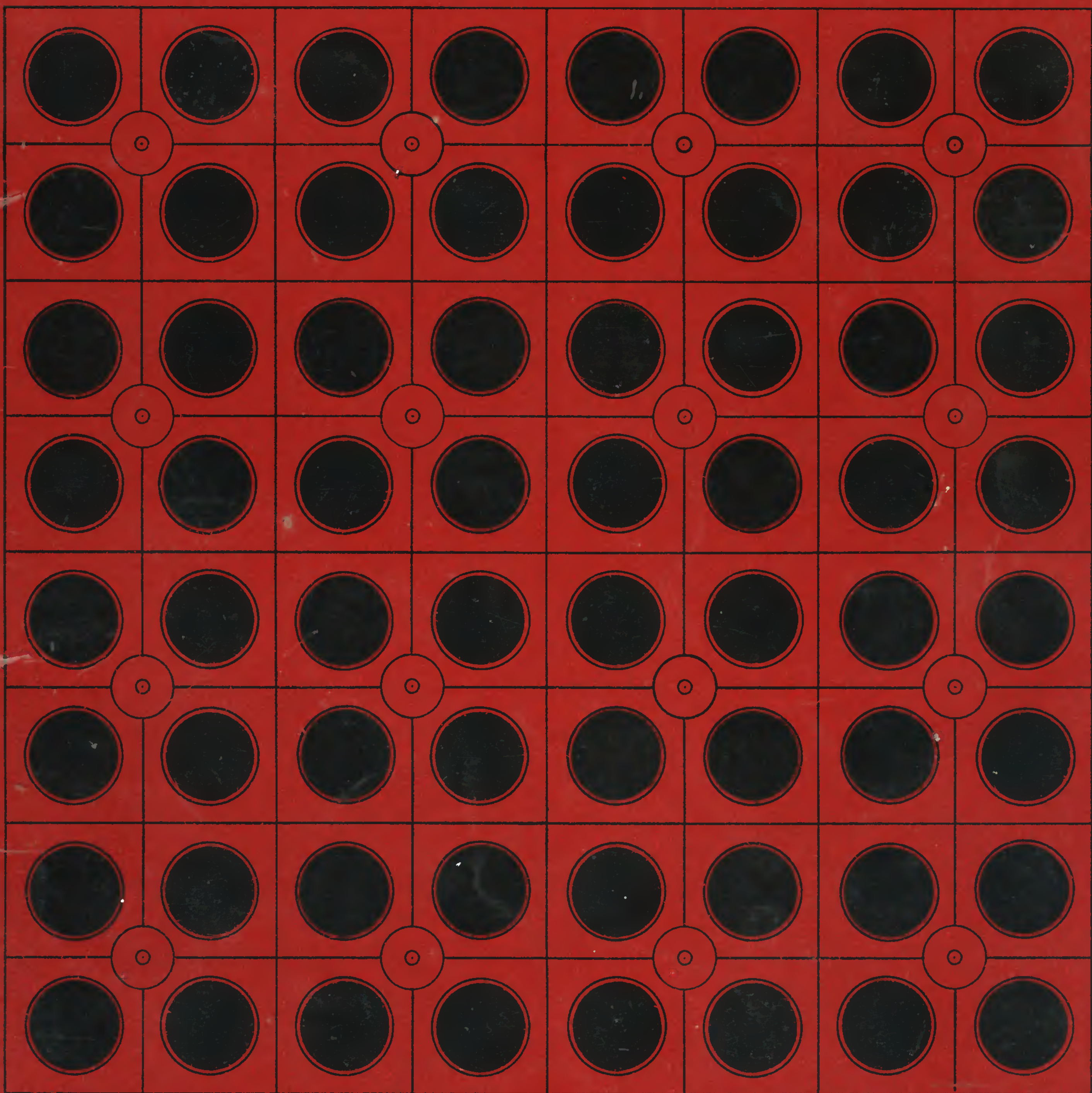
Berkeley Nuclear Laboratories



Berkeley Nuclear Laboratories

Central Electricity Generating Board
Berkeley, Gloucestershire

Director

C. P. HAIGH, BSc, PhD, FInstP

Berkeley Nuclear Laboratories

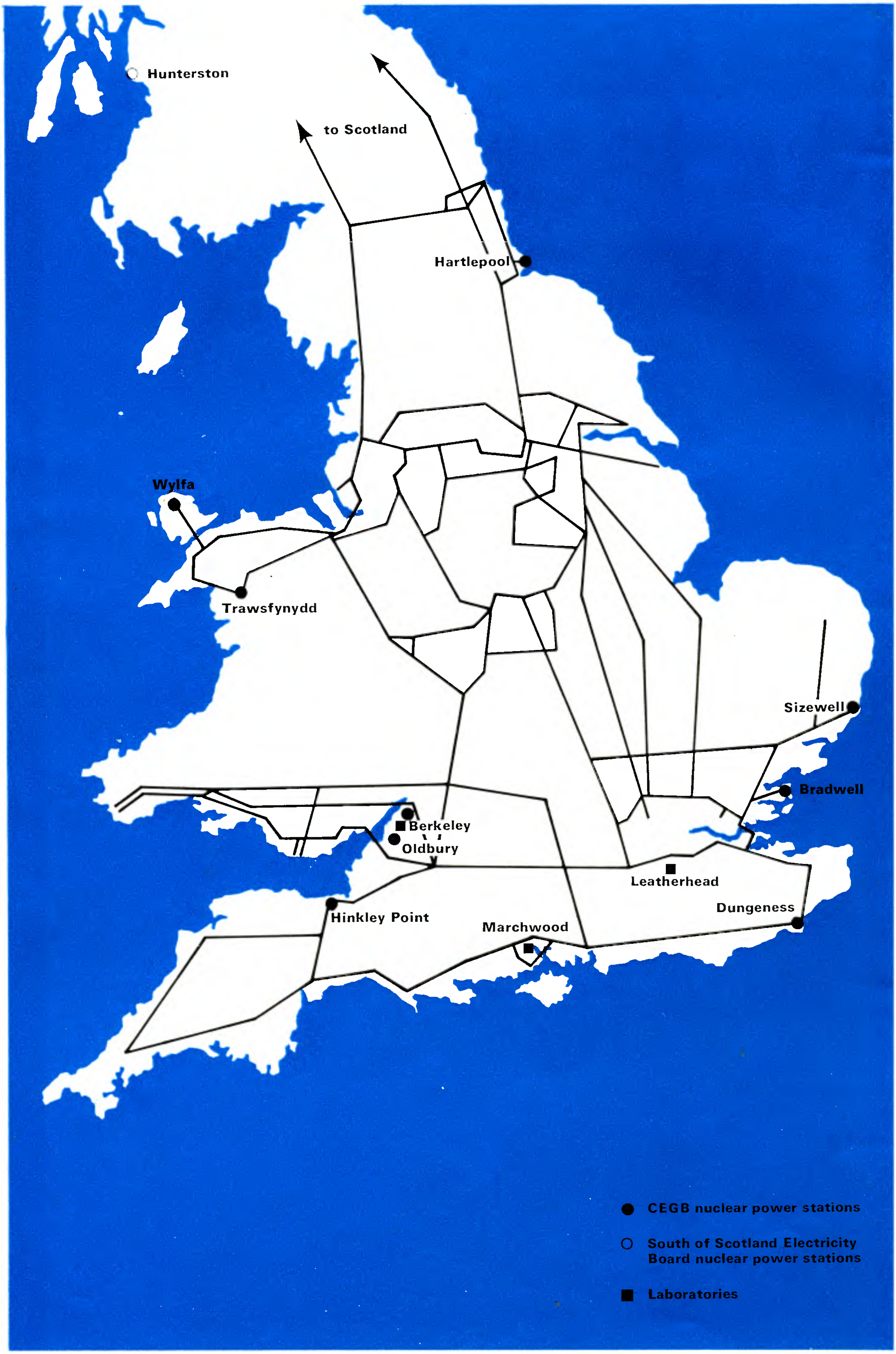
The Central Electricity Generating Board are responsible for the generation and transmission of electricity throughout England and Wales. They own and operate over 200 power stations, inter-connected by a transmission system known as the Grid. This system is the largest integrated electricity network under unified control in the world and at the end of June 1969 had a generating capacity just under 45,000,000 kilowatts. Demand for electricity doubles every 10 or 11 years and to meet this increasing demand new plant is continually being installed.

A large power station takes up to six years to design, build and commission and the Generating Board's programme for new plant provides a stimulus for important technological progress throughout the country. In sustaining such technological advance, the Generating Board maintain an extensive research and development department.

The organisation of the Generating Board comprises a Headquarters and five Regions and, within the Headquarters group, three main laboratories are responsible for research. The Central Electricity Research Laboratories at Leatherhead, Surrey, are concerned with research into conventional generation and transmission. Pilot scale engineering research is undertaken at the Marchwood Engineering Laboratories near Southampton and the Berkeley Nuclear Laboratories are the centre for the nuclear power research programme.

Within the five Regions there are regional research laboratories whose concern is with day-to-day generation problems, although they also have specialist knowledge in particular fields.

This brochure is about the research work and the organisation of Berkeley Nuclear Laboratories.


Hunterston
to Scotland
Hartlepool
Wylfa
Trawsfynydd
Sizewell
Bradwell
Berkeley
Oldbury
Leatherhead
Dungeness
Hinkley Point
Marchwood
CEGB nuclear power stations
South of Scotland Electricity Board nuclear power stations
Laboratories

The British Nuclear Power Programmes

The first nuclear power programme, introduced by the Government in 1955, planned for the installation of 5,000-6,000 megawatts of generating capacity. By 1969 over 3,000 MW of plant was in service. This first programme was based on the magnox thermal reactor system using natural uranium as a fuel. Magnox alloy is used as the canning material, graphite as the moderator and carbon dioxide gas as the coolant.

Heat produced in the reactor replaces the heat from combustion at coal or oil-fired power stations. Carbon dioxide gas transfers the heat to the heat exchanger where steam is generated to drive conventional turbo-generators. Nuclear power stations have a relatively small operating cost but a high capital cost, although this is steadily falling as the programme proceeds. To date, the first seven nuclear power stations are operational and in the year ending March 1969 generated 19,843 million kilowatt-hours of electricity (11·4 per cent of the total). This is much more than the combined commercial output from all the other nuclear power stations in the world over the same period, and the Government's second programme of 8,000 MW by 1975 reflects confidence for the future.

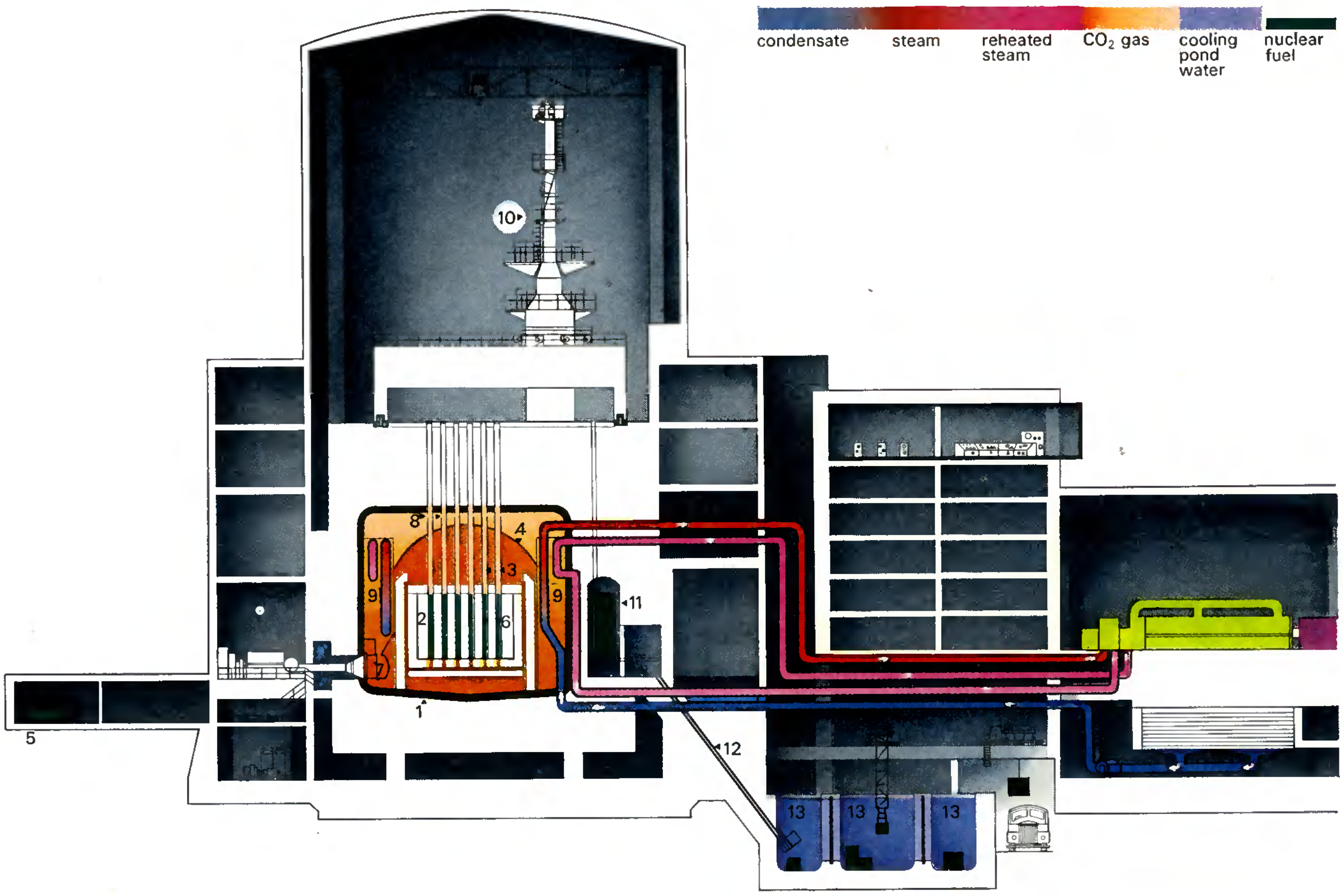
The CEGB commenced the second programme by inviting tenders for all types of commercially available nuclear generating systems, including water reactors developed in the USA. Their assessment of the tenders in July 1965 showed that the British advanced gas-cooled system (AGR) was the most commercially attractive for UK conditions and three power stations with a total capacity of 3,600 MW are now under construction. When commissioned, they are expected to generate electricity at a lower cost than the best coal or oil-fired power station available at that time.

CEGB Nuclear Power Stations—Capacities and Dates 1969

			Commissioning date	
Magnox power stations	**Capacity MW s.o.**	**Work started**	**Reactor 1**	**Reactor 2**
Berkeley (Gloucestershire)	275	January 1957	June 1962	October 1962
Bradwell (Essex)	300	January 1957	July 1962	November 1962
Hinkley Point A (Somerset)	500	November 1957	March 1965	May 1965
Trawsfynydd (Merionethshire)	500	July 1959	March 1965	May 1965
Dungeness A (Kent)	550	July 1960	October 1965	December 1965
Sizewell (Suffolk)	579	April 1961	March 1966	September 1967
Oldbury-on-Severn (Gloucestershire)	600	May 1962	December 1967	September 1968
Wylfa (Anglesey)	1,180	September 1963	1970	1970
AGR power stations				
Dungeness B (Kent)	1,200	February 1966	1972	1972
Hinkley Point B (Somerset)	1,252	September 1967	1972	1972
Hartlepool (Durham)	1,320	October 1968	1974	1974

The advanced gas-cooled system is a significant development of the uranium/magnox system but still uses graphite as a moderator and carbon dioxide gas as a coolant. It utilizes the ceramic uranium dioxide slightly enriched in U^{235} as a fuel, 'canned' or enveloped in stainless steel instead of magnox. This allows higher temperatures and power ratings to be obtained from the fuel. Advances made in the use of reinforced concrete pressure vessels used on the later magnox power stations are being applied to the AGR programme, with resultant increases in pressures and subsequent reduction in capital costs. Later commercial reactor systems will depend on advances in basic knowledge and technological development, and may include either the steam generating heavy water reactor or the High Temperature Reactor (HTR) using particulate fuel, graphite cans and helium cooling. The latter type offers the prospect of partial breeding using a thorium fuel cycle. Ultimately, the fast reactor breeder system with either liquid metal or gas cooling, where the moderator is no longer required and where very much higher power densities are possible, should be introduced.

1 Pressure vessel
2 Moderator
3 Fuel channels
4 Inner Pressure dome
5 New fuel store
6 Loaded fuel stringers
7 CO_2 gas circulators
8 Outlet ports
9 Heat exchanger
10 Refuelling machine
11 Irradiated fuel store
12 Chute
13 Cooling pond



Berkeley Nuclear Laboratories

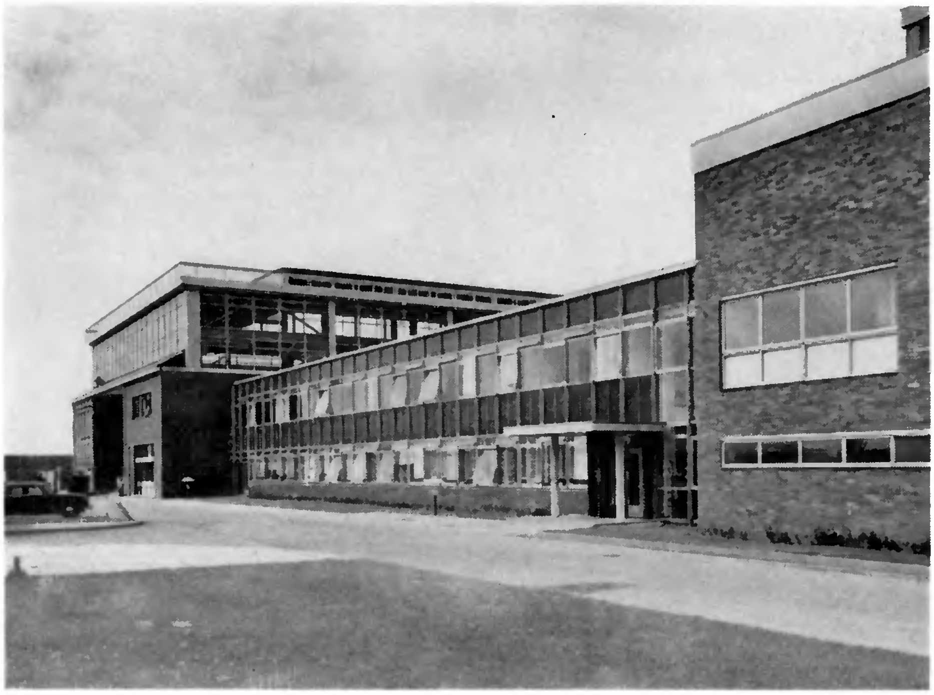
The Berkeley Nuclear Laboratories exist as a comprehensive nuclear power research unit to provide the electricity supply industry, from its own resources, with the basic scientific and technical information it needs to establish nuclear power as an economic means of electricity generation.

The Laboratories stand on the banks of the River Severn at Berkeley in Gloucestershire, about 20 miles north of Bristol. This site was chosen for its proximity to one of the Generating Board's first nuclear power stations: it is in the area of the UK with a concentration of nuclear stations that is the greatest in the world. It has good University connections (Bristol, Oxford, Birmingham, Bath), excellent local industrial facilities and rapid means of communication with the rest of the country. BNL now has over 200,000 square feet of laboratories and a staff of more than 550, including 220 professional scientists. The programme is one of objective basic research directed to solve, at laboratory level, technological problems in the design and operation of reactor systems. This requires a wide range of scientific and technical expertise. For administrative convenience the Laboratories are divided into three disciplines—Materials Science, Physics and Engineering Science—working collaboratively on a common nuclear research programme.

The Laboratories situated beside the River Severn

So rapid has been the growth of nuclear power, and with it the demands for research and development, that parts of the CEGB's nuclear research programme that do not require the specialist facilities of a nuclear laboratory are now being carried out in other Board laboratories at Leatherhead and Marchwood.

All the research work at BNL is supported by the necessary administrative and technical services, including a design office and workshops, and operational health physics. A research planning service, available for management and the research staff, develops and operates improved methods of strategic planning research, including resource allocation and cost effectiveness.



Main entrance to the Laboratories

The physics laboratory with the reactor physics facility

The Research Programmes

About half of the scientific activity at Berkeley is long-term to support or to influence design decisions which may have to be made by the Generating Board in the future. Much of it is fundamental and demands a high standard of scientific ability. The remaining work, which ranks equally, is directed in support of operations to ensure the safety and maximum economic life of the power stations. The programmes are orientated primarily around the components of the reactor system which are conveniently classified as follows:

Reactor Core—the assembly of moderator control rods and fuel.

Pressure circuit and shielding—steel and concrete.

Moderator—graphite in both the current programmes.

Coolant—carbon dioxide gas, helium gas and liquid metal in future systems.

Fuel—the primary heat source containing the fissile uranium.

Reactor Operations—mechanisms and fuel handling. Fuel cycles. Control and instrumentation.

Reactor Safety—Gas circuit physics and Health physics.

In this short account it is impossible to cover all aspects of the work, but typical examples are given.

Reactor Core In thermal reactors the fast neutrons generated by fissioning of the fuel U_{235} atoms are slowed to thermal energy levels by the moderator. This is graphite, in both the magnox and AGR systems. The distrubition of the graphite within the core relative to the fuel decides the reactivity and power spectra. Design and long term operation requires an extensive knowledge of reactor physics.

The role of Reactor Physics is primarily to study the power distribution within the core of a reactor. Within the limitations set by the properties of the core materials, it is difficult to optimise the power output of the reactor for both minimum cost and maximum safety. As in many other branches of physics, the essence of the approach is to develop calculation techniques which are then continually refined by comparison with experiment. The nature of large nuclear power stations is such that development must rely to a large extent on extrapolations from data obtained with small experimental models. At Berkeley, an unusually versatile experimental facility has been constructed in which to investigate particular aspects of core geometry. The centre of the facility is a concrete building of 35 ft internal dimensions with 5 ft thick shield walls. Within this structure—large enough to accommodate assemblies with fuel elements whose size approaches that of power station elements—a wide range of experimental facilities can be constructed.

In conjunction with the experiments, a great deal of allied computation work is carried out on the Generating Board's computers. Many of the programs used are designed to give the histories of neutrons in the core. Although Monte Carlo methods can explore the life cycle of individual neutrons, they are expensive in computer time and the many programs based on neutron diffusion or transport theory, each with varying degrees of restrictive assumptions, all find their particular uses. Clearly, the choice or development of the correct calculation approach and its subsequent evaluation by experiment provides great scope for original work. Typical of the programme of work is an investigation of both AGR and HTR cores where the effects of enriched fuel, the spacing between fuel channels and the complex assembly of fuel elements within each channel all need careful and detailed assessment.

Beyond the design and construction stage the management of the fuel cycle needs very careful attention, for the possible economic returns can be of the order of a few million pounds a power station. As each fuel element uses up its fissionable atoms, it is withdrawn and replaced by new fuel. However, with a generating system in which power must be effectively maintained at all times, the fuel cycling must, after the initial charge, be a continuous process. One of the fuel policies found to be economically attractive requires the use of a burnable poison (i.e. a material which captures thermal neutrons and hence reduces the fission rate of the fuel, but which then, having captured a neutron, loses its capture properties). As well as these predominantly physics problems, the search for a suitable burnable poison involves problems of chemical/metallurgical compatibility.

In a reactor the fuel does not burn uniformly, the burning rate at the centre of the core being faster than near the surface. There may be an economic return if, at about half way through the lifetime of a fuel stringer in the core, the outer and inner fuel elements are interchanged

Experimental fuel being loaded into a zero energy assembly simulating an AGR reactor core. Results are used to test reactivity predictions by axial and radial shuffling. A study of this problem can be made by the use of available computer programs, but again the physicist runs into the usual problems associated with extrapolating forwards in time, so that at each stage of the calculation the data has to be checked against the measured properties of fuel at different stages of its life in the reactor. In addition to average properties, attention has to be paid to detailed flux distributions along the fuel elements, for it is in the detailed variations that the ultimate limits to reactor safety are to be found. Consequently, another experimental programme is aimed at providing the detailed variation of properties at points where the complex geometry exerts its main influence, e.g. at the ends of fuel elements or in regions where the general pattern is perturbed, such as near control rods or empty channels.

Operating console of the zero energy critical reactor facility. The flexible design of the facility allows rapid assembly of a wide variety of reactor cores.

Not all the programmes are carried out on experimental facilities; several projects use actual power stations as their laboratory bench. A neutron pulse technique, conventionally used for small reactor systems, has been developed for use on the larger commercial reactors. Essentially the method consists of injecting a short pulse of neutrons into a sub-critical reactor and measuring the decay with time of the neutrons produced in the core. This decay is characteristic of the reactivity state of the reactor and the techniques will be used to study the history of the worth of control rods as a function of their irradiation —an essential factor in the assessment of reactor safety. Another power station study is concerned with reactor 'noise', by which is meant the small, random fluctuations superimposed upon the mean levels of many physically measurable parameters such as temperature, neutron flux and gas flow. Current work includes the development of techniques for the recording on magnetic tape of this random noise. By using recently developed spectral analysis methods, both analogue and digital, valuable information about the reactor characteristics can be obtained.

Pressure Circuit Research A comprehensive programme of experimental and theoretical research to establish design criteria for pressure containing structures was initially undertaken to ensure the integrity of nuclear pressure vessels and associated coolant circuit equipment, but the basic methods of analysis which have been developed are equally applicable to conventional plant. The main CEGB research on stress aspects of turbines, boilers and nuclear plant, is now centred at Berkeley. Close collaboration is maintained with the Generating Board's Design and Operations Departments, and with the relevant British Standards Committees, to ensure that the results of research are widely known and applied.

Computational techniques for the analysis of stresses and strains in structures of complex shape have been developed in conjunction with the Board's Computing Branch. Elastic, elastic-plastic and creep solutions are available for many types of structure. The present phase of this work is aimed at providing a portfolio of fully compatible programs with simplified input and graphical output, which can be used throughout the CEGB.

An equally important aspect of research relates to the formulation of basic laws governing the behaviour of materials and their failure criteria that can be used in conjunction with stress and strain analyses. The main application is in the performance of structures at high temperature where there is interaction between creep and cyclic damage. The failure work includes various aspects of cyclic loading on materials and on welded geometries containing fillet and butt welds. The approach is an inter-disciplinary one, and involves collaboration between materials scientists and welding technologists at Berkeley and other CEGB Laboratories.

Prestressed concrete pressure vessels, which are now universally used for gas cooled power reactors, present special problems because of the brittle nature of the concrete. Methods are being developed to analyse the redistribution of stress which takes place during the life of the vessel due to creep. From this work, the best disposition of reinforcement round openings and other stress raising features can be established for specific vessel designs.

In support of the theoretical analyses and to provide information on real structures, a large experimental facility has been established. Here, model and full-sized features of pressure vessel plant and turbines can be tested under accelerated conditions and subjected to simulated service stresses. Current work includes shakedown tests on boiler drum components, creep tests on nozzles in spherical vessels, and models to examine transient thermal stresses in turbine casings.

The test facility is fully automated, and a digital computer is used to provide a graphical display of the results.

Vibrations can arise, for example, in parts of the coolant gas circuits and lead to fatigue failures. To investigate this aspect, a research programme is aimed at establishing the nature and causes of vibration and defining acceptable levels of vibratory stress. Classical mechanical methods of analysis are unsuitable in situations where many modes of vibration exist. Fundamental work on plates, rods and cylinders forms a basis for the examination of statistical energy and similar techniques.

A programme on the criteria for crack propagation and its relationship with mechanical properties and proof test procedures will lead to new design rules and operating procedures for certain high temperature plant.

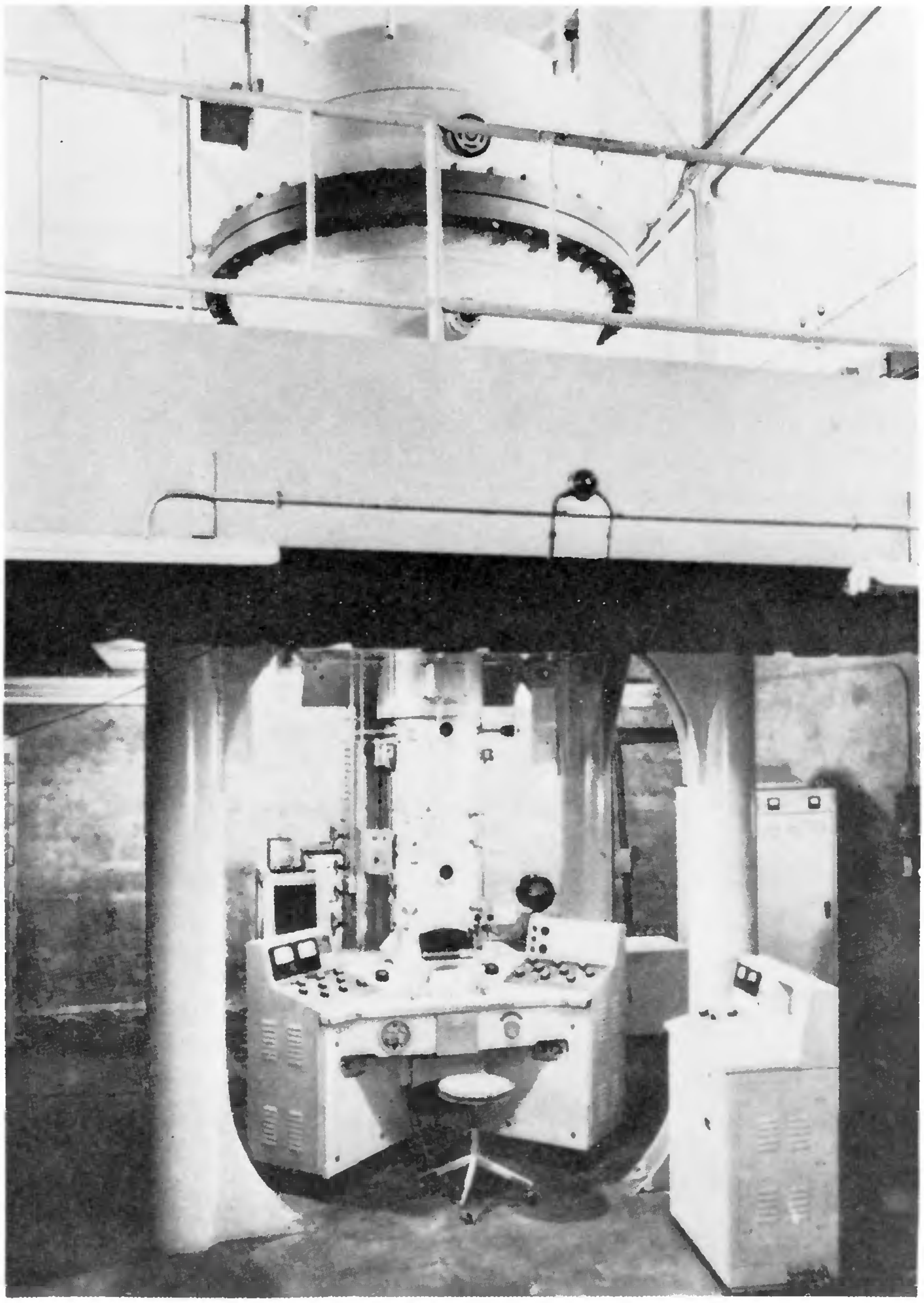
Large-scale experiments are being conducted to confirm the results of laboratory tests on the properties of dynamic cracks in steel pressure vessels.

Large experiment on cylinder/cylinder interactions to confirm theoretical design predictions

Basic Work A significant proportion of the effort is devoted to basic work to cover future unidentified needs. One such area is radiation damage where current work centres upon the vacancy cascades and distributed interstitial atoms which are the immediate result of a fast neutron striking a reactor material. Standard techniques of solid state physics are used: X-ray diffraction, electron microscopy, field-ion microscopy, internal friction and mossbauer effects. Materials are damaged either by reactor irradiation or heavy ion bombardment. The latter is a useful quantitative tool in that the energy and mass numbers of the ions can be chosen over a wide range. The results contribute to the understanding of technological results obtained from the steel, graphite and fuel element monitoring programmes where samples are withdrawn throughout the life of operating reactors to give precise experimental data on the long-term effects of irradiation. The laboratory give unparalleled opportunities for rapid application of basic scientific data, thus for example the mossbauer equipment originally designed to study irradiation damage effects is now in intensive use to cover oxide transformations in steel oxidation—thus providing fundamental scientific data for an important technological problem.

A 1 MeV electron microscope is available to extend the basic work and this will be used to explore a wide range of physical metallurgical problems including radiation damage, ceramics, large scale precipitation and irradiation growth and swelling.

High voltage electron microscope



The Moderator The moderator graphite is subjected to structural corrosion by the coolant gas, and irradiation damage throughout the life of the reactor. Vital features in the design of the moderator are the effects of irradiation on the material which increase at higher power densities.

The polycrystalline graphite suffers changes of shape on irradiation, and the various mechanisms involved in this shape change are being studied for use in the design of future systems (e.g. the cooled reactors). An example of the basic work used to back up such studies is given in the electron micrographs on this page which show large interstitial loops produced in graphite by annealing a sample irradiated at low temperatures. Detailed studies of the loops have shown that the activation energy for the annealing is about 8·3 eV, the self-diffusion energy. Similar studies have been made on vacancy loops.

Many complex reactions are possible between the various trace components in this system and the studies range from basic studies of the radiolytic processes to technological tests of apparently desirable gas compositions. In addition to the use of a gamma cell giving high radiation doses with computerised data handling facilities an important source of data comes from samples withdrawn from operating magnox power stations and this is a good example of the close collaboration which exists between basic fundamental work and applied research in direct support of reactor operations.

Studies of the effect of irradiation on mechanical properties and of irradiation creep are also being made to ascertain the extent to which graphite can withstand the internal stresses developed by the anisotropic crystal growth.

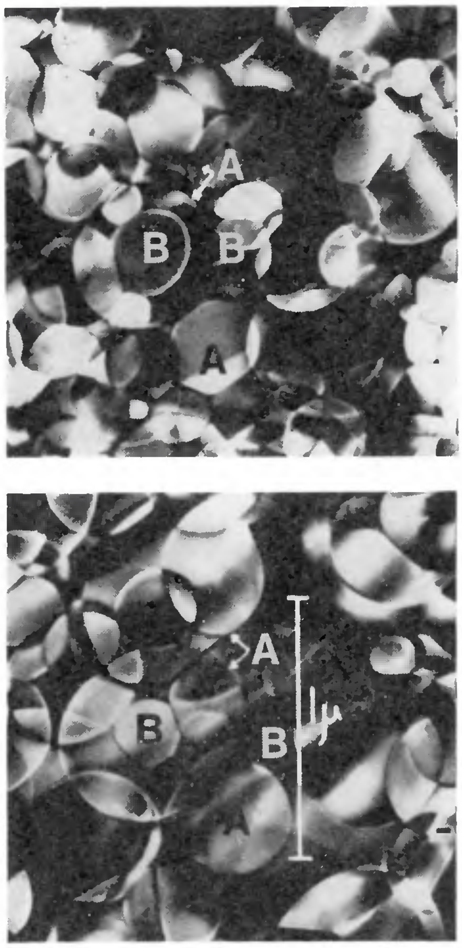
In the HTR certain parts of the moderator may be removable, so the prediction of structural stability is particularly important.

Coolant Both the magnox and AGR systems use carbon dioxide gas as the coolant which is forced under pressure through the fuel channels, extracting heat and transferring it to the heat exchangers. In its passage around the circuit the coolant comes into contact with many different materials, with any of which it could, in principle, react and on any of which it could lay down a deposit.

A large programme of work is concerned with the radiolytic reaction between the coolant gas and graphite which leads to conversion of graphite to carbon monoxide. This work involves the use of a large cobalt 60 source with an emphasis on isotopic tracer techniques. Basic topics under study include carbon dioxide radiolysis using both ^{14}C and ^{18}O labels, and the role of energy transfer from the solid in heterogeneous radiation chemical systems. The mechanism by which methane inhibits the reaction between carbon dioxide and graphite is being studied using ^{14}C labelled graphite. This inhibition is important both in the AGR reactors, where methane is deliberately added, and in magnox reactors, where it is formed in the reactor itself. The reverse reaction, to produce carbon from carbon monoxide has been under study for many years.

The simple reverse reaction is now sufficiently understood to enable control measures to be specified where control is technologically important as, for instance, deposition on the moderator and on some exposed electrical insulation. The emphasis now is on the mechanism of the reaction in the presence of methane and on methods of continuous measurement.

The research is complemented by reactor observations, such as coolant analyses by station operators, and examination of samples and



Electron micrographs of large dislocation loops produced by annealing irradiated graphite. The loops have been shown to be invariably interstitial. (a) before annealing and (b) the same area after annealing. Some loops labelled A have grown, and some labelled B have shrunk. Analysis of this behaviour shows that the activation energy for the annealing is about 8·3 eV components removed from reactors. This enables predictions to be refined for application to existing and future reactor systems.

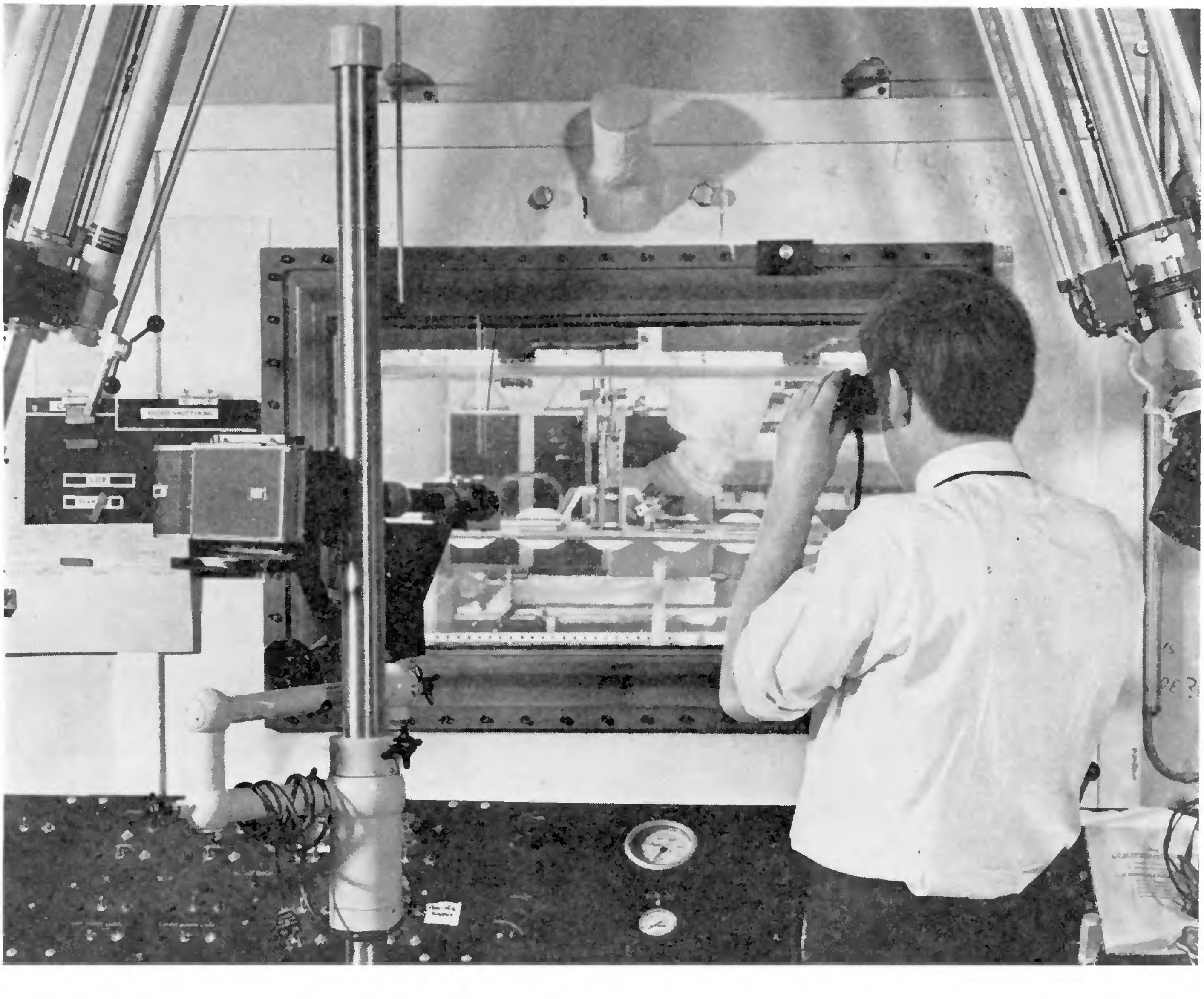
The coolant for the high-temperature reactor will be helium and a similar programme is proceeding on the interactions of trace impurities, particularly H_2O, with graphite. A special laboratory is available for chemistry and chemical engineering studies of sodium, a possible coolant for fast reactors. Mass transport of impurities in sodium is being studied in relation to two important problems. A gamma spectrometer is being used to study the behaviour of fission products in sodium.

A flowing sodium loop is available to study the behaviour of hydrogen and water injected into sodium; this is relevant to leak mechanisms in Na/H_2O heat exchangers. Entrainment of bubbles into sodium circuits and the interference caused to normal processes of flow and heat transfer under conditions of very high heat fluxes are also under examination.

Fuel Fuel for the magnox programme is natural uranium enclosed in a finned magnox alloy can. During service, fuel elements are subjected to a wide range of deformation modes due to fuel growth and fission gas release.

There are over half a million fuel elements in the Generating Board's reactors and many tens of thousands of these elements have undergone extensive irradiation under commercial operating conditions in the reactors of the magnox programme. Fuel elements are withdrawn from the reactors at intervals and examined in the Shielded Area

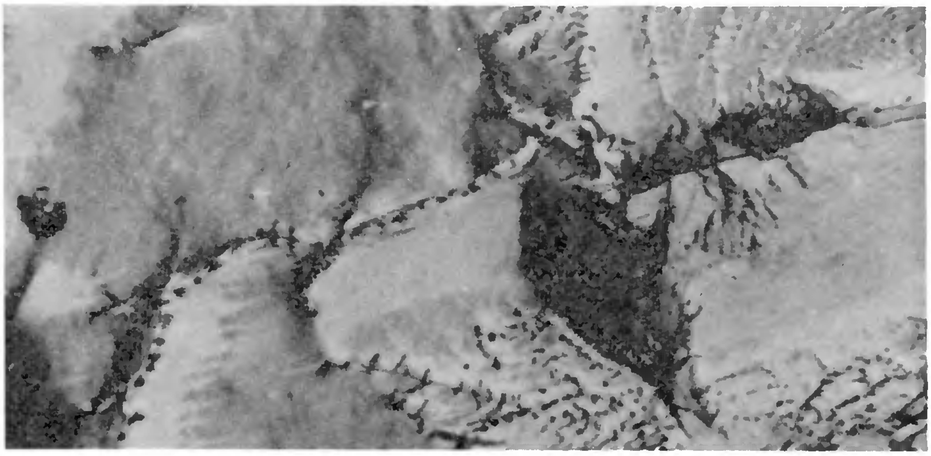
Remote examination of a monitoring fuel element in the Shielded Area of Materials Division. Here the deformations resulting from reactor operations are being measured and samples prepared for further study. These examinations provide essential confirmatory data for the basic studies which then contribute to improving the confidence of predicting future safe and economic operations



(a) Electron micrograph of a replicated fractured surface of an irradiated uranium fuel bar showing fission gas bubbles approximately 200Å diameter decorating microstructural boundaries. Magnification × 24,000

(b) Photomicrograph of a remotely sectioned and prepared sample of an irradiated fuel bar showing voidage in the uranium arising from stresses developed from the irradiated growth process. Magnification × 2,000

(c) Nabarro Herring or diffusional creep in a fuel element sprung arm spider



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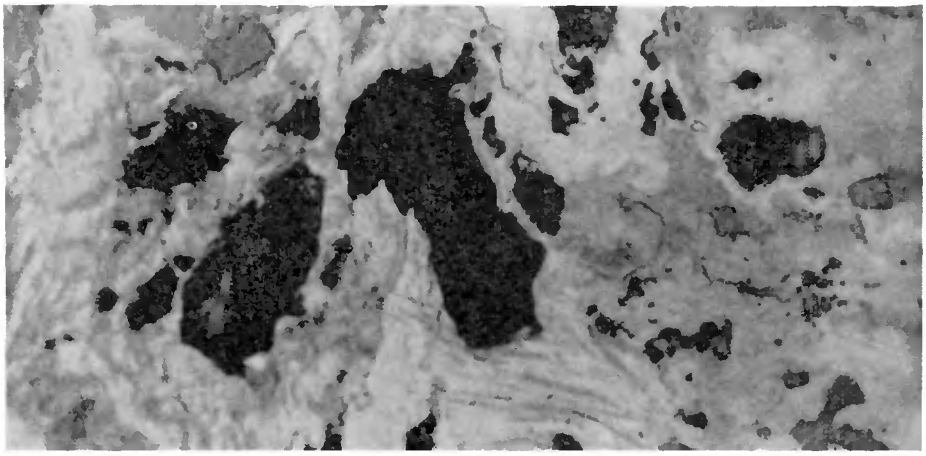

b

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facility at Berkeley where their performance is assessed. Current work is directed to monitor their continued performance and to give confidence in their safe operation as well as to test schemes for further increasing the life of the elements.

The fundamental work is designed to obtain the necessary scientific information to aid the interpretation of the data arising from these examinations and the out-of-pile deformation studies. For example, work on creep mechanisms in magnox alloys has given confidence in performance and explained certain deformation phenomena in terms of vacancy diffusion creep. Similar studies are now current on basic grain growth mechanisms and fatigue.

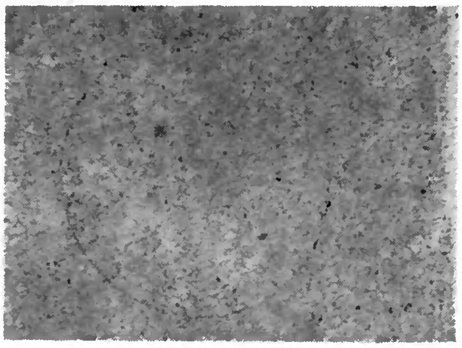
These predictions have been confirmed by actual measurements on monitoring elements and show that the performance of the canning material will allow the target irradiation of the fuel to be exceeded. Work continues to determine the final life limiting mechanism. The ultimate limits of growth and swelling are being explored by correlating the monitoring measurements with the fundamental work on the mechanisms which cause irradiation damage. The further study of the mechanisms of breakaway swelling which occurs in a limited temperature band is an important programme of work for the high voltage electron microscope.

The fuel for the commercial advanced gas-cooled reactor is the ceramic uranium dioxide, capable of withstanding higher temperatures and burn-up. The UO_2 pellets are encased in a thin sheath of stainless steel and the element consists of a cluster of 36 slender pins. These are separated in stainless-steel grids within a graphite sleeve which allows the gas flow in the reactor to be re-entrant, thereby avoiding excessive temperature in the moderator. The fuel element pins must withstand the strains imposed by the reactor environment without failure, and studies of these environmental effects will ensure an adequate prediction of performance.

(a) Classic Hertzian crack in silicon carbide caused by a spherical indenter. The studies showed this lower limit to fracture for silicon carbide which contributes to its rejection as a fuel cladding material in some circumstances. Magnification × 90

(b) The above crack at higher magnification shows that the crack propagation is unimpeded by the three disparate phases present. Magnification × 1600

a



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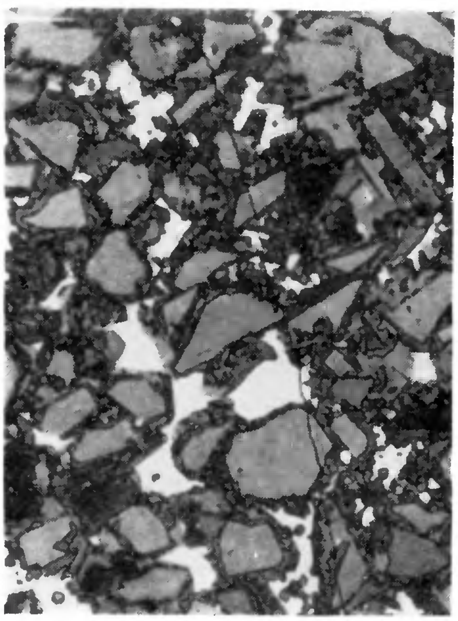
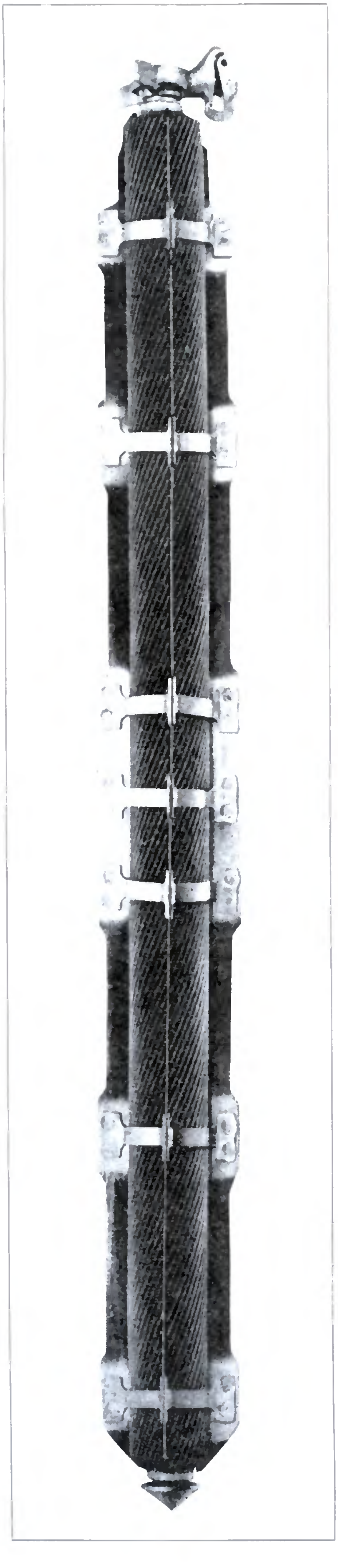
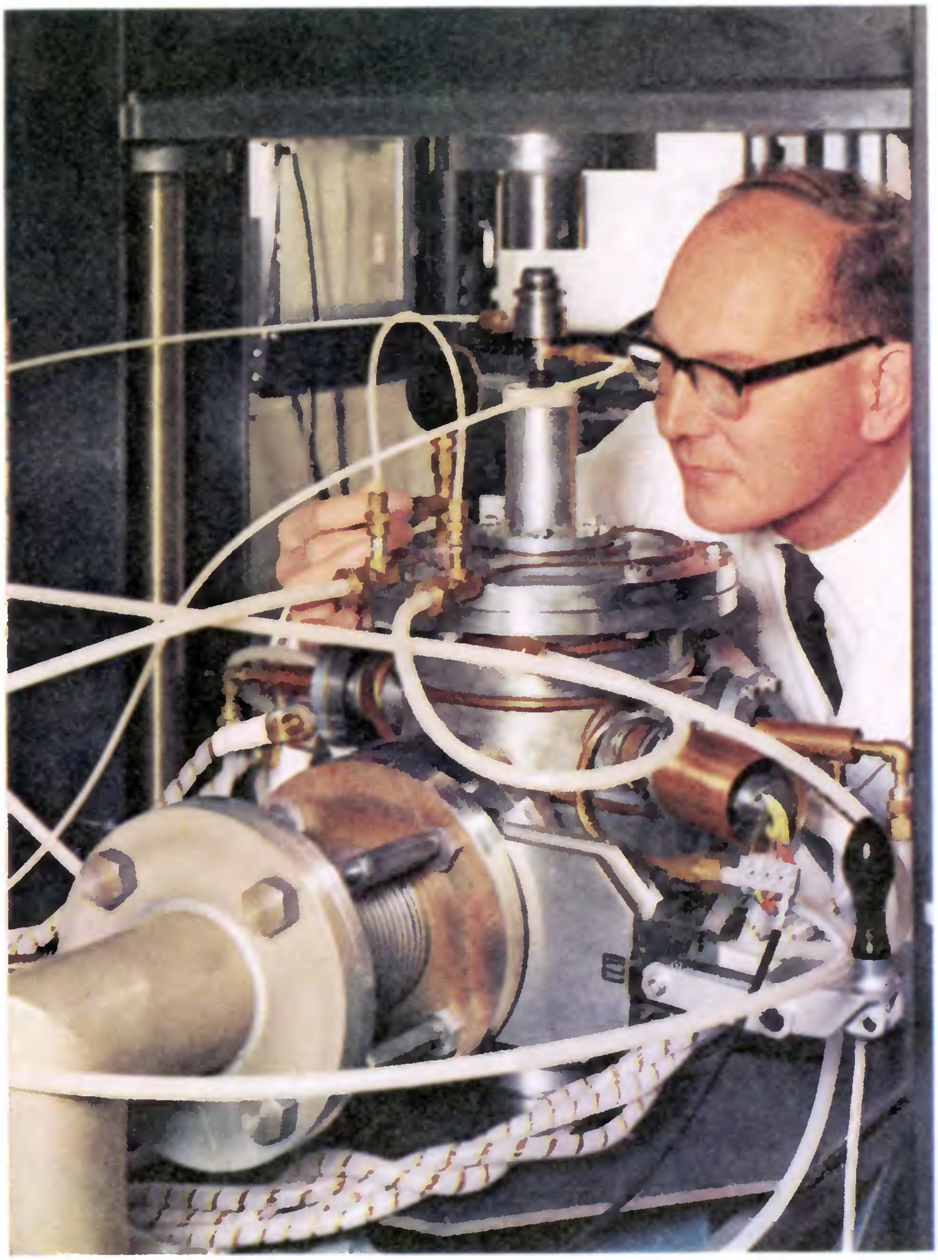


The ceramics section is currently studying the fundamental laws governing the key areas of UO_2 behaviour. These include the escape mechanisms of gaseous fission products—including the bubble precipitation and re-solution processes as well as the thermal and irradiation creep behaviour. The work of this section is being extended to cover the behaviour of other fission products—particularly for future systems.

Work on the cladding includes its oxidation behaviour, including studies of the interaction of deformation and oxidation, and basic studies of the various possible deformation laws. An emerging programme of work concerns the combination of various damaging deformations (creep, fatigue, etc.) to produce accurate prediction of failure times under randomly varying loads.

A proportion of the laboratories effort is devoted to problems arising in possible future systems. For example the basic studies of irradiation creep were recently extended to produce independent predictions of the life of pressure tubes (or zirconium alloy), an essential component of steam generating heavy water reactors. A programme of work is now starting on the mechanical performance of composite structures (e.g. coated particle fuel), on oxidation in low concentrations (e.g. impure helium) and on fission product diffusion through future fuel materials.





Left: A typical fuel element of the magnox type

Adjusting the conditions of a high temperature controlled atmosphere compression apparatus for the determination of the deformation characteristics of uranium dioxide, the ceramic fuel for the AGR stations

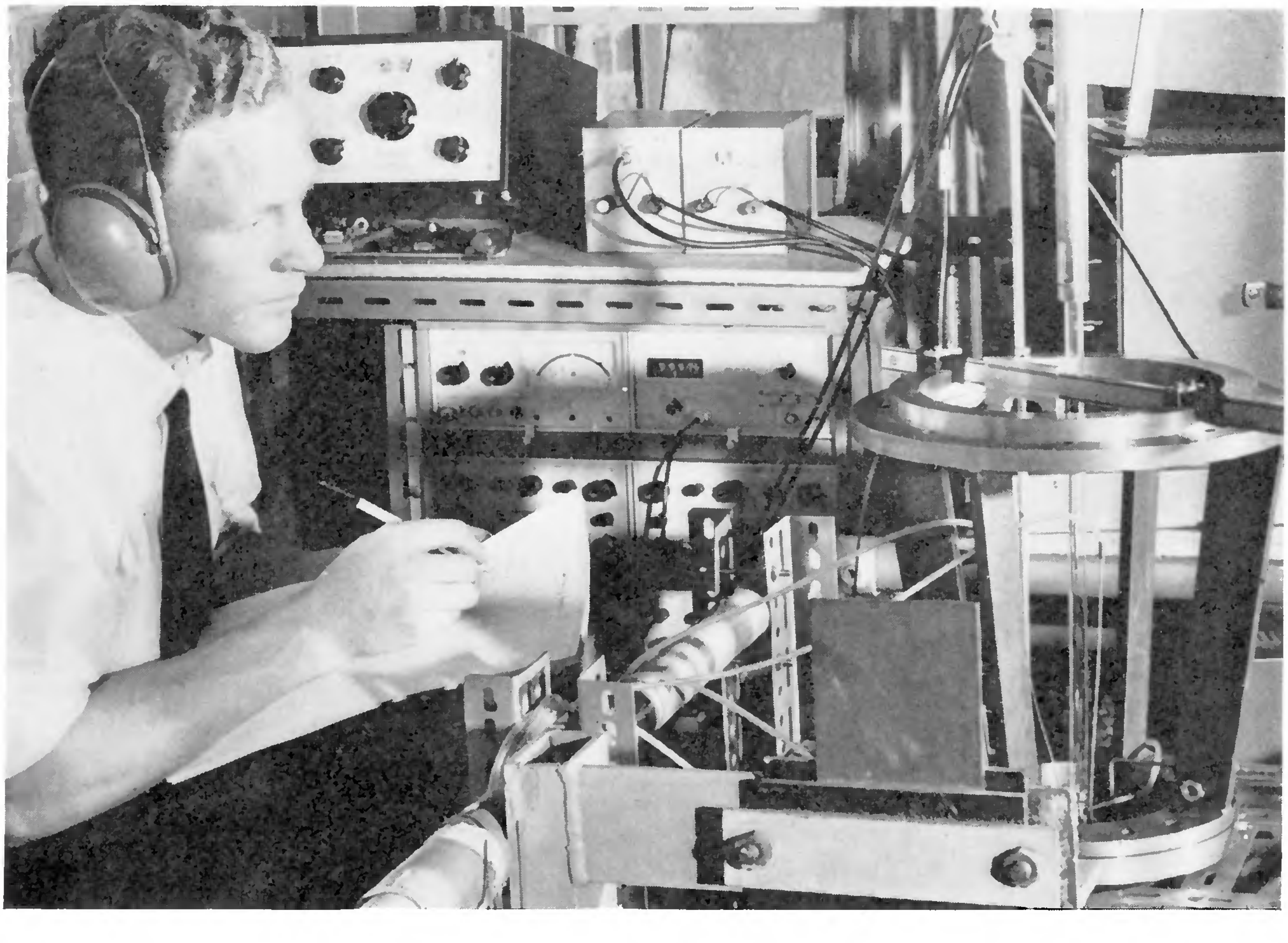
Careful measurements of the heat transfer and frictional performance of magnox fuel elements under operating conditions continue to be required. Elements with improved heat transfer performance are being developed for several of the Board's stations. With the higher temperatures and ratings of the AGR fuel the large area fins of the magnox elements have been replaced by smaller diameter pins with roughened surfaces. To study the heat transfer phenomena in such surfaces and assemblies, a large-scale rig to study flow conditions is becoming available. This enables detailed study of flow distribution, mixing and heat transfer coefficients.

Roughened heat transfer surfaces formed by various shapes of transverse and multi-start helical ribs are being developed for AGR fuel pins. Both types of surface offer some improvement in heat transfer over the present square, transverse ribbed surface. The multi-start helical ribbing has the additional advantage that it leads to a very large increase in mixing within the cluster and hence to a substantial reduction in local high temperatures and temperature gradients. The multi-start concept will require development into an acceptable reactor fuel element design.

This development work is supported by a wide range of more basic studies on turbulent flow in rough and smooth ducts and on the nature of the flow over individual roughness elements. These studies have already allowed a more precise prediction of flow distribution, and hence of temperature distribution within clusters.

The AGR heat transfer studies naturally extend to HTR. In particular, work on flow and heat transfer in concentric and bowed annuli and on the effect of flow disturbances such as might be caused by structural members. Research on mean and fluctuating velocities and temperatures very close to a heated smooth surface should help to put on a more scientific basis the effect on heat transfer and friction of fluid property variations which occur in the fluid close to a heated surface.

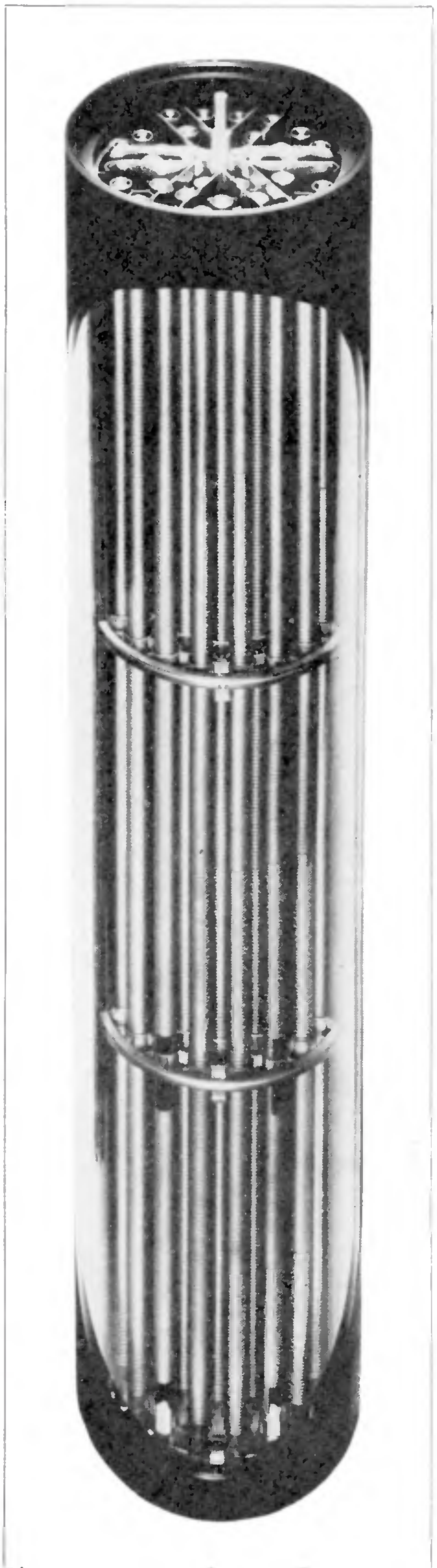
A basic study of turbulence in gas flow. This apparatus is measuring the fluctuating components of velocity in an annular duct. The results are applied to the prediction of velocity distribution in rod clusters



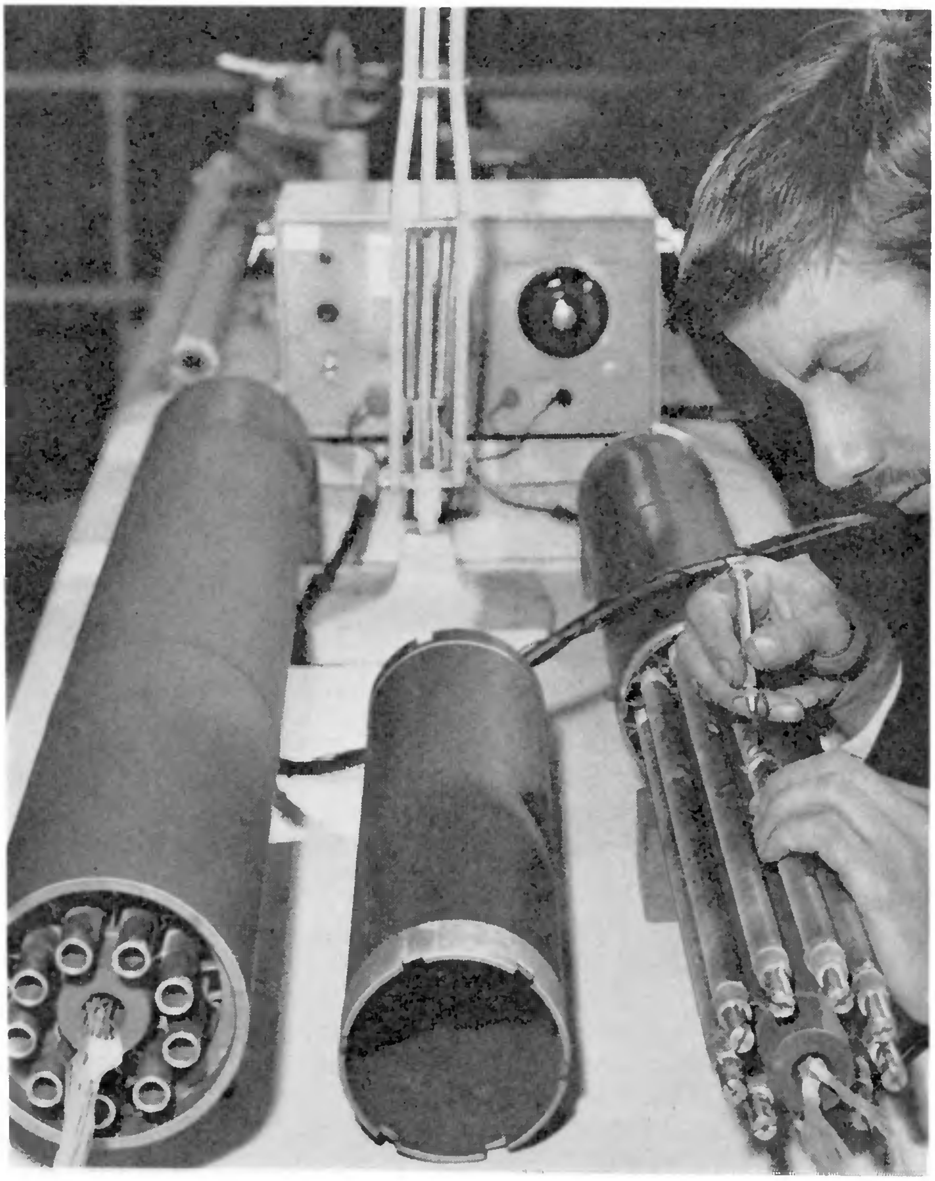
Reactor Operations Measurement of reactor environment requiring specialised techniques is important to the reactor operator and to the identification of improvements since small increases in performance give large economic gains. However, they must be accompanied by adequate confidence based on sound theoretical studies supported by experimental confirmation. This work has already produced a range of Health Physics instruments and made available a television system for use in the onerous conditions of reactors at full power. A remotely operated still camera system which can be used for the fuel standpipe makes a useful contribution to maintenance. Current work which includes noise analysis, pulsed neutron and ^{16}N measurements should improve operational procedures, and work on delayed neutrons could contribute to melt-out protection.

Research results often require the development of specialised devices. An example is the AGR fuel cycle simulator which will enable the operators to preplan their fuel management operation.

To ensure the reliable control, operation and refuelling of reactors it is necessary to guarantee that all moving parts operate satisfactorily under quite exacting conditions in the hostile environment inside the reactor. With the development of more advanced reactor systems, conditions will become even more onerous and the problems of friction, lubrication and wear are likely to be important. In general, fluid lubricants are precluded, and a research programme is directed towards understanding the nature of contact between solids and the micro-deformation processes which occur at surfaces and manifest themselves as friction and wear. The objective of the programme is to



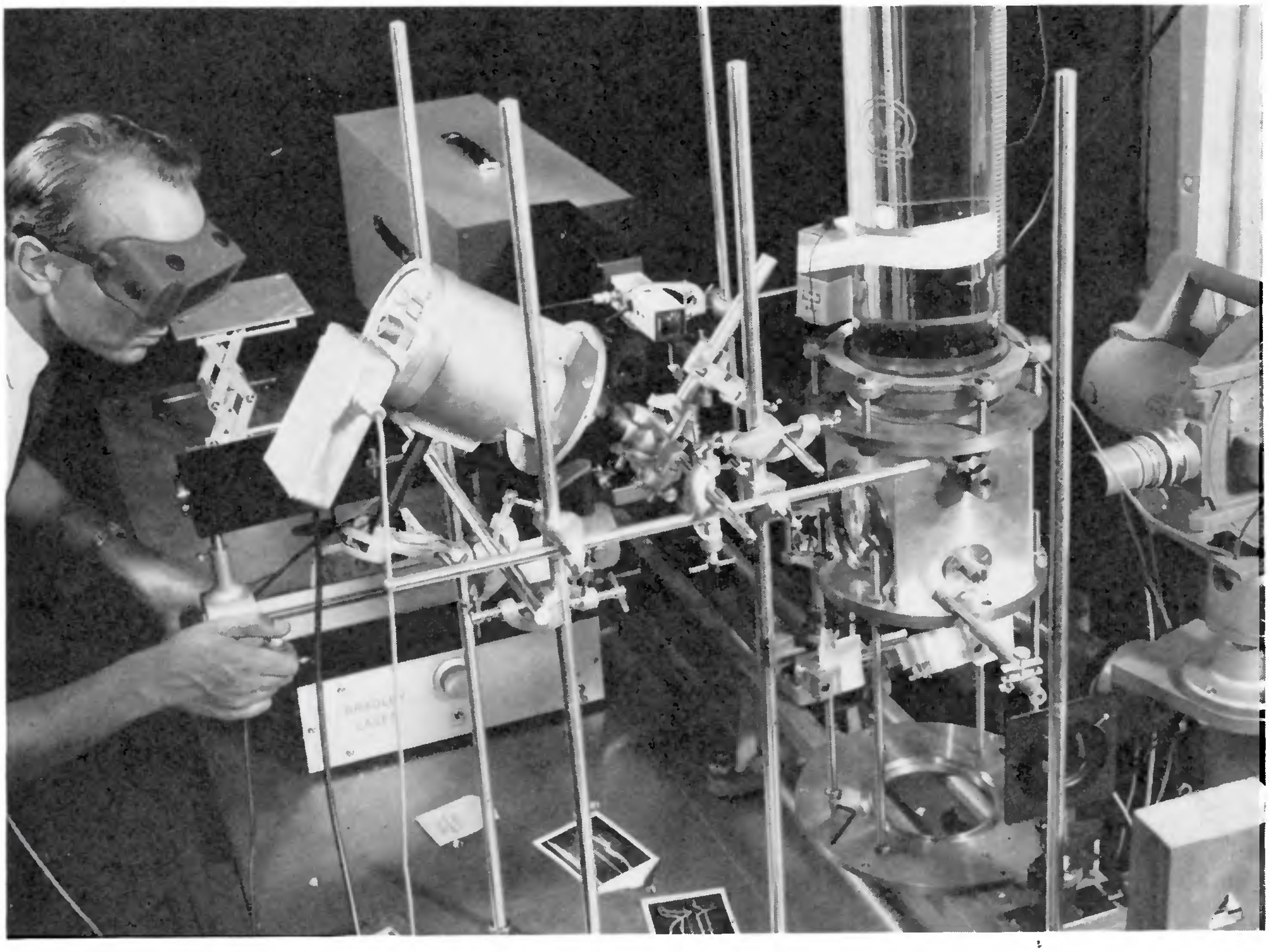
AGR fuel element cluster for Dungeness B. The outer casing is cut away, showing some of the 36 fuel rods



Assembly of heated rod heat transfer experiment to simulate AGR type rod clusters develop the theory of friction to the level where quantitative laws may be proposed and studies include surface micro-topography, deformation processes in individual surfaces, and the surface physics of adhesion. In order that the results of this programme can be related to reactor operation, comprehensive failure analysis techniques are being developed which will enable the reliability of specific mechanisms to be assessed at the design stage.

Reactor Safety All the work of the Laboratories has the underlying requirement to make a contribution to the reliable and safe operation of existing and future reactor systems for power generation. In particular gas circuit physics is concerned with the fate of fission products and its measurement.

Continuous economic operation of the Board's reactors requires the prediction of the fate of any fission products released into the gas circuits, as parts may require removal or maintenance. The environment is unusual in that it is a hot, weakly ionised gas. Research is concentrated on aerosol physics, surface physics and radioactive material transport so that an understanding can be built up of the respective roles of dust entrapment, surface deposition and resuspension on the capture of fission products.



Studies of explosive boiling in liquids—relevant to fast reactor safety. A high powered laser is being used to vaporize metal in a liquid environment and a variety of diagnostic techniques are being used to study the resulting transients

The design of a reactor biological shield is made difficult by the need to have penetrations in it to enable fuelling operations. The calculation of gamma and neutron radiation through such channels gives rise to difficult theoretical problems in radiation physics and confidence in these calculational methods is being built up by measurements on power reactors. This has necessitated the development of special equipment that will measure radiation of various types over a wide range of energy and intensity.

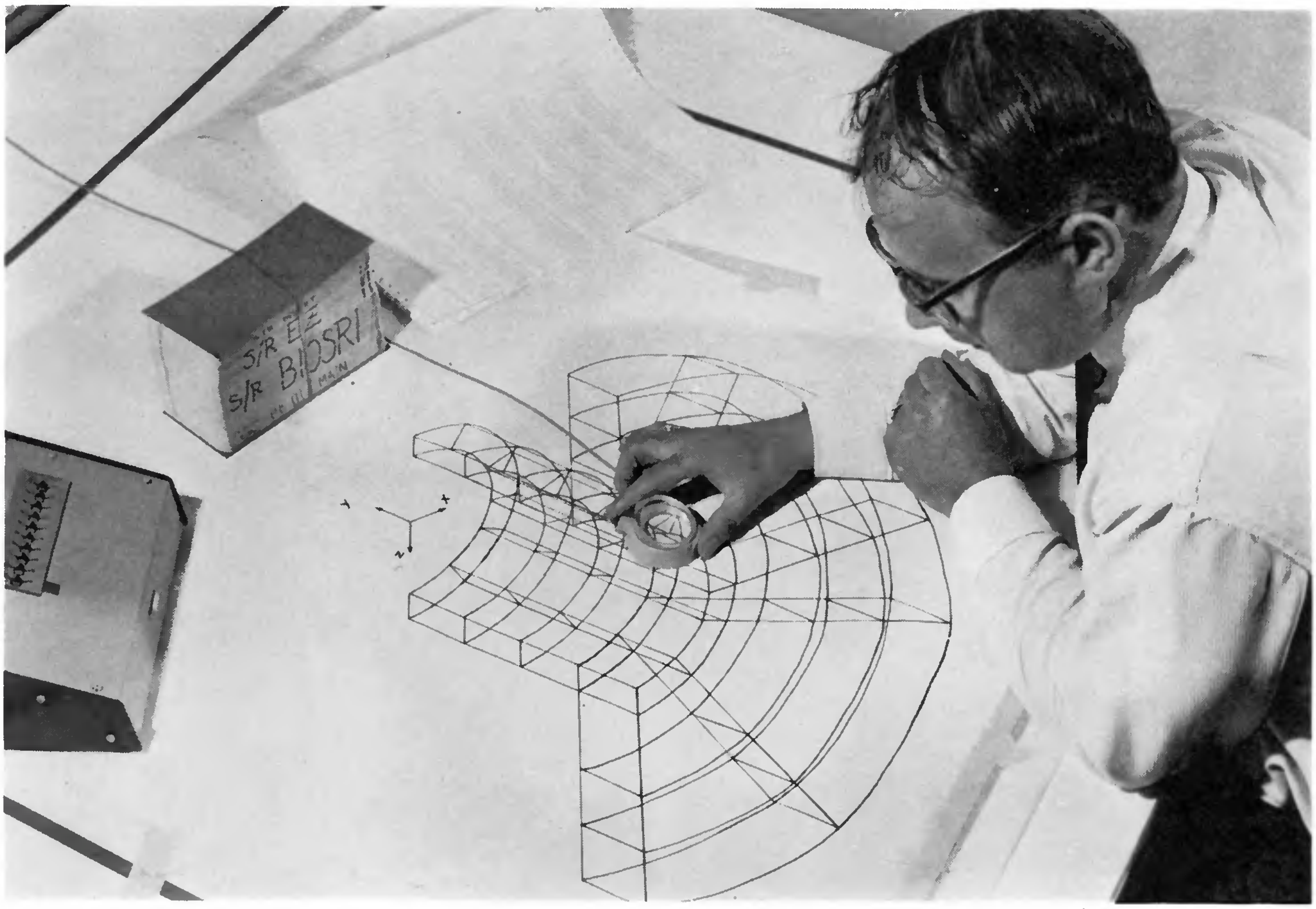
Health physics Nuclear power involves the production of radiation and radioactive material, which like other industrial by-products, can be dangerous if not intelligently controlled. Radiological protection is a wide field of study covering many disciplines in the physical and life sciences. The Laboratory does not conduct much biological research, but maintains close collaboration with experts in this field.

Forms of radiation and radioactive material in nuclear work are such that a wide range of studies is essential. It is necessary to determine levels at which the radiation doses are acceptable for workers and the public. The Laboratory contributes to the work of the International Commission on Radiological Protection, whose Recommendations are taken as a basis for legislation and CEGB Rules. The Laboratory contributes advice to help ensure safety requirements without extravagance. It is necessary to check that the operations are within the acceptable safe limits by measuring the public and working environments, and estimating the personal dose to individual workers. The safe limits are in terms of radiation dose in specified parts of the body, and since these cannot be directly measured, skill is required in specifying external measurements from which these can be estimated economically. This involves such studies as the physics of radiation detectors, the electronic engineering of display circuits, and the physics and chemistry of aerosol filters. A mathematical dosimetry study showed that the beta ray component of dose was higher than previously thought. This led to improved dosimetry methods based on thermoluminescent materials, to the development of a flat ion chamber monitor, and to the establishment of accurate standards. This example is typical of the way in which the solution to a practical problem requires research in a number of different fields.

One important aspect of this work is the maintaining of accurate standards for all types of radiation. These are compared with the national standards, and BNL's unique radiological calibration services are used throughout the Generating Board and elsewhere.

Computing Facilities

Comprehensive facilities are available to Berkeley staff at the Generating Board's Computing Centre in London. Digital computers include an IBM 360/75 controlled by an IBM 360/50. An EAI 8900 Hybrid computer is available for those problems which are more easily dealt with by composite analogue/digital computational methods. A comprehensive range of scientific Fortran programs are available through the Computing Branch but, where the scientific work calls for it, particular programs or modifications are designed by the research staff. A 24-hour turn round of processing is possible by using card preparation at Berkeley and overnight transport. A data link will be available if and when the traffic requires it. Examples of problems which are in production are fuel management, long-term reactivity, and transient and non-linear structural behaviour of reactor structures.



The shape of a component can be automatically described in punch card form by the use of the co-ordinate digitising table. The cards produced form part of the computer input for transient temperature or stress analysis calculations. This technique has been developed at BNL for use in the finite element method for the structural analysis of power plant components

Collaboration with Outside Organisations

The Generating Board's policy of wide dissemination of their work is further stimulated by their encouragement of co-operation and collaboration with industrial organisations having allied interests. An important aspect of this is the excellent relationship with the UKAEA whose role is to develop reactor systems to the point of practicality, at which time they are considered by the CEGB as possible means of electricity generation, and ultimately taken over by the Generating Board for exploitation.

Close contact with the UKAEA is maintained at all levels and co-operation takes the form of consultation on programmes of work and collaboration on particular aspects of work of mutual concern. Contacts are also maintained with the nuclear construction industry in association with the Generating Board's Generation Design Department. It is a measure of the success of such co-operation that the maximum utilisation of effort is maintained by eliminating serious duplication whilst preserving the Laboratories' mandatory function of technically monitoring the design and operational characteristics of reactor systems for commercial operation.

Berkeley Nuclear Laboratories and the Universities

Links with universities and other research centres are strong. Considerable importance is attached to some of the fundamental research carried out in university departments which complements the Generating Board's own basic work. Contracts are placed annually with universities for investigations in the nuclear field, and contact between the CEGB and individual universities is provided by technical correspondents who are members of the Laboratories' scientific staff.

A number of research fellowships, some tenable at the Berkeley Nuclear Laboratories, are awarded by the Generating Board each year. The election is made from honours graduates with post-graduate experience who can show a high standard of research ability. Fellows undertake research within the field of interest of the particular laboratory with which they become associated. They work closely with their colleagues on the permanent staff and one of the great values of the fellowship scheme lies in the mutual benefit of a free interchange of ideas and experience between them. A limited number of these fellowships are available to American nationals wishing to gain research experience in this country. Research staff are encouraged to read for higher degrees whilst at the Laboratories, subject to the necessary arrangements being possible with the universities.

Information Services and Publications

It is the policy of the Generating Board to encourage the wide publication of its scientific work and about 200 internal reports are issued by BNL each year. These reports are used to disseminate the results of research programmes and to make appropriate recommendations within the CEGB. Often they are accepted with little modification for external publication in technical and scientific periodicals. Additionally, papers are written especially for submission to the main scientific journals in the customary way.

BNL also participates in international conferences both by the submission of papers and by the attendance of individual research officers working in the particular field. Reports and publications are issued by the Berkeley library, which also supplies an information service in collaboration with the Generating Board's Central Library in London. The usual library facilities are available and close contacts are maintained with the libraries of other organisations.

Bibliographies of the published works of the scientific staff are available on application to the Information Officer.

BNL Research Topics and Organisation

Materials

FUEL ELEMENT Predictions of performance from basic and empirical studies of irradiated fuel elements.

CERAMICS Physical properties and basic irradiation behaviour of UO_2, UC, SiC, Al_2O_3 and graphite.

IRRADIATION DAMAGE Basic mechanisms: general effects on mechanical properties.

MECHANICAL PROPERTIES Fundamental studies on the aspects of mechanical properties important in the design and operation of reactors.

CHEMISTRY Radiolytic reactions CO_2/CO/hydro carbons and graphite: gaseous oxidation: analysis of radioactive isotopes: helium and sodium chemistry.

REACTOR SAFETY Measurements on samples from reactors correlated with basic data to ensure safety.

Physics

REACTOR PHYSICS Studies on the physics of reactor cores: fuel cycles.

EXPERIMENTAL PHYSICS Radiation physics: gas circuit studies.

HEALTH PHYSICS Research involving the interaction of radiation with man: dosimeter calibration.

Engineering

APPLIED MECHANICS Stress and vibration analysis of pressure circuit components: numerical materials laws: environmental tests.

REACTOR HEAT TRANSFER Mechanisms of heat transfer between fuel element and coolant: fluid mixing in rod clusters: rough surfaces.

REACTOR CHEMICAL ENGINEERING AND MECHANISMS Chemical engineering studies of circulating reactor coolants: sodium technology: tribology and its application to mechanisms for hostile environments.

Services

ADMINISTRATION Personnel: Finance: Purchasing.

LIBRARY Information Services: reports.

OPERATIONAL HEALTH PHYSICS Radiation and contamination control: compliance with nuclear legislation, personnel dosimetry, conventional safety.

RESEARCH PLANNING Strategic planning: resource allocation: cost effectiveness: research on methods.

ENGINEERING SERVICES Design and manufacture for experimental work: maintenance and plant operation: new works.

Enquiries for further copies to:
The Personnel Officer
Berkeley Nuclear Laboratories
Central Electricity Generating Board
Berkeley
Gloucestershire

or
Information Services
Central Electricity Generating Board
Sudbury House
15 Newgate Street, London EC1

Regional Public Relations Officer
South Eastern Region
Central Electricity Generating Board
Bankside House
Sumner Street, London SE1

Regional Public Relations Officer
South Western Region
Central Electricity Generating Board
15-23 Oakfield Grove
Clifton, Bristol BS8 2AS

Regional Public Relations Officer
Midlands Region
Central Electricity Generating Board
Haslucks Green Road
Shirley, Solihull, Warwickshire

Regional Public Relations Officer
North Western Region
Central Electricity Generating Board
825 Wilmslow Road
East Didsbury, Manchester 20

Regional Public Relations Officer
North Eastern Region
Central Electricity Generating Board
PO Box 177
Merrion Centre, Leeds 2

Administrative Officer
Southern Project Group
Central Electricity Generating Board
Squires Lane
Finchley, London N3

Administrative Officer
Midlands Project Group
Central Electricity Generating Board
PO Box 314
341 Bournville Lane, Birmingham 30

Administrative Officer
Northern Project Group
Central Electricity Generating Board
Warren Road, Cheadle Hulme
Cheadle, Cheshire

Administrative Officer
Transmission Project Group
Central Electricity Generating Board
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Portsmouth Road, Guildford, Surrey

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