere, for reactor irradiations of a specialised nature in which some degree of research or special supervision is necessary. It is also concerned with reactor measurements associated with the production of new isotopes or novel irradiation facilities.

A radioactive standards service is operated by which absolute measurements of radioactivity are made for the Authority and for other British and overseas users on request. This is backed up by fundamental research into methods of absolute measurement, in full collaboration with the National Physical Laboratory and other standards authorities. This section was the first to introduce a reliable method of measuring electron capture isotopes. The standards work forms part of a wider programme of research



HEALTH PHYSICS DIVISION. A small wind tunnel being used to study the deposition of radioactive aerosol particles on horizontal surfaces. In the photograph a Chattock-Fry gauge is being used in conjunction with a pitot tube to measure the air speed



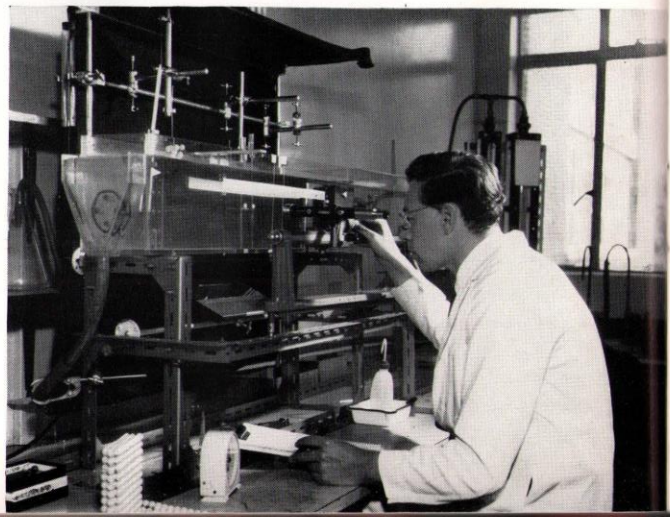


CHEMICAL ENGINEERING DIVISION

(*Above*) High-pressure two-phase heat-transfer rig in course of construction

(*Left*) Experimental plant for the incorporation of fission products in glasses

(*Below*) The measurement of drag forces in a hydraulic tank



in dosimetry and measurement which is associated with many of the activities of other groups in the Division.

Practical advice is also given and experiments undertaken in special aspects of isotope application, particularly gamma radiography.

Experimental and Advisory Service

This service provides advice and information on isotope techniques, mainly to industrial users but also to hospitals, universities and other establishments. Experimental work is undertaken if required and varies from initial feasibility studies to complete investigations on the site of the problem.

Typical tracer investigations are the determination of mixing efficiency of minor constituents in such diverse substances as cattle food, chocolate, hardboard and gramophone records. Field investigations have also been made to detect leaks in water mains, to trace the fate of fuel spilled from an aircraft in flight and to test the efficiency of ventilation systems. Radioisotopes, in conjunction with suitably adapted detection equipment, have been used to study hydraulic flow in pipes and in rivers, to measure silting of rivers and harbours and to follow the movement of sea-beds in studies of coastal erosion.

Close liaison with research associations and establishments of the Department of Scientific and Industrial Research is maintained through a small unit from the Department, attached to the Division.

The Research Reactors Division

Because Harwell's research is concerned principally with the study of materials for the nuclear power programme, the establishment has need of reactors of medium and high flux, for nuclear physics measurements and for examining the effects of radiation on materials and components. Medium flux reactors are GLEEP, BEPO and LIDO and high flux are DIDO and PLUTO. In 1960 these and the other Harwell reactors were placed in the charge of the new Research Reactors Division. This division has three main responsibilities: firstly, the operation and maintenance of the reactors themselves; secondly, the design and engineering of many of the experiments associated with them; and finally, the design of new research reactors. The division is divided into four groups the functions of which are discussed in the succeeding paragraphs.

The Operations and Plant Engineering Groups are responsible for running and maintaining the reactors. The first, besides operating the reactors, studies their behaviour under varying conditions; the group's responsibilities include the experimental facilities that are provided within or adjacent to the reactors. The Plant Engineering Group's primary responsibility is to ensure the reliable maintenance and safe operation of the reactors and their equipment. The work ranges from the interpretation of operational measurements to the study of new designs and the problems of control and instrumentation in research reactors.

The Design Group is concerned with all aspects of engineering design within the Division. It is divided into sections dealing specifically with the design of in-pile equipment; the alterations and additions to reactors; the instrumentation and control of reactors and in-pile experiments; the testing and commissioning of in-pile experiments; and the preparation of design studies for new reactors. Irradiation equipment is also designed for use by other divisions; notably the Metallurgy, Chemistry and Nuclear Physics Divisions. The Group collaborates with the Operations Group on proposed modifications to the reactors and on the operational aspects of the irradiation equipment.

The Physics Branch includes a Physics Group and is also responsible for the Harwell Reactor School. The latter is an essential part of the Authority's training programme. Its main purpose is to train United Kingdom and overseas staff concerned with the design, instrumentation and construction of power reactors.

The Physics Group is responsible for providing the necessary physics information relating to the safety, operation and use of research reactors. The physics characteristics of all the research reactors and their associated experiments must be studied and understood. As modifications to the reactors are frequently suggested and undertaken there is an almost continual experimental and theoretical study of such features as neutron flux distribution, mean neutron lifetime, reactivity calibration curves of control absorbers, xenon poisoning, etc. A technical section employing professional engineers within the group and using data obtained on the reactors, provides a service to reactor users and designers: it has been concerned with problems associated with nuclear heating, heat transfer, neutron flux depressions caused by experiments, and neutron and gamma-ray shielding.

Some basic research work closely connected with the uses of research reactors is also undertaken. A typical example is the attempt being made in collaboration with Metallurgy Division to correlate fast neutron spectra with radiation damage in various reactor materials. This has led to the development of fast neutron detectors and new methods of calculating fast neutron spectra.

The more general work in which the Division is engaged includes the modernisation of BEPO; improvements in facilities of the heavy water reactors; and the design and construction of DAPHNE, the heavy water zero energy reactor.

The Engineering Contribution to Research

The scope for the professional engineer at Harwell is very wide, and indeed the several Engineering Groups together comprise 2,600 people of whom 350 have professional status. The engineer has several essential functions to fulfil, viz., to build, maintain and operate

the research tools the scientist requires to obtain his results, and to apply those results together with any necessary engineering development to the practical problem of harnessing nuclear power.

In the development of reactors these roles are complementary and regenerative. Thus it was the engineers' task in 1947 to translate the theories of the physicist into the working realities of the early research reactors GLEEP and BEPO. These research reactors were initially in themselves experiments on a grand scale; once the engineers had designed and built them, and established their operational routine, they became standard services for the use of the scientific divisions for irradiation experiments. These experiments then frequently became complex, simulating the problems of reactors of the future fluid circuits; and their design, construction, erection, operation and maintenance are again the concern of the engineer. Some of the experiments in BEPO were undertaken to provide data for the design of the Calder Hall reactors, while others gave the results needed for examining the feasibility of more advanced research reactors at Harwell and elsewhere. A similar cycle has evolved from the building of the heavy-water high-flux research reactors DIDO and PLUTO, with the engineer playing a vital part in each phase.

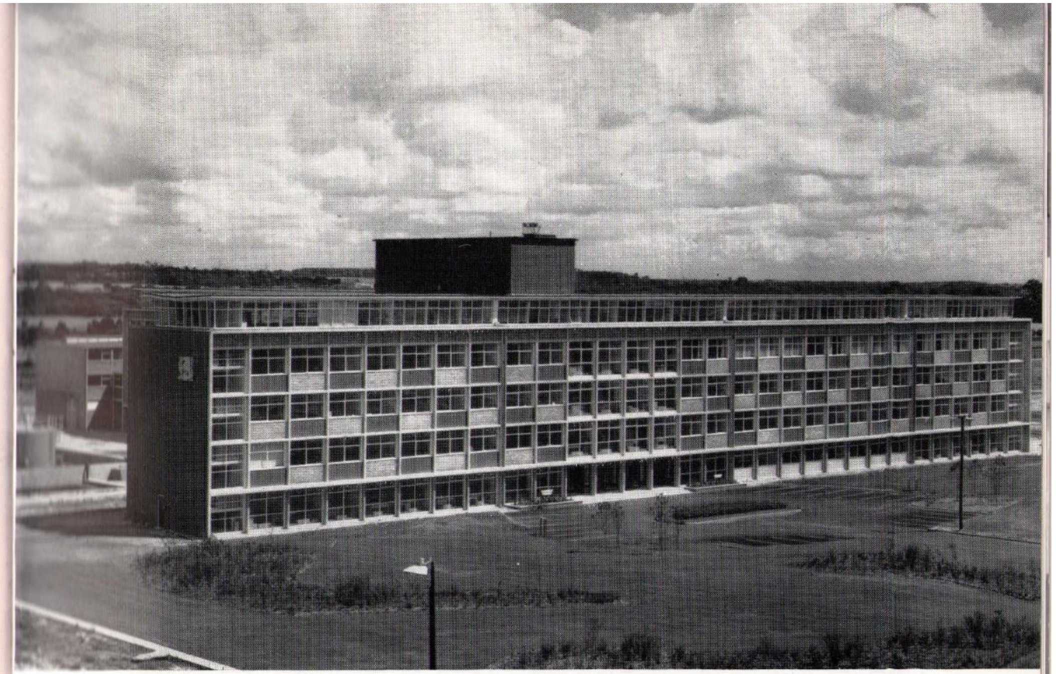
The engineering of either a new reactor or experimental equipment presents many interrelated problems of limited space and novel materials. The change of properties of the materials under irradiation together with the effect of radio-activity make high demands on engineering design skill. Thus the mechanical engineer has to be circumspect in his choice of material. This has led to the use of unconventional materials such as beryllium, titanium gold, platinum and zirconium. He has also to ensure reliable equipment to operate in situations inaccessible for maintenance, while the electronic engineer has to design control and indicator instrumentation to function accurately and reliably in a radioactive environment.

A large number of engineers are engaged on the particle accelerators with which the physicist explores the detailed structure of matter. The most spectacular of these machines is the 7,000,000,000 eV proton synchrotron, under construction for the Rutherford Laboratory.

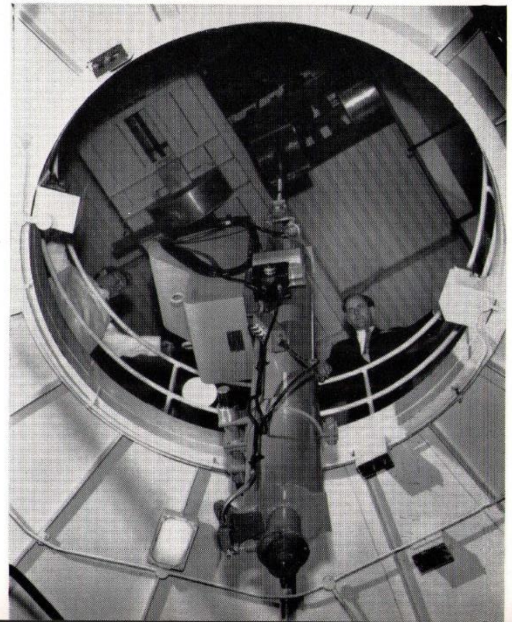
In common with so much of the engineering effort at Harwell, this machine has demanded bold and original thinking since there was little experience to draw upon. Among the many problems that are being solved is that of laying accurately the concrete monolith which is the foundation for the 7,000 tons of magnet ring. The monolith is required to be free from either sagging or hogging, and to tilt by not more than $\frac{1}{4}$ in. over its 150 ft diameter, in order that the magnets themselves may ultimately be levelled to within 10 seconds of arc from the horizontal. The torus-shaped vessel which will contain the proton orbit is being designed to a demanding set of conditions: it must contain a vacuum of better than 10^{-6} mm. of mercury, yet be built of a material that will neither distort the magnetic field nor degrade under proton bombardment. To produce the required field in the magnet throat, the electrical engineers have had to design a 120,000 h.p. tandem motor-alternator set to supply a reversing current oscillating with an amplitude of 10 kA in a period of less than two seconds. The reversible mechanical forces invoked in both the motor-alternator and the magnet structure create problems of resonance and fatigue which have to be carefully considered, especially in view of the economic necessity of limiting the number of major overhauls to five-yearly intervals.

In other fields no less than in those mentioned engineers are collaborating with physicists to examine fundamentally new ways of exploiting nuclear power. One of these is by means of the controlled fusion of ionized deuterium, and it was to this end that Harwell engineers built ZETA and then continued to help the physicists solve the further problems this machine brought to light. Another group of physicists and engineers is studying the feasibility of other ways of converting nuclear energy directly to electrical energy without an intervening steam cycle.

Finally, mention should be made of the Group where equipment and technique are evolved to enable materials to be handled and worked behind a radioactive barrier. The design frequently appears pleasantly unsophisticated, but creates intriguing problems for the engineer with a flair for ingenious mechanisms.

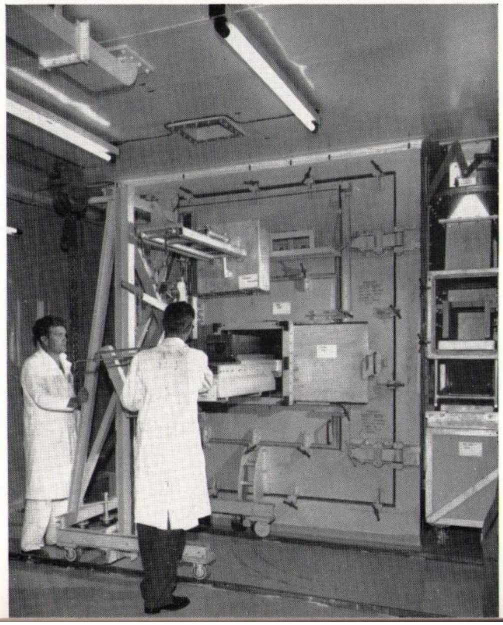


The Reactor Group offices: Atomic Energy Establishment, Winfrith



Reactor fuel element loading flask being lowered into the reactor bonnet: Winfrith

The P A C E analogue computer: Winfrith



S C O R P I O II: insertion of the hot graphite block into the cooling chamber: Winfrith

3

The work of the Research Group: Winfrith

As was said in the introduction to this booklet, the Atomic Energy Establishment, Winfrith, is the Authority's principal centre for basic work on reactors considered as complete entities, that is for work on reactor physics, on reactor engineering physics and technology, and on the assessment of different reactor concepts. These wide fields of study are perhaps not as familiar as some others and it therefore seems appropriate to describe them in a little detail, especially inasmuch as they define, to a large extent, the responsibilities of the principal research divisions at Winfrith. Supporting these divisions are computing, medical, radiological safeguards, and engineering services which also are described below.

Reactor Physics

The term 'reactor physics' covers investigations into the way in which the nuclear chain reaction is maintained by the flow of neutrons in a reactor. Part of the work is theoretical and part experimental. The experimental work mostly consists in assembling fissile material, with or without a moderator, and making a chain reaction take place at a very low rate so that the heat output is negligible. Some of the assemblies are in the form of zero energy reactors, in which the chain reaction is self-maintaining; others are sub-critical and must be fed from an external source of neutrons. Many important features of the behaviour of a reactor operating at a high power level can be deduced from these studies.

Basic Reactor Engineering Technology

The term 'basic reactor engineering technology' covers a variety of work concerned with the flow of heat in nuclear reactors, with the flow of fluids which are used to remove the heat, and with associated phenomena. Although there is nothing novel about the use of fluids to transport heat, the reactor designer requires information that has not so far been found necessary for ordinary engineering purposes. The work in this field at A.E.E., Winfrith, is mainly experimental, to determine the physical properties of materials and the behaviour of engineering systems applied to reactors. The investigation and development of special equipment required to operate under novel engineering conditions is also undertaken.

Control and Instrumentation

Developments in reactor systems call for concomitant developments in methods of control to keep pace with changes in dimensions of reactors and their operating temperatures and to cope with variations in neutron flux distribution. More elaborate automatic control systems will be needed than hitherto. Fission chambers and other flux measuring instruments must be capable of working reliably under far more exacting conditions. This entails the development of techniques to enable detection devices to work reliably at high temperatures. These and other problems of control, in general and for particular reactors, are studied at Winfrith together with work on new techniques and devices for instrumentation.

Scientific and Technical Services

Theoretical studies in the fields described above demand the use on a large scale of both digital and analogue electronic computing machines. The computer service is equipped with Mercury and PACE computers, with access via direct links to machines at other establishments of the Authority.

Specialised engineering services are required at an establishment like Winfrith. There is a group to design and develop research equipment and to provide operations teams to operate the reactors and other research installations. There are workshops in which specialised pieces of research equipment of novel type and of a high standard are made. These are additional to the normal maintenance and manufacturing services.

To safeguard against exposure to radiation, special monitoring services are provided in addition to normal medical services. The work includes environmental surveys of the areas surrounding the site.

The Reactor Systems

There are a number of types of nuclear reactor which appear to merit further development, but serious limitations may be encountered with any one of them. For this reason, work is going on in the Authority with the object of improving our knowledge of several of these types and of the problems which will be encountered in their development. The types to which the present work at A.E.E. relates are briefly described below.

First are the magnox reactors, fuelled with uranium metal rods sheathed in the magnesium alloy from which they derive their name. The moderator is graphite and the coolant is carbon dioxide. Reactors of the magnox type have been operating since 1956 at Calder Hall, and since 1959 at Chapelcross. Larger reactors of the same type, but of more advanced design, are being constructed by industry for the electricity authorities under the Government's Nuclear Power Programme. At Winfrith work is in preparation to study the effects on reactor physics of the build-up of plutonium in the uranium fuel as it is burnt.

The next step beyond the magnox reactor is the advanced gas-cooled reactor. This is based on the use of uranium oxide sheathed in stainless steel and later in beryllium. The moderator is to be graphite and the coolant carbon dioxide. The rate at which heat is extracted from the fuel, and the coolant outlet temperature, are to be higher than those that can be attained by the magnox type of reactor. The fuel will be slightly enriched in the uranium-235 isotope. A prototype advanced gas-cooled reactor is being constructed at Windscale by the Development and Engineering Group of the Authority. The work at Winfrith relating to this type of reactor is mainly in the field of reactor physics, but there is also some work on the stability of thin sheaths of stainless steel.

In the third system, the high temperature reactor concept, it is proposed to use a refractory non-metallic fuel consisting of fissile materials dispersed in a solid moderator. The fuel will also contain thorium which will be transmuted to the fissile isotope uranium-233, so maintaining reactivity. Helium is preferred for the coolant because it is chemically inert. Much of the work on the high temperature gas-cooled system, being undertaken by the Authority at Winfrith, is in direct support of the Dragon Project, which is building an experimental reactor of this type.

An entirely different system is the fast reactor. In this no moderator is used, so that the neutrons retain the high velocities with which they emerge from fission. The core of the reactor must contain a much higher proportion of fissile material than is needed in the other systems. The most suitable coolants are liquid sodium and sodium-potassium alloy. An important advantage of the fast reactor is that a larger proportion of the neutrons can be used to transmute fertile into fissile material, thus reducing fuel costs.

The feasibility of some of the novel features of the system is being investigated with the high-power reactor that has been built by the Authority at Dounreay. Further reactor physics studies are needed to carry the development of this system forward and a zero-energy fast reactor named ZEBRA is to be built at Winfrith.

Lastly a wide variety of reactor types, in some of which the functions of coolant and moderator are combined, can be conceived using liquids containing light or heavy hydrogen. Amongst these types are the boiling water reactor and the organic liquid moderated reactor. None of them has yet been chosen for development as a power reactor by the Authority, but some are under consideration, especially with the propulsion of merchant ships in view.

Work is going on at Winfrith in the field of basic engineering technology on heat transfer in these systems, including studies of boiling and burn-out. A basic study of the reactor physics of light hydrogen-moderated reactors is also being undertaken.

The DRAGON Project

The joint project known as the O.E.E.C. High Temperature Reactor Project or simply as the DRAGON Project has arisen out of discussion which took place under the auspices of the European Nuclear Energy Agency of the Organisation for European Economic Co-operation. In March, 1959, twelve O.E.E.C. countries agreed 'to participate in studies and research in connection with the high-temperature gas-cooled reactor system and in the possible design, construction and operation of a reactor experiment'.

Six countries—Belgium, France, Italy, Luxembourg, the Netherlands, and Western Germany—will participate through Euratom, the other partners in the enterprise being Austria, Denmark, Norway, Sweden, Switzerland, and the United Kingdom. The agreement provides for a joint project in the field of high-temperature gas-cooled reactors with its headquarters in the United Kingdom at Winfrith, and covers a period of five years, from April 1st, 1959.

The objectives of the joint project are two-fold, namely to carry out a programme of research and development work on high-temperature gas-cooled reactor systems and to design, construct, and operate a reactor experiment embodying the results of this research and development work. The research and development work will continue over the whole period as, although the basic design of the reactor experiment has to be frozen early on in the programme, there is always the need to carry out continuing work in support of the engineering design. Staff needed for the work at Winfrith have been seconded to the project by the different countries so that an international team has been built up. In addition contracts have been placed in the various countries for research and development work and for the supply and manufacture of plant and equipment.

There have been several schemes for high-temperature gas-cooled reactors described in the technical literature during the last few years, the main difference between these schemes being in the form of the fuel elements which it is proposed to use. In the reactor experiment for the joint project the fuel elements are cylindrical and consist of an 'impermeable' graphite can containing the fuel inserts. The helium coolant removes the heat from the core of the reactor as it flows under pressure past the fuel elements. In the heat exchanger the heat is removed from the hot gas (800°C) and rejected to the atmosphere, while the cool gas (350°C) is pumped by the circulating fans around the inside of the pressure vessel back to the reactor core to complete the circuit. Provision is made for having an inward leakage of helium into the fuel element can: the gas is then passed through a fission product trap and returned to the circuit. This keeps the activity of the main coolant circuit as small as possible.

4

The work of the Research Group: Amersham

The Radiochemical Centre has the responsibility of producing and marketing all the radioisotopes offered for sale by the Authority for civil purposes. It is an Establishment of rather more than three hundred people within the Research Group, and its head offices and principal laboratories are situated at Amersham in Buckinghamshire, twenty-five miles north-west of London in the Chiltern Hills. It also has a department at Harwell for exploiting the reactors there.

Chemists are the largest professional group of the Centre, but the work is increasingly concerned with the production of very large quantities of radioisotopes—to some millions of curies in the case of cobalt 60—and accordingly its operations are becoming more complex from the engineering and physical aspects. Opportunities for physicists and engineers are therefore increasing.

The range of isotopes produced by the Centre is very wide and the chemical interests correspondingly so. Some eighty to ninety radioactive isotopes are extracted in simple chemical form, either from irradiated materials or from fission products.

Many hundreds of 'labelled compounds' are derived from these isotopes by chemical synthesis or by biochemical techniques. For example more than two hundred compounds containing carbon 14 have been synthesised, including amino-acids, steroids and other compounds of biological interest. Special compounds are often required by research workers in industrial or medical pursuits, and these bring their particular problems. The various radioelements which occur in nature form an important part of the Centre's interests, and from these as well as from artificial radioisotopes, a wide range of radiation sources containing alpha, beta or gamma emitters is manufactured. These are used in industrial instruments in radiography and radiotherapy.

There is a close liaison with many users of radioisotopes throughout the world; the staff of the Centre advises them in solving their problems and is constantly engaged in devising means of providing special materials to meet their particular needs, and generally in extending the range of products in all categories.

The chemical scale of the work is usually small, but the scale of radioactivity now extends up to the thousand-curie level. Work with radioactive substances brings with it the problems of radiation effects on materials and upon the course of chemical reactions, of dealing with weightless ('carrier-free') materials and the necessity of operating processes remotely to avoid exposure to radiation.

This work is particularly attractive to chemists who have a sound general grounding in inorganic, physical or organic chemistry, and who are interested in such experimental techniques as gas-phase chromatography, paper chromatography, ion-exchange methods, microchemical and microbiological methods, vacuum manipulation, autoradiography, and 'hot atom' chemistry.

A heavily screened bench for chemistry with radioisotopes:
Radiochemical Centre, Amersham