E·MINIMIS·MAXIMA

Research Careers in Atomic Energy

at Harwell, Culham 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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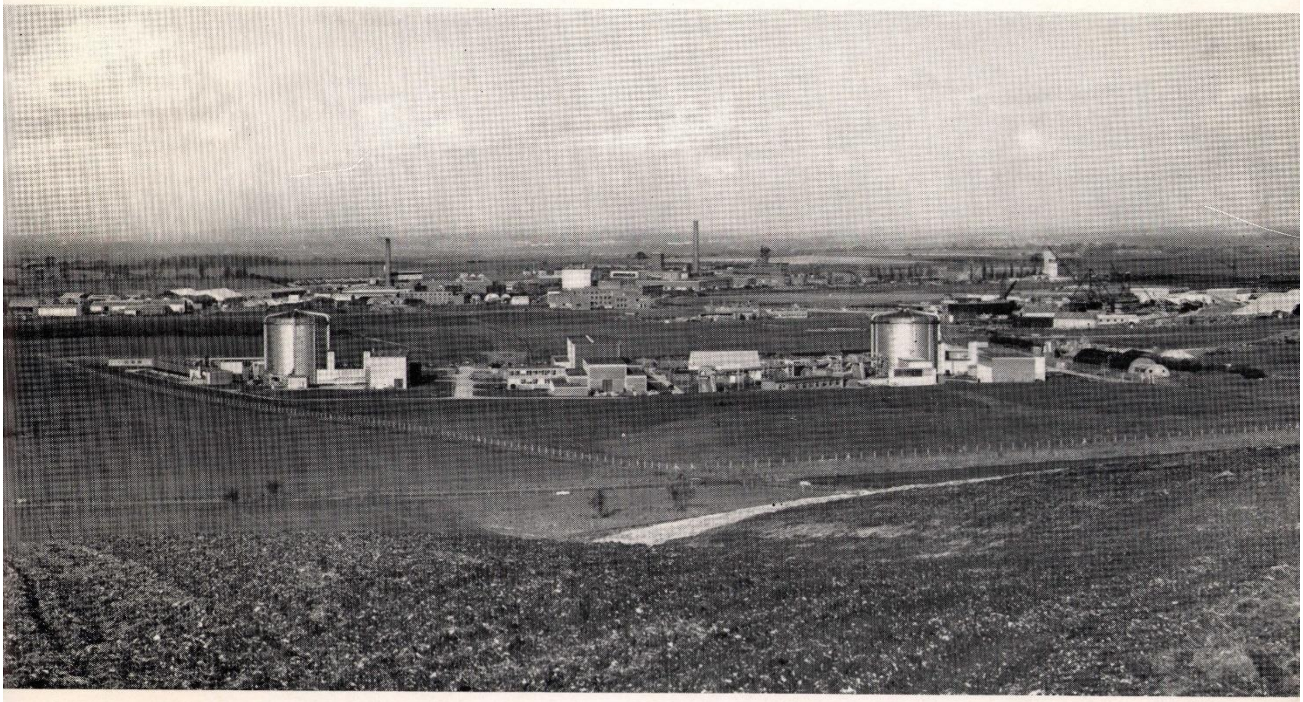
Contents

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. 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



Atomic Energy Research Establishment, Harwell

The Harwell Library: Enquiry Desk and Reading Room 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.

Whilst fission reactors have been developed and improved, considerable attention has been given to the feasibility of a fusion reactor. The general approach entails the use of highly ionised gases (plasma), whose ions may undergo fusion at a rate depending on their temperature. It is likely that temperatures in an ultimate fusion reactor would have to be in the order of 100 million degrees C. The study of plasma physics and means of attaining such temperatures has called for considerable research. It may be considered as analagous to the nuclear physics research, which prepared the way for fission reactors. The high temperature plasma state is proving complicated, very prone to instabilities and difficult to control. New ideas, techniques, instruments and materials are all needed in the field, which is providing a challenge for engineers, scientists and theoreticians alike.

The Culham Laboratory has been set up near Abingdon, in Berkshire, as the Authority's centre for an extensive programme of plasma physics and fusion research and groups previously working on controlled thermonuclear research at Harwell and Aldermaston are being brought together at Culham. The moves have already started and should be completed by the end of 1964. As befits a field of research where collaboration is widespread and free from restriction, Culham is an open laboratory where international projects may be undertaken.

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.

Work of the kind outlined has been going on for thirteen 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.

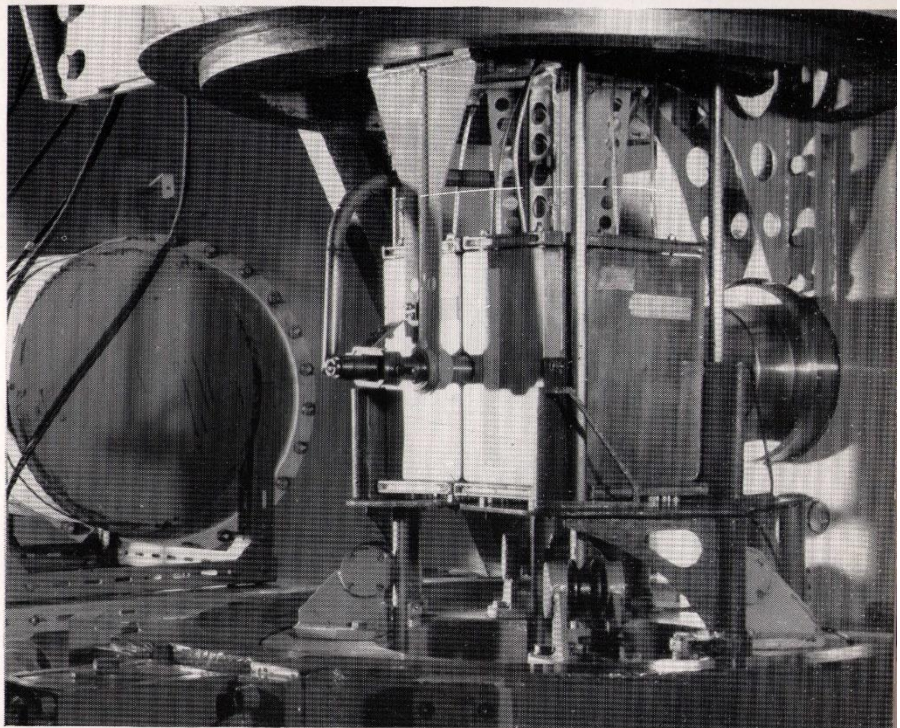
Many of the staff who had been employed on atomic research during the war were appointed to the new establishment and they were supplemented by some of the men who had worked on radar; additional workers were rapidly recruited in almost every branch of pure and applied science. From the first, the work 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. As the Authority's interests widened, especially in the development of nuclear power stations, new research establishments and factories were opened and the total staff increased. In 1959 the Industrial Group was divided into two, the Development and Engineering Group and the Production Group. Two years later the first of these was again divided into the Reactor Group (which includes the Atomic Energy Establishment, Winfrith, formerly part of the Research Group) and the Engineering Group. Thus at present the Authority has five groups—Research, Reactor, Engineering, Production, and Weapons—and a London office, with a total payroll of 40,000 persons.

This development from the relatively small establishments of the Ministry of Supply has taken place in the sixteen years since January 1946. During this period the establishment at Harwell also has changed and proliferated. In 1959 a new laboratory was opened at Wantage, for isotope research, and a new establishment, subsequently transferred to the Reactor Group, at Winfrith, to which work and staff were moved from Harwell. Notwithstanding this the total number of staff of the establishment has risen from about 500 in 1946 to 6,000 in 1961: of these more than a quarter are graduates or hold equivalent qualifications.

The Research Group now consists of three major establishments, viz. A.E.R.E. and its outstations, the Radiochemical Centre, and the new Culham Laboratory for research into controlled thermonuclear reactions, which is in an advanced stage of construction at Culham near Abingdon.



THE HARWELL NEUTRON PROJECT

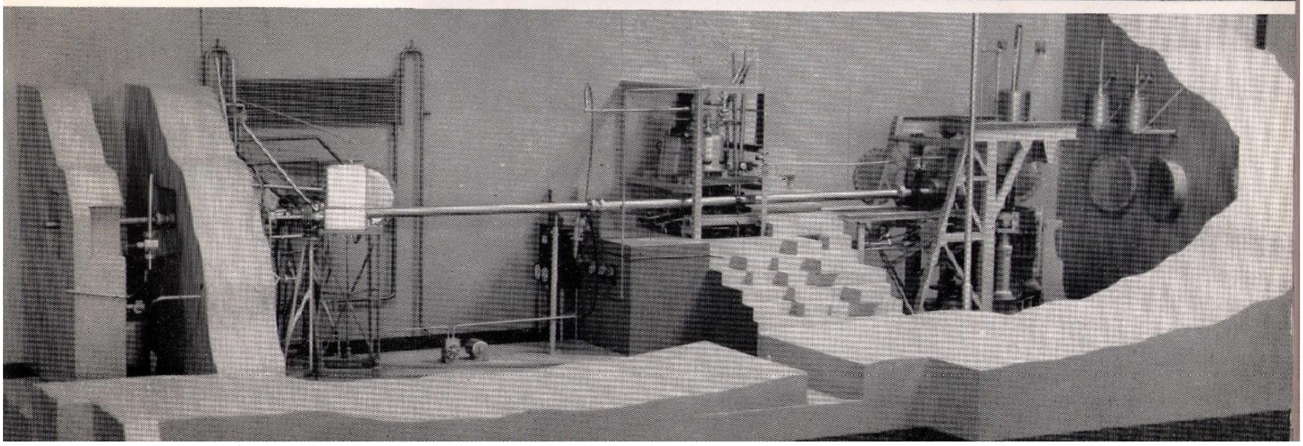
Nuclear Physics Division

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. It is intended for use in neutron time-of-flight experiments

(*Above*) General view

(*Right*) Neutron booster with lead shield open

(*Below*) Model of target cells



A Ferranti Mercury Computer, Theoretical Physics Division, 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 seventy and is divided into five groups. Four 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 fifth 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 extent, field theory and very high energy nuclear physics.

The Solid State Theory Group has extremely wide interests, including magnetic neutron diffraction, properties of transition metals, their alloys and their salts, thermalisation of neutrons, paramagnetic resonance in salts, hyperfine fields in salts and metals, electronic correlation phenomena in solids, band structure and many other aspects of the theory of the electronic structure of solids. The main emphasis of the work is quantum mechanical. Full use is made of the available computing facilities in the pursuit of this work.

The Crystal Defects and Radiation Damage Group which has recently been set up is interested mainly in the fundamental study of the properties of imperfections in crystalline solids and the processes of radiation damage in solids. Initial emphasis will be given to the study of the energy levels and states of imperfect crystals and to the statistical description of systems close to equilibrium.

The Atomic Cross Section Group is concerned with the calculation of accurate cross sections for all kinds of atomic processes particularly those of importance in gas discharges and in the plasma research experiments performed at the new Culham Laboratory.

The Applied Mathematics Group (formerly the Computing Group) has three main functions: (i) to study and advise on major mathematical problems; (ii) to help physics groups with planning and programming difficult computations; (iii) to provide 'open-shop' computing facilities to the whole Establishment. It uses high-speed electronic digital computers which are among the most powerful in the world. At persent these include the IBM 7090 at Aldermaston, IBM 704 at Risley, and Ferranti Mercury and IBM 1401 at Harwell; shortly an IBM STRETCH will be available at Aldermaston and later, at N.I.R.N.S. Harwell, a Ferranti ATLAS to which most of the Establishment's work will be transferred. Work under the above three headings includes: (i) theoretical and computer studies of coupled sets of quasilinear partial differential equations of elliptic, parabolic and hyperbolic types in up to three space dimensions; automatic coding techniques; (ii) evaluation of two-centre integrals for Solid State Theory; neutron spectrum calculations in heterogeneous systems by Monte Carlo methods; (iii) teaching FORTRAN automatic coding, and advisory service to users; data handling techniques. Research aspects are being built up, and there is a lively interest in all branches of mathematics which might ultimately benefit the Authority. All aspects of the work entail close contact with physicists and other scientists, and its variety caters for many different interests.

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 Direct Conversion Group

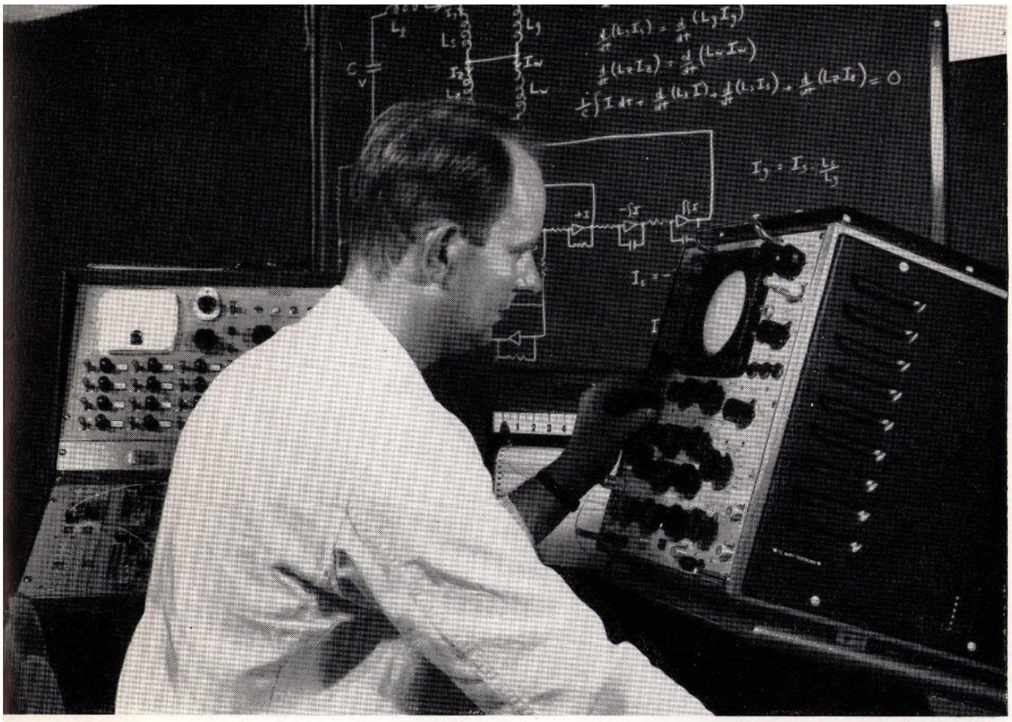
As has been explained in the introduction, the bulk of the work of the former Accelerator Division at Harwell, has been transferred to the Rutherford High Energy Laboratory, belonging to the National Institute for Research in Nuclear Science. The Direct Conversion Group will, however, remain a part of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

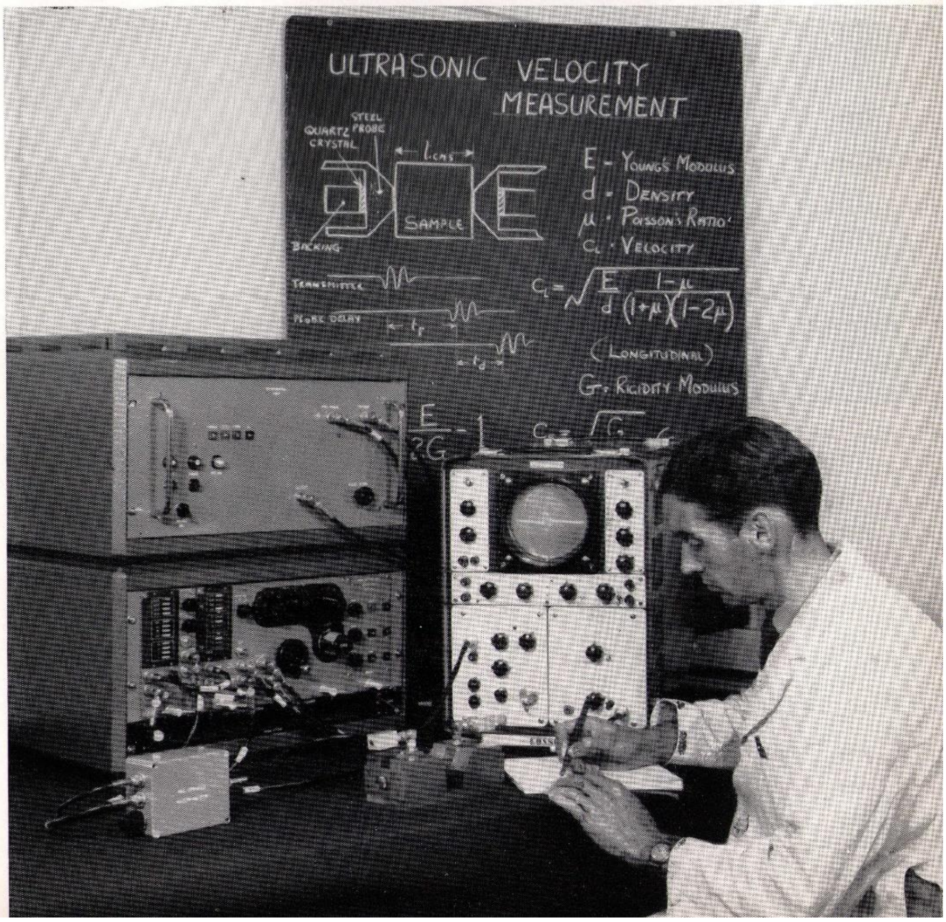
The Electronics Division

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.

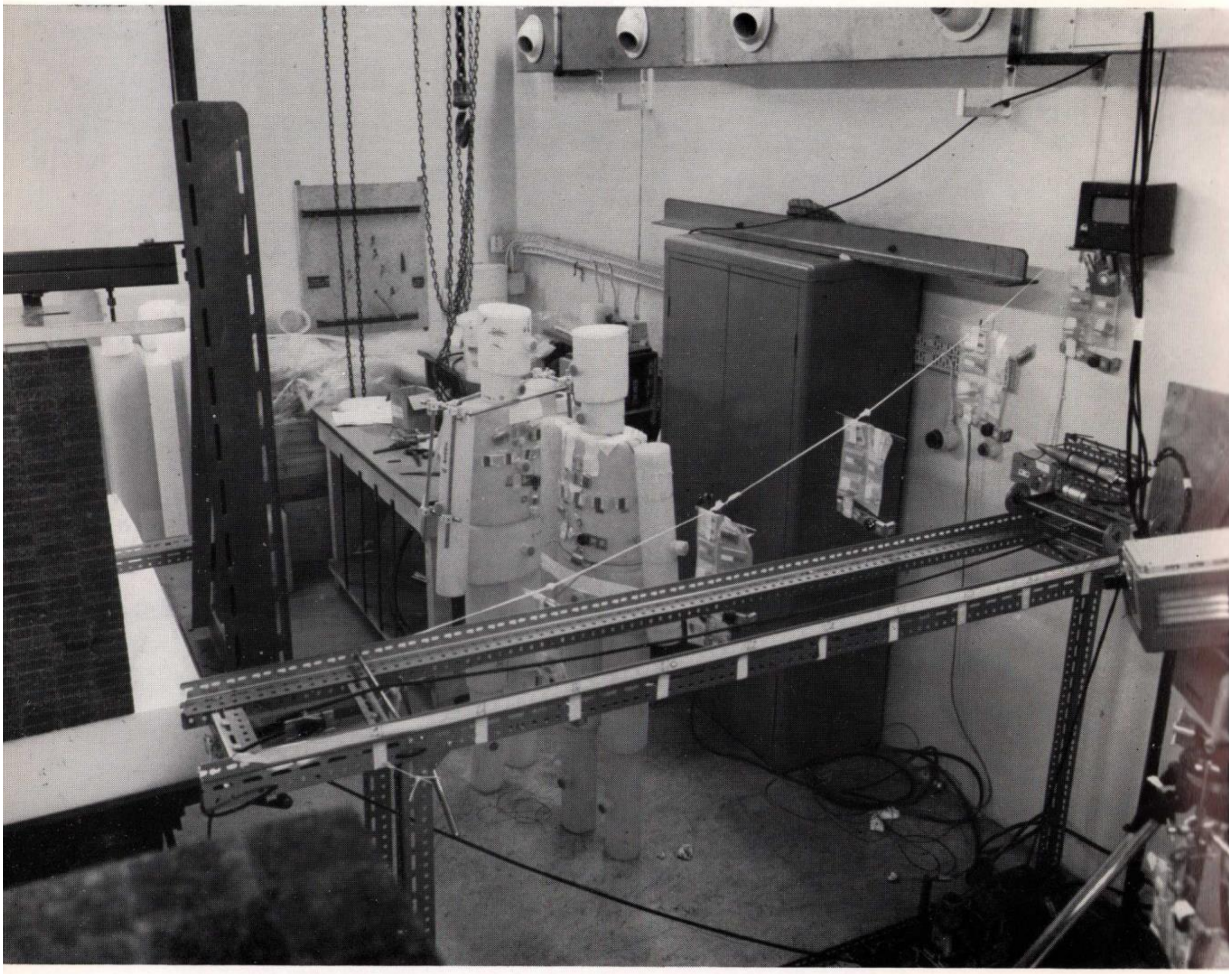
Nuclear experiments using the new high-energy particle accelerators are capable of providing information at a great rate; in order to make the best use of the time of these expensive machines this information must be analysed and recorded very rapidly by specialised electronic data-handling systems and 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.



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



Equipment designed for metallurgical studies: Electronics Division, Harwell



Measurement of neutron and gamma-ray dose to the body from a critical assembly of slightly enriched uranium: joint experiment carried out at Dounreay, by the Dounreay Experimental Reactor Establishment and the Health Physics Division, Harwell

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 requirement in all atomic energy work is to ensure that no one suffers any injury due to radioactive substances or ionising radiations. Fundamental knowledge on the hazards of radiation is limited, therefore the Health Physics Division at Harwell carries out research in the physical sciences on selected topics in this interesting, though difficult, field. Current research includes radiation dosimetry of all types of radiation, the measurement of radioactivity in the human body, the behaviour of airborne radioactive particles and the uptake and fate of radioactive substances on silt and clay. Side by side with research the Health Physics Division 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 laboratories for handling thousands and tens of thousands of curies. Topics for new and profitable lines of research stem from this close association with the health physics problems of research and operational work.

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.

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.

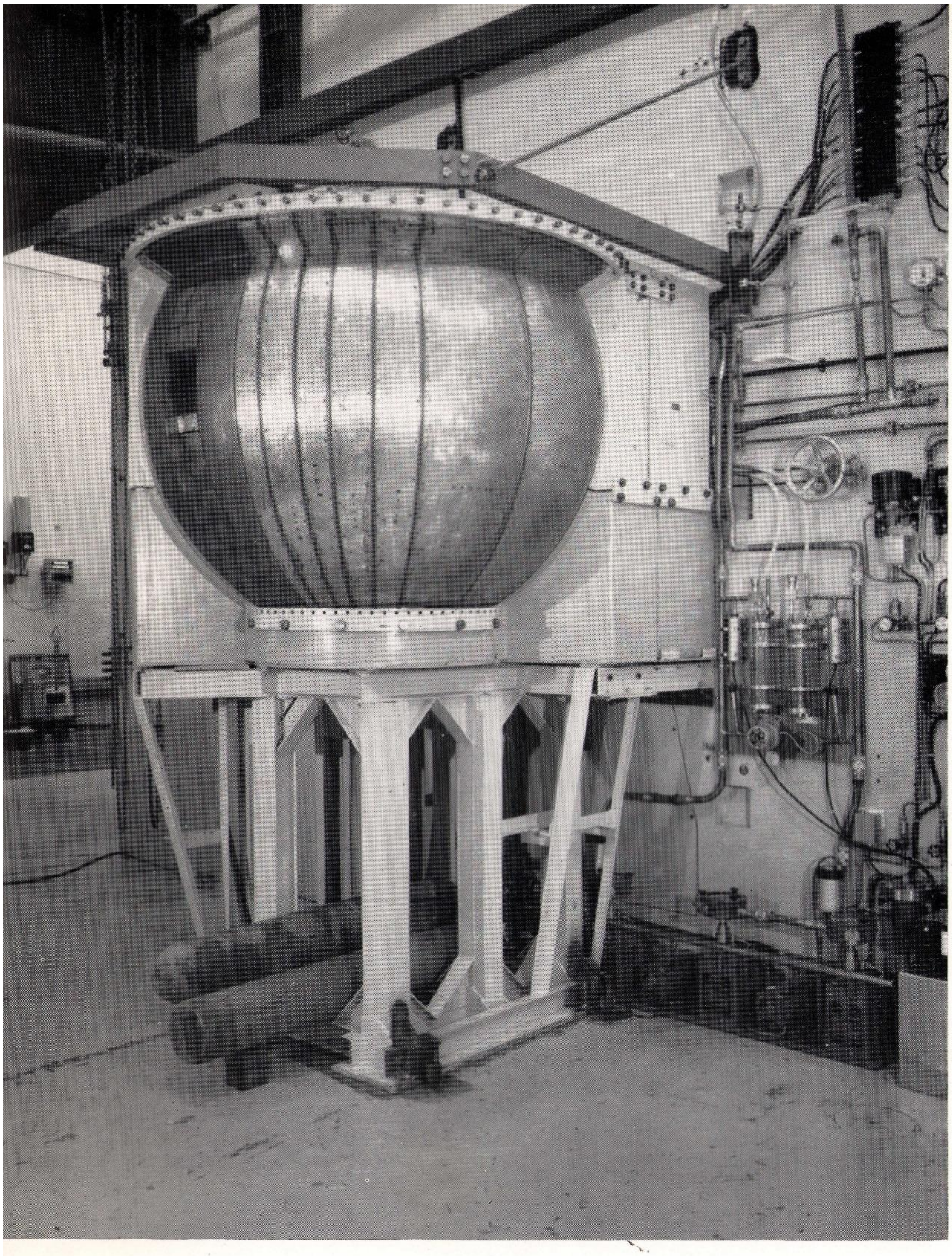
The Metallurgy Division

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.

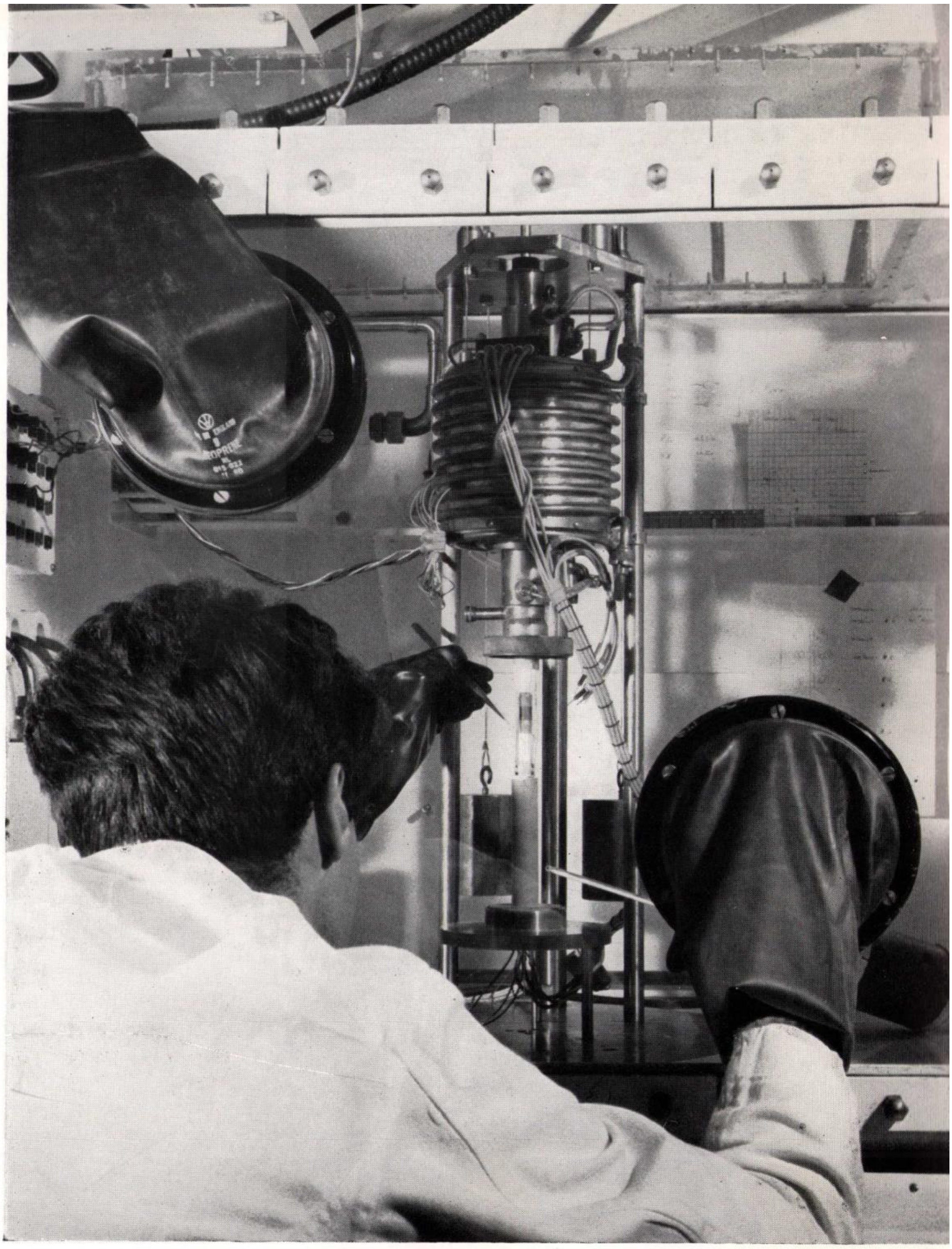
There are general features of similarity between these metals. The extraction processes are all relatively complicated compared with those of the more readily available metals. All these metals are reactive and in many cases their physical properties, notably their ductility, are highly sensitive to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



The twin-rotor mechanical neutron-velocity selector:
Solid State Physics Division



High temperature measurement of the thermal conductivity of a ceramic fuel pellet: Metallurgy Division, Harwell 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 equipment, 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: Actinide Analysis, 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.

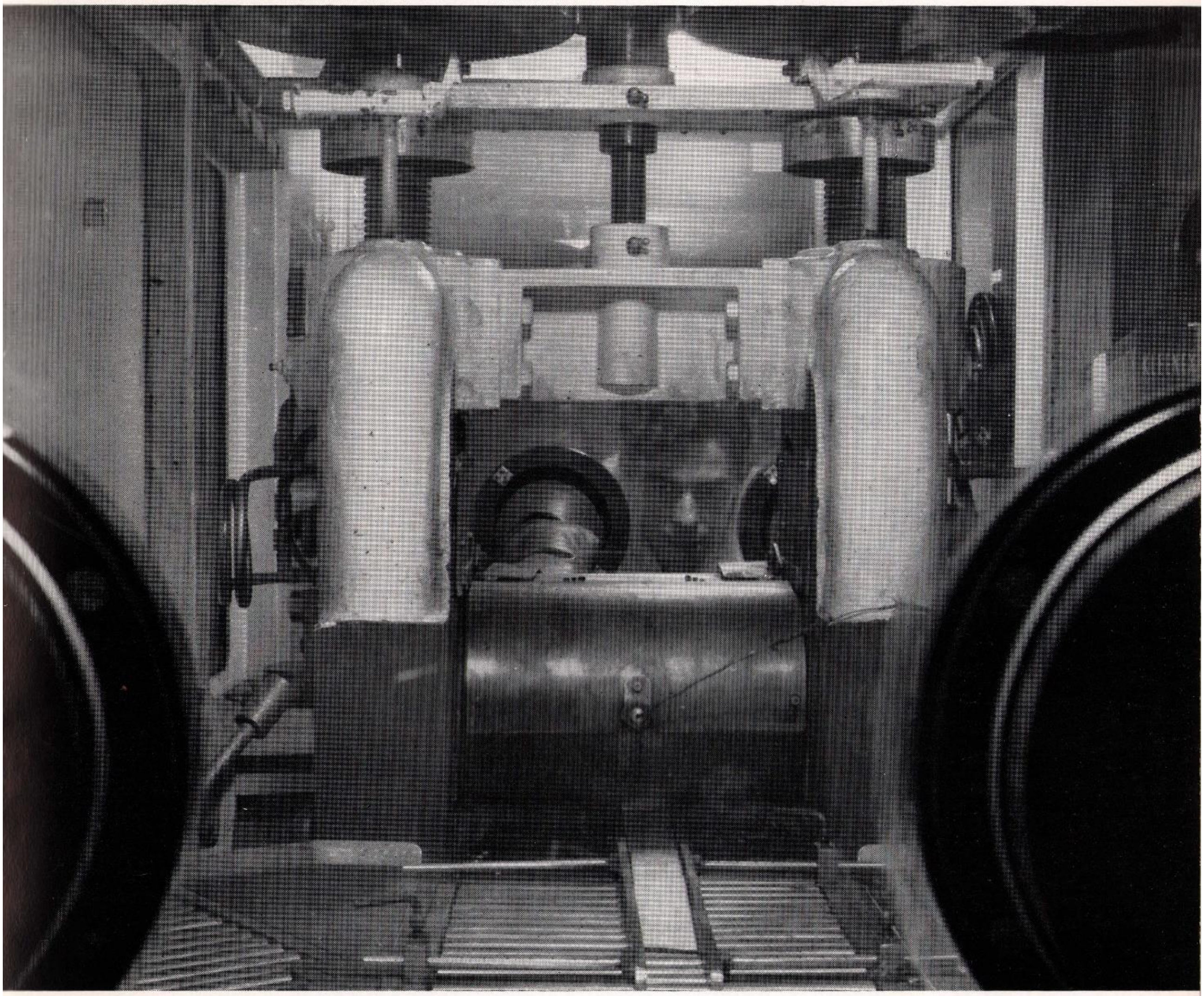
Moderator: New moderator materials, preparation and properties, e.g., beryllia.

Analytical control of impurities in moderator materials.

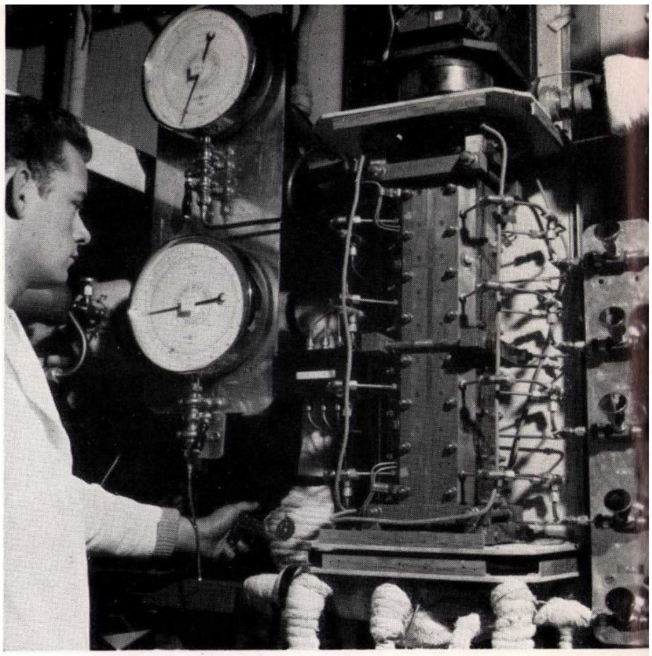
Coolant: Removal of fission products from a contaminated coolant circuit (gaseous or liquid).

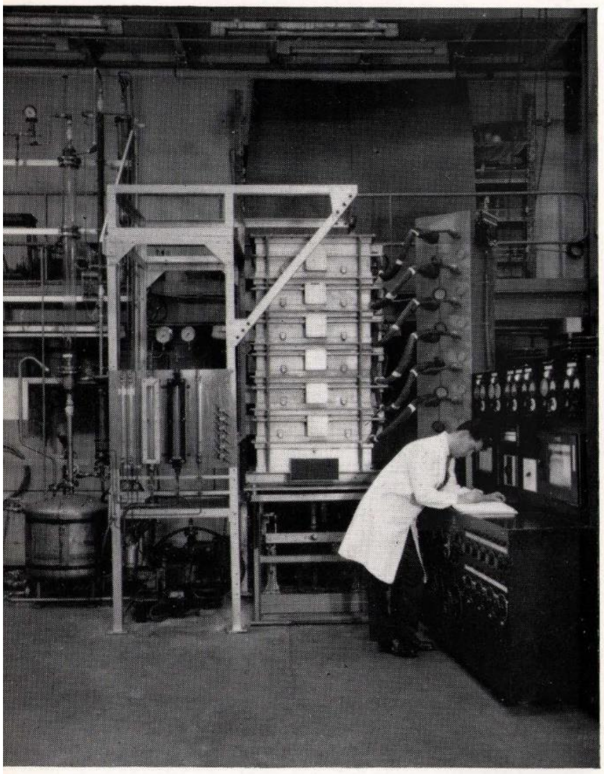
Radiation effects in organic coolant-moderators.

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



Rolling of cermet fuel plates containing plutonium:
Metallurgy Division, Harwell

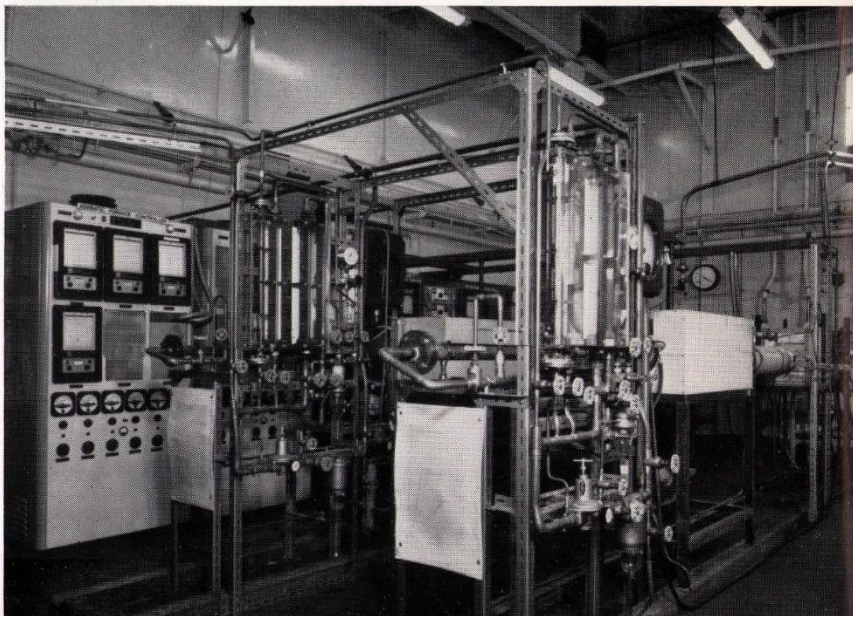




(*Above*) A 'Maltese Cross' test section — designed to simulate effects in rod cluster fuel elements operating with steam-water mixtures: Chemical Engineering Division, Harwell

(*Left*) Experimental plant for the incorporation of fission products in glass: Chemical Engineering Division

(*Below*) Graphite oxidation rig: Chemical Engineering Division



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, for the separation of irradiated fuel, and for 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 Reactor 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 are being carried out at pressures 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 being built and should be in operation early in 1962. 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 have collaborated 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.

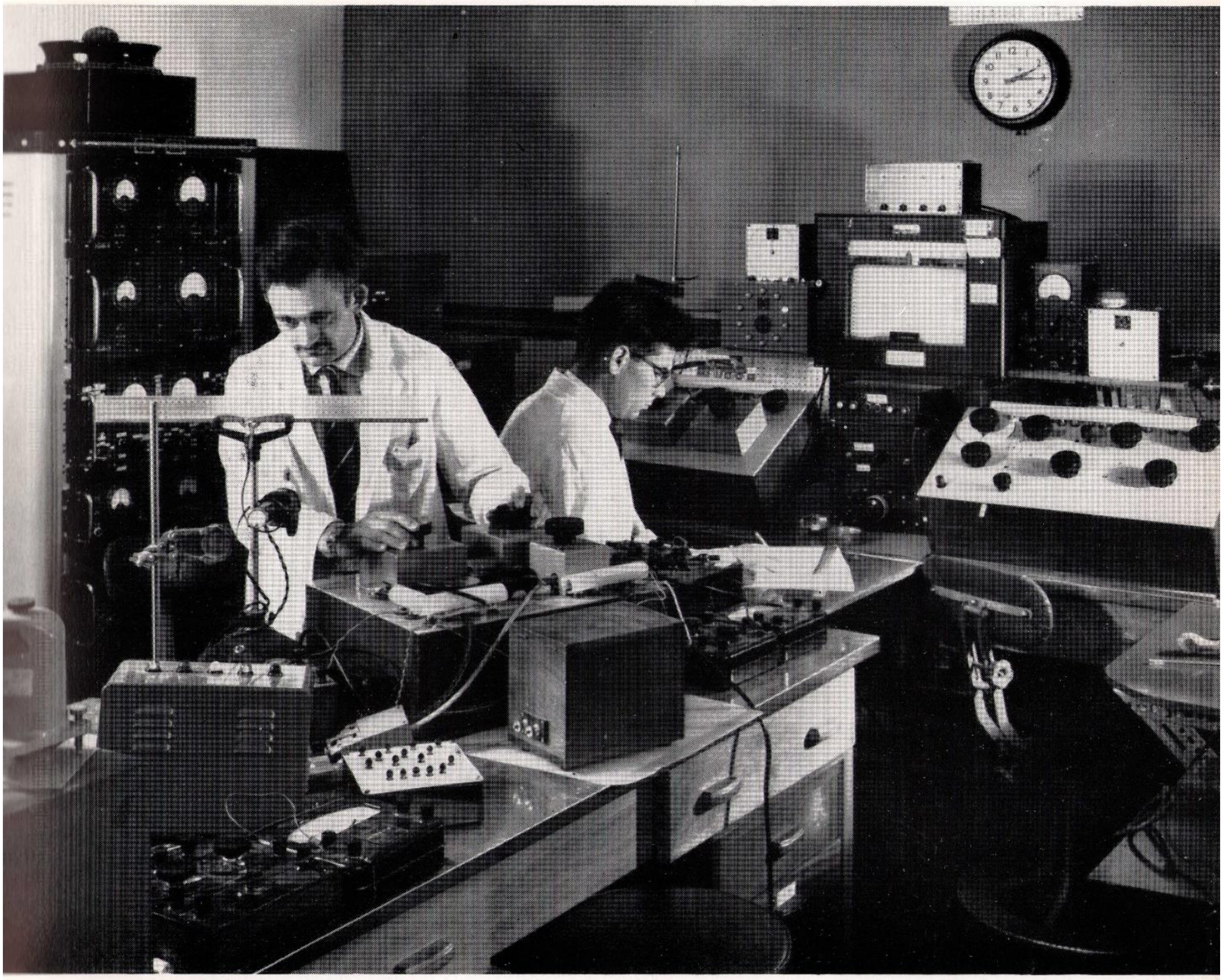
The Research Reactors Division

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.



View of the stored energy laboratory:
Research Reactors Division

HERMES (Heavy Element Radioactive Material Electromagnetic Separator) in operation. Looking from the control desk into the active room, the radioactive source is shown on the left and the collector on the right: Engineering Division, Harwell

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

Engineers at Harwell practise almost every technology. The total engineering staff is about 2,500 including 300 professionally-qualified engineers. Their work is particularly broad in scope and often has a high technical content.

The first function of the Harwell engineer is to build, maintain, and operate the research tools that the scientist needs to investigate the validity of his theories. Established theories are then applied to practical problems, the engineer's second function being to design and develop unusual prototype machines. This may give rise to fresh scientific problems, and the need for further research tools to be developed by the engineer.

One of the first engineering tasks at Harwell was to translate the theories of the physicist into the working realities of the early research reactors GLEEP and BEPO. These reactors, were developed into standard services which are still used for irradiating the scientists' experiments. Such experiments frequently become complex, particularly those simulating other types of reactor. Their design, construction, erection, operation and maintenance are again the concern of the engineer. Experiments in BEPO provided data for the design of the Calder Hall reactors, and more advanced research reactors. The latter include the heavy-water, high flux reactors, DIDO and PLUTO, from which a similar cycle has evolved with the engineer playing a vital part at every phase.

Reactors are by no means the only large machines at Harwell. There are nearly as many particle accelerators, all of which have been designed and constructed by engineers and are now operated and maintained by them. Two of these accelerators were too large to be housed in existing accommodation, and now have their own special buildings. Harwell engineers were responsible for the design and initial construction of the spectacular 7,000,000,000 eV Proton Synchrotron at the Rutherford Laboratory. The proton beam passes through a vast underground magnet room, 200 ft in diameter, and the whole machine occupies an area several times this size. Three electro-magnetic separators have been built at Harwell. At the time of writing HERMES is the only one in the world that successfully separates the isotopes of plutonium.

The engineering of such large machines presents many inter-related problems of limited space and novel materials. The choice of a material for use under irradiation is often severely limited by its resulting activity or other changes in its properties. This has forced the engineer to use such unconventional substances as beryllium, titanium, gold, platinum and zirconium. Their cost necessitates economy in the use of the material and hence new techniques of design and manufacture. Reliability is another important factor, particularly for equipment that has to operate in situations inaccessible for maintenance and a great deal of time is spent in assessing the safety of the different systems to safeguard those who will operate and maintain them.

Each large machine results in many additional items of equipment that are interesting in themselves. For instance Harwell has an international lead in the field of thermal neutron choppers. These are in the form of metal discs about 10 in. diameter and 3 in. thick, rotating at speeds of up to 40,000 r.p.m. In the discs are cut curved slots, 0.1 in. wide, and pulses of neutrons of selected energy are allowed through these slots by controlling the speed of rotation. The design involves the use of air-bearings, magnetic support and a hysteresis motor controlled in phase to within 1 degree.

Many pressure vessels are constructed. A typical one is the Čerenkov Counter used for measuring the speed of π-mesons. This is unusually shaped, highly stressed, and made of non-magnetic materials. Many difficult heat transfer problems are encountered in the design of experiments for reactors. Other important design aspects include low-vacuum technology and very low temperature engineering (cryogenics). The electrical engineer has to design electrical supply systems, special instrumentation and control systems that will function accurately and reliably under active conditions.

Besides supporting the scientists with their experiments, engineers are helping more directly to exploit nuclear power. One way of doing this 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 that 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 heat as an intermediary. Engineers have also supported the power programme by building

FINGALS CAVE. This prototype equipment has been designed for the fixation of fission products from power reactors into glass ingots so that they can safely be left to decay underground. The Engineering Division advises generally on the disposal of active materials, and on decontamination problems which can be simplified by careful choice of materials.

Another responsibility of the engineer is the development of remote handling equipment. Materials that are toxic or produce contamination have to be handled inside special containers called glove-boxes. These have perspex windows, and objects inside can be manipulated using rubber gloves projecting through sealed holes in the walls. Argon is circulated through many of these boxes, and one building has been specially fitted with a huge argon circulating and purification plant. Materials giving out large amounts of irradiation, such as irradiated fuel elements, can be handled remotely from behind zinc bromide windows up to 6 in. thick. Elaborate manipulators are used that faithfully reflect the movement of the operators' hands. There are large numbers of machine tools at Harwell, and some have been adapted for use in glove boxes or by manipulators.

Finally, mention should be made of the many ingenious mechanisms that have been designed for isotopes. Recently Harwell engineers have built several large irradiation plants for the Isotope Research Division. These are being used for the sterilisation of medical supplies on a production basis.

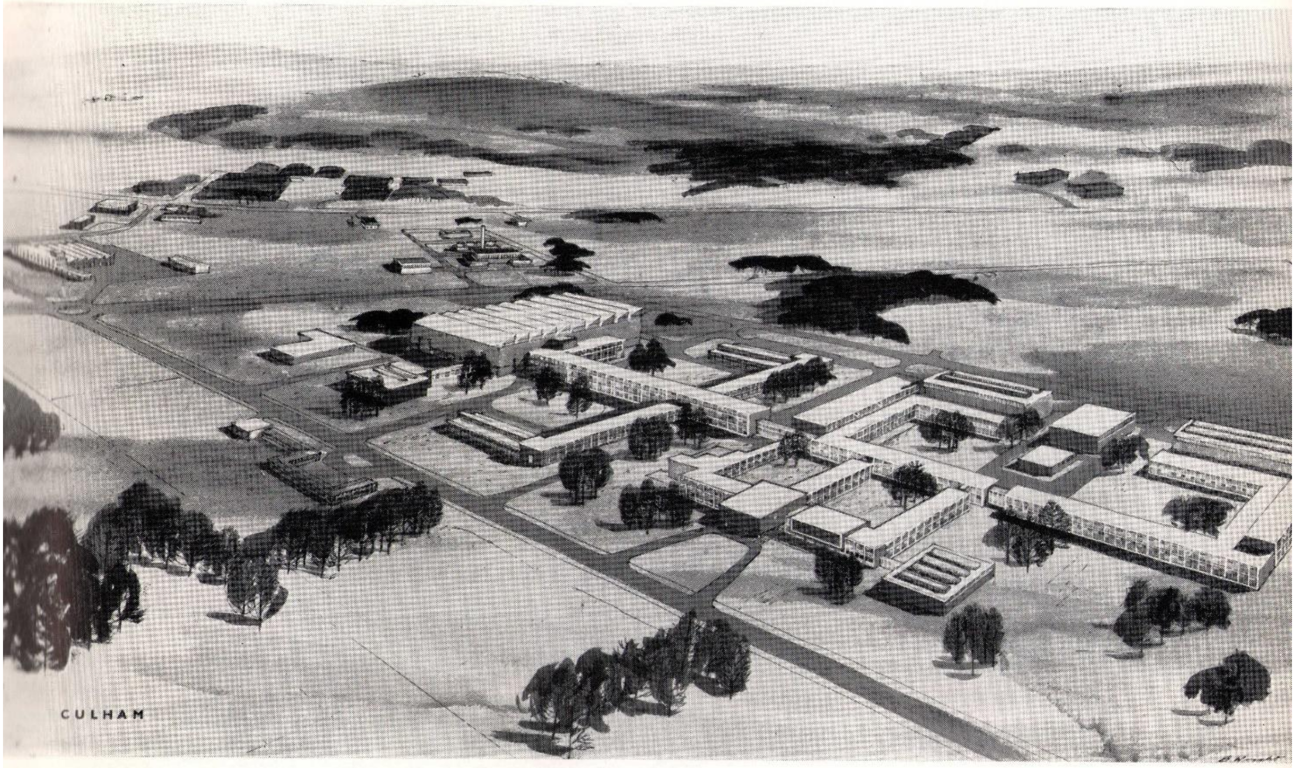
3

The work of the Research Group: The Culham Laboratory

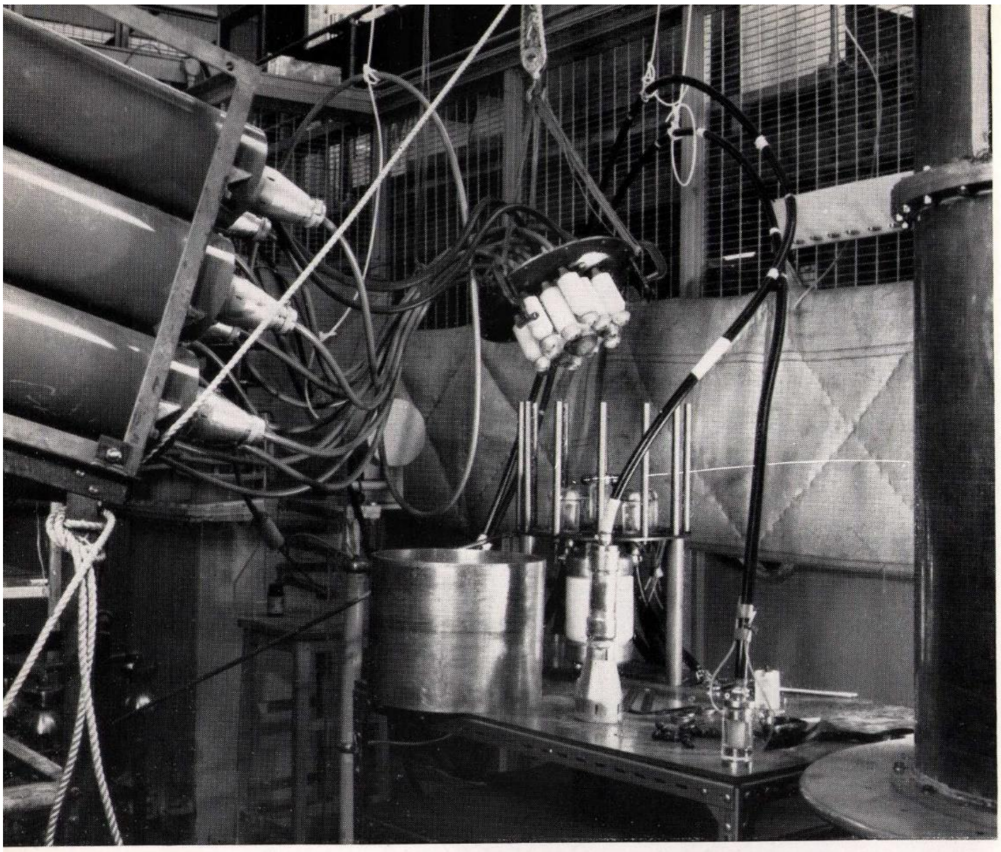
The Culham Laboratory is to be the Authority's centre for plasma physics and fusion research. Although there may well be other practical applications, the motivation of this work is the hope of showing that a fusion reactor is possible. The most likely approach involves the intense heating of highly ionised gases (i.e., plasma), and in consequence a detailed study of their behaviour and control is being undertaken. Most of the matter in the universe is believed to exist in this form. Exploring this plasma state, whose properties are so little understood, is proving an intellectual and technical challenge of the highest order.

One of the principal problems is that of devising means of isolating the plasma from other matter. As a highly conducting medium, its interaction with magnetic fields should provide a means of confining plasma. In practice, it is proving difficult to obtain a system which remains stable long enough for appreciable fusion to take place. Much of the work is concerned with attempts at confinement and observations on the processes causing instability. In some devices, such as ZETA, the magnetic field of the plasma current itself tends to keep the discharge to the centre of the enclosure. Another system has a conducting core carrying the discharge current back through the centre of the plasma, which is forced outwards, a further magnetic field holding it away from the walls. Ions can be injected into a solenoidal magnetic field with maxima towards the ends, a proportion of the ions being trapped for a while by reflection at the effective field bottle-necks, where the lines of force crowd together. Radio-frequency field systems are being explored as possible means of minimising the effects of the instabilities which have arisen in all attempts at plasma containment.

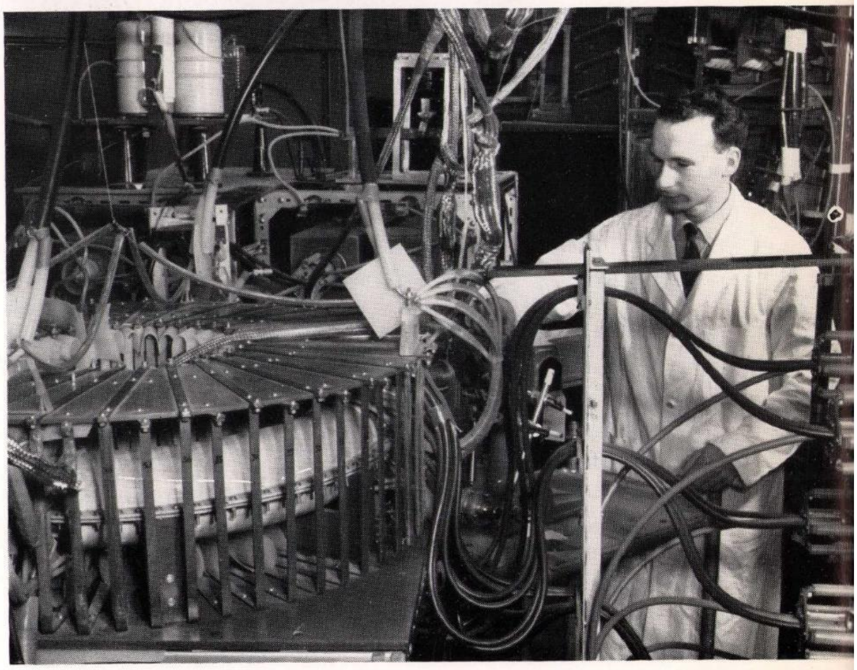
Another problem is that of heating the plasma to temperatures of the order of 100 million degrees C. This has been attempted by discharging heavy currents through the plasma (as in ZETA), and by adiabatic compression using rapidly increasing magnetic fields. The temperatures achieved are clearly limited by the energy losses and these have proved to be very high. Detailed investigations on ZETA have revealed that at the higher pressures in use, radiation from minute quantities of impurities represents major energy loss, whilst at the lower pressures plasma has escaped to the walls.



Artist's impression of the Culham Laboratory



40 kV spark gap testing: Culham Laboratory



A fast pinch experiment, which 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 are of interest for stability and shock-heating studies. Shown is 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: Culham Laboratory

In parallel with this work, study is being made of more specific aspects of plasma physics. These include the propagation of disturbances, particularly shock and Alfven waves, and cross-section measurements which determine the probability of particle collisions of various types.

Substantial effort is devoted to obtaining as complete a picture as possible of the physical conditions existing in plasma, i.e., for determining the variation in time and space of such properties as the temperature, density, electric and magnetic fields, resistivity, impurity content and degree of ionisation. Experimental studies of plasma of thermonuclear interest are dominated by its short life (usually between 10^{-6} and 10^{-3} seconds) and its tenuous nature, since only very small quantities of materials are used. Because of the sensitivity to contamination, the short time scale, and low collision frequencies, it is hazardous to simplify measurements and their interpretation. Consequently a wide variety of measurements is attempted in any given experiment.

High speed photography has been extensively used to investigate general phenomena, such as the presence of instabilities and shocks, with some quantitative work on their velocities and rise times. Most of the work has used visible light with existing techniques.

In cases where the plasma can be treated as a significant circuit element, electrical measurements on the external circuitry give information on energy balance, and estimates of magnetic field configurations and plasma oscillations. Fluctuations of currents and voltages in the external circuits also provide evidence of instabilities. Measurements of magnetic fields have required the physical presence of probes within the plasma, and because of contamination and other disturbances to the plasma, the technique has always been suspect. In many cases, however, they have given observations in agreement with other types of measurement or with theory. The development of some independent method of measuring the magnetic field is clearly needed.

Spectroscopic observations have played a major role in the measurement of plasma properties and in the interpretation of experiments. While much work has been done in the visible range of existing techniques, other important regions for spectroscopy are the far infra-red, the far ultra-violet and microwaves. Extensive and expensive development work is needed before observations in the first two regions can be accurately carried out on the short time scale of the experiments. For some hot dense plasmas, the soft X-rays (wave length less than 10 Å) are sufficiently intense to provide estimates of the electron temperature from crude absorption spectrometry.

Further development of diagnostic techniques is essential, and this will find application in the study of astrophysical plasmas and ionospheric research.

Fusion research has become dependent on technological and design development which must constantly keep ahead of experimental needs. These activities fall into two broad categories, electrical engineering and materials.

Conventional engineering practice has no ready-made solutions to the problems concerned with the production of high power pulses—the storage of electrical energy, its switches and transmission. For the fast-rising magnetic field, the usual energy store is a condenser bank. This may need to deliver 1 million MW for very short periods. The associated switching system will possibly handle several hundred kiloamperes and around 100 kV, for periods as short as one ten-thousandth of a second. The synchronous operation of a multiple switch has necessitated the development of new systems, based on vacuum and high pressure spark gaps. The associated cables require special design to ensure low inductance losses under these conditions.

The suitability of materials requires special consideration when designing vessels to contain very hot plasma. The walls must endure repeated short duration heat pulses and must not be a source of impurities. The electrical insulation has to withstand a predetermined number of high voltage impulses. Mechanical forces and shocks, arising from the sudden changes in magnetic fields, present further difficulties.

Additional problems are those of maintaining ultra high vacuum (10^{-9} mm Hg pressure) in vessels of several cubic metres capacity, and in designing apparatus of adequate flexibility to permit a wide range of experimental observations on the contents.

There are two broad aspects of the theoretical work, namely the improvement of theoretical methods and the application of current theory to specific experiments, the latter involving extensive use of computers. Fundamentally, plasma phenomena are governed by Newton's Laws of Motion and Maxwell's equations. Whilst the essential physics is thought to be entirely classical, there is difficulty in applying these equations to the many-particle problem. Forces between charged particles are long range (unlike intramolecular forces), and co-operative effects arise from the interaction of many particles. Approximations and simplifications are necessary in calculations, and the experimental results both guide and test the validity of these assumptions.

Research into plasma physics thus ranges widely, calling for new approaches from all concerned. With the added challenge of establishing the feasibility of a fusion reactor, there is every stimulus to the active mind. No single laboratory can hope to cover all aspects, and there are similar research programmes in the U.S.A., U.S.S.R., Europe and elsewhere. The freedom from security restrictions in this field of science permits the closest relationships between Culham, the universities and other laboratories throughout the world.

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.

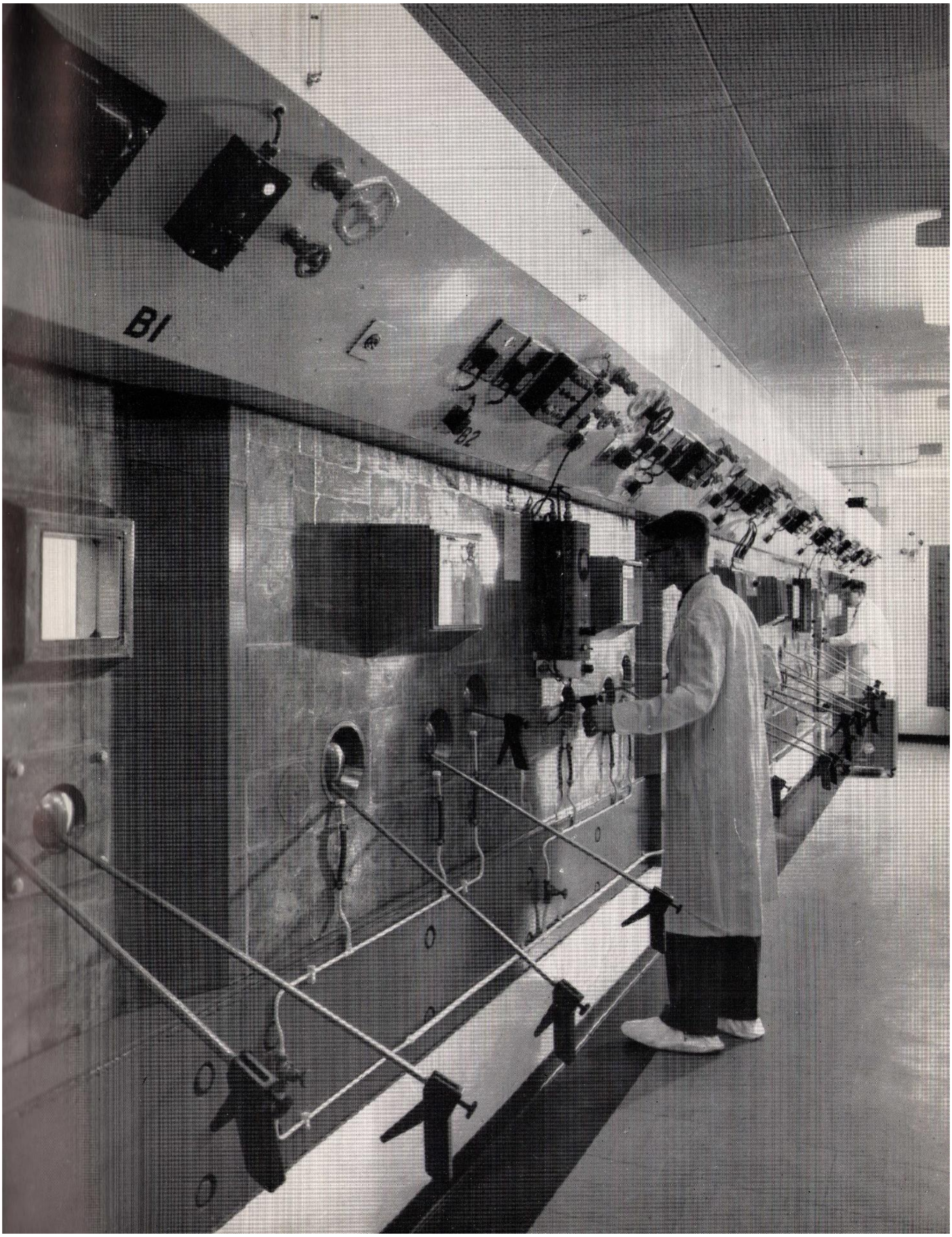
Many hundreds of 'labelled compounds' are derived from these isotopes by chemical synthesis or by biochemical techniques. For example more than two hundred compounds containing carbon 14 have been synthesised, including amino-acids, steroids and other compounds of biological interest. Special compounds 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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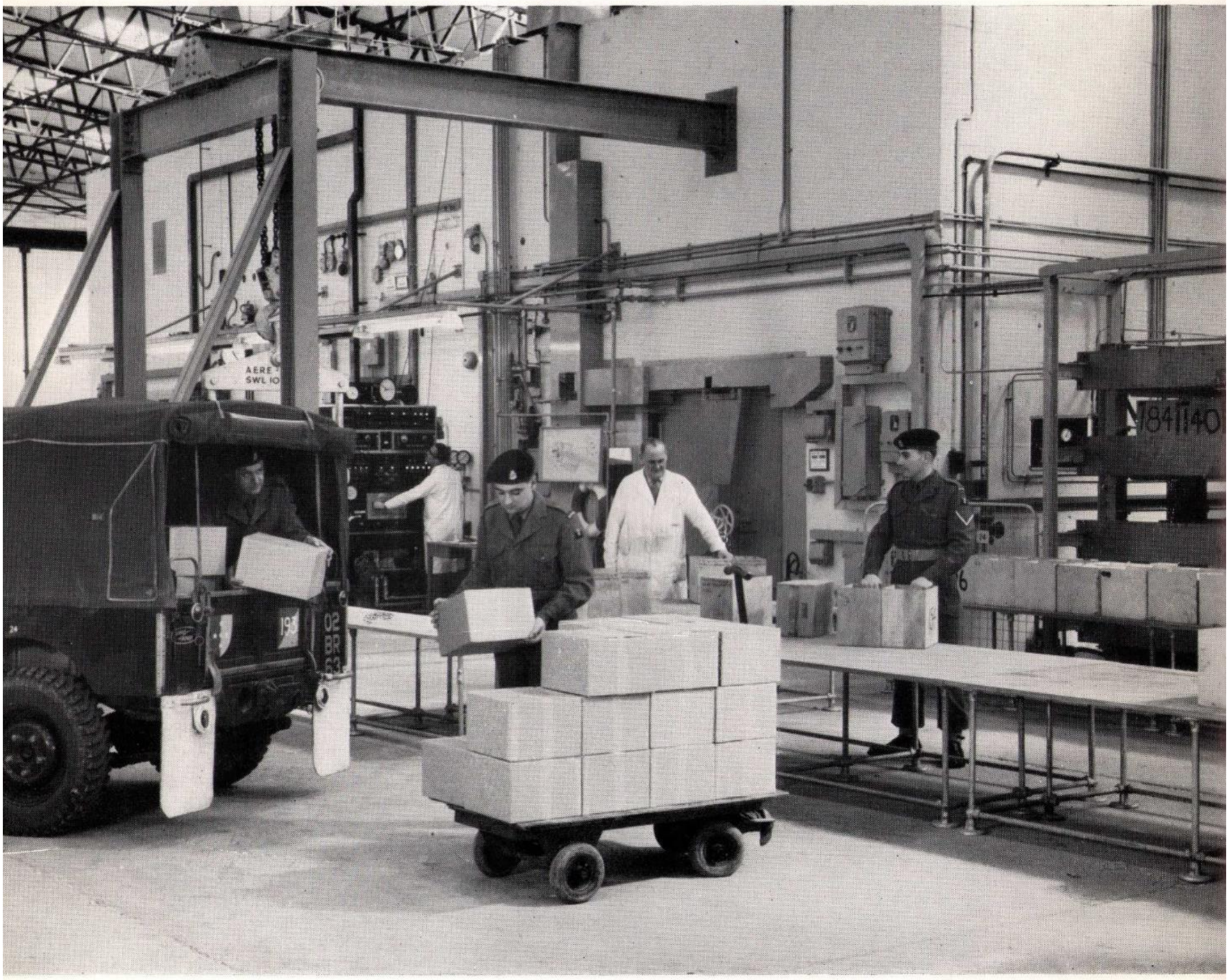

Package irradiation plant at Wantage Research Laboratory:
medical supplies being delivered for sterilisation

5

The work of the Research Group: Wantage

The Isotope Research Division

The Isotope Research Division is based at the Wantage Research Laboratory about ten miles from Harwell. A small section of the Division is based at Harwell to make special irradiations and to do research directly connected with reactors.

The aim of the Division is to help all present and potential users of radio isotopes in this country and abroad to derive the greatest possible advantage from their use, and to devise and develop new techniques.

The Division is divided into two main branches, the Isotope Branch and the Radiation Branch, each of which is, in turn divided into smaller groups.

The Isotope Branch

This Branch includes the Isotope Advisory Service which handles 3,000-4,000 enquiries a year, about three-quarters of which are from industry. It is supported by an experimental service which accepts industrial problems for solution in the laboratory or brings isotope techniques to the factory or the field to tackle outstanding problems on the spot. The service is mainly operated by the Physics and Chemistry Groups and its demands play an important part in stimulating further research into new techniques.

Work in the Chemistry Group includes a service for radioactivation analysis, the sensitive analytical technique which depends on the radioactivity induced in materials when they are placed in a nuclear reactor. Current research features an investigation of electroplating processes using radioactive tracers, aimed at explaining the mode of action of 'brighteners' and 'levellers' added to plating baths to improve the product.

The technique of autoradiography is being developed and improved by a small team of chemists and physicists working together. An important step forward was achieved in the ability to make colour prints of the autoradiographs superimposed on photomicrographs of the same surface in a different colour. This shows clearly the distribution of a radioactive tracer in relation to the crystal structure of a metal, for example. It has been turned to good account by the chemists in studying the effects of minor constituents in aluminium-magnesium-zinc alloys. More fundamental researches include a study of the chemical properties of technetium, the 'missing' element with atomic number 43, which has been isolated from fission products. The scope and limitations of analysis by X-ray fluorescence spectroscopy using radioactive isotopes has also been studied.

In the Physics Group of this Branch radioactive tracers are applied to a variety of physical problems, which range from the measurement of bulk flow and mixing in manufacturing processes to the tracing of sand and silt movements in the estuaries of rivers. A special investigation has been made into the use of tracers for measuring water flow in pipes, now the most accurate as well as a very convenient method of calibrating large water flows for hydro-electric stations, though as yet not widely used. This Group is also interested in the measurement of tritium in very small concentrations and its use to measure the movements of water underground. In another project, gas leakages in small sealed components such as transistors, are detectable at rates down to 10^{-4} cm^3 per year by a pressurising technique using radioactive krypton.

Nucleonic thickness, density and level gauges, are now firmly established in industrial process control and suitable gauges are commercially available. Attention has, therefore, been turned to newer aspects of nucleonic gauges. Secondary X-rays are being studied, both in the design of bremsstrahlung sources for such uses as the monitoring of sulphur contamination in petroleum or of ash in pulverised coal, and also for direct measurements, as in X-ray fluorescence gauges for surface coatings. Detecting instruments are being developed and adapted with special reference to their uses for isotope applications. In particular, semiconductor detectors are being applied to gamma-ray measurement in both industrial and medical trials.

The possible applications of portable electrically operated neutron generators are being explored for use in radioactivation analysis and to facilitate the use of very short-lived radioactive tracers far away from a reactor.

The Reactors and Measurements Group, partly at Wantage and partly at Harwell, arranges for the reactor irradiation of materials which require special attention. This service is intended primarily for other groups at Wantage. The Group also operates a Radioactive Standards service for measuring the disintegration rates of radioactive sources. This is done jointly with the Radiochemical Centre, the more unusual isotopes being measured at Wantage, where research into new techniques is pursued. There is close contact with the National Physical Laboratory, which holds such National Standards as have been agreed.

The Radiation Branch

This Branch investigates possible industrial uses for the large amounts of radioactive materials obtainable directly from the nuclear power programme.

Fuel elements from the Harwell research reactors DIDO and PLUTO are used for the irradiation of industrial materials at the bottom of the 18-ft deep Irradiation Pond, where the canned elements awaiting chemical repurification carry total activities up to two million curies of mixed fission products. The irradiations are made continuously, in sealed containers lowered into the pond.

Most of the radiation research at Wantage is carried out by using gamma rays from cobalt-60. Twenty-three cells, with concrete walls up to 5 ft 9 in. thick, house cobalt sources from 100 to 8,000 curies in activity which are used for experimental irradiations of samples. A 4 MeV linear accelerator provides high energy electrons for surface irradiations at high dose rate. The Package Irradiation Plant, in a separate building, houses 250,000 curies of cobalt-60, to which standard packages of about three-quarters of a cubic foot capacity can be exposed on a conveyor belt system. This plant can handle up to 15 tons of packages, the rate of treatment depending on the amount of radiation they are to receive: for example it can sterilise about a ton and a half of pharmaceuticals or surgical appliances in a day. It is used to provide practical experience in the pilot-scale treatment of commercial products and 80 per cent of its available space is used for this purpose, the remainder being reserved for further research by the Division. These irradiation facilities are controlled by the Physics and Engineering Group.

The principal task of the Chemistry Group of the Radiation Branch is the investigation of chemical reactions which are of potential industrial importance and which might be carried out more conveniently at high yields and lower costs by the use of high energy radiation. A subsidiary task of the Group is the investigation of radiation damage, and if possible, prevention of radiation damage caused when materials are subjected to doses of radiation sufficient to sterilise them.

In order to fulfil its main function, the Chemistry Group is investigating a number of chemical reactions in which initiation by radiation produces products different from those obtained using conventional initiators. In this category are reactions such as low temperature polymerisation where ionic mechanisms rather than free radical processes predominate, radiation cross linking of natural and synthetic rubbers in the presence of disubstituted monomers. Oxidation in both the gas and liquid phases is being studied.

By introducing substances which act as electron traps recombination of the primary ions produced by radiation is hindered and, as a result, ionic reactions are favoured. The Group is, therefore, working on the effects of radiation on hydrogen in the presence of such substances in order to investigate the reactions of the ions produced in the primary steps of radiolysis. A parallel study is also being carried out on polymerisation in order to study ionic initiation.

As an adjunct to the radiation sterilisation programme the Group is investigating the effects of radiation on cellulose and allied substances. This is the basic material for surgical dressings, etc. The effect of radiation on intravenous solutions is also being investigated with a view to the application of the radiation sterilisation technique to perfusion fluids.

An important aspect of the use of radiation for commercial processes is the development of radiation detectors which will ensure that material to be sterilised has been given the correct dose. The Group has developed a number of detectors for this purpose.

Effects of radiation on plants are studied in the Biology Group, including research into mechanisms of genetic mutation, with a view to producing desirable mutations of value to the plant breeder. In general it has been found that radiation is a less effective means of producing new strains than the use of chemical mutagens. It has, however, a special advantage in allowing the cross-breeding of otherwise incompatible strains. By chromosome breakage, it can also achieve the separation of otherwise inseparable hereditary characteristics, to permit their introduction into improved strains.

Some plant seeds are much more sensitive to radiation than those of other species and it has been found at Wantage that the resistance of seeds to radiation is affected markedly by soaking them with extracts of more, or less, resistant seeds. Some of the compounds responsible for these effects have been isolated and the effect is still under study.

The Entomology Group has made progress in establishing the doses of radiation needed to prevent the spread of weevils, flour mill moth and other insect pests in stored grain and an appraisal has been made of the economics of radiation disinfestation on a commercial scale.

Sterilisation of medical supplies by gamma irradiation has been established as a successful process by the Food and Medical Group, which includes a small team of bacteriologists. Surgical gloves and instruments and rubber catheters, sterilised after enclosure in hermetically sealed packages, are already commercially available. Plastic hypodermic syringes, sterilised in bulk by gamma radiation, can be produced more cheaply than conventional syringes can be cleaned and sterilised.

Experimental investigations are being carried out into the possibility of increasing the storage life of foods by the irradiation of partially cooked food, and on extending the storage life of fresh meat in domestic refrigerators, and strawberries at room temperature, by low pasteurising doses. Many foods, however, are subject to slight flavour changes on irradiation and research is being directed to find methods of inhibiting these changes. Salmonellae food poisoning organisms, sometimes found in whole egg or desiccated coconut, can, however, be eradicated by moderate doses of radiation without undue changes in quality of flavour. The properties and palatability of irradiated foods are studied both objectively by bio-chemical tests and subjectively by volunteer taste panels at Wantage and many are found quite acceptable. The use of such foods for public consumption must await the completion of exhaustive trials with animals fed on irradiated and unirradiated diets.