Berkeley Nuclear Laboratories

"Nuclear energy assumes increasing importance on almost any view of the future, both as a means of extending the period over which the limited supply of fossil fuels meet the bulk of energy needs, and as a replacement thereafter."

Energy Research & Development in the UK. A Report prepared under the aegis of the Secretary of State's Advisory Council on Research and Development for Fuel and Power (ACCORD). 1976.

Cover

This contour chart shows the distribution of fission products across a graphite block forming part of an experimental fuel element; UO_2 fuel pellets were contained in the eight holes in the outer ring. Such charts are produced automatically by a device known as a gamma-scanner. The gamma radiation from each small area of specimen surface is converted electrically into a spot of light coloured according to the intensity of the radiation and this spot is projected onto film to build up the final chart.

Foreword

This booklet has been prepared at a time when the future of nuclear power is being subjected to a great deal of scrutiny.

Behind the welter of conflicting views, certain facts, which are frequently forgotten or deliberately ignored, stand out and are worth underlining.

First, modern living standards depend upon plentiful supplies of energy at costs which are not prohibitive. Secondly, while other measures may have considerable impact, there is no alternative to nuclear power for the longer term security of energy supply. Thirdly, nuclear power stations can be operated safely, reliably and cheaply.

Unchallengeable evidence for this third point is provided by the first generation of UK nuclear plant. Its success is due entirely to the imaginative and dedicated efforts of a range of people spanning the whole field from fundamental research to plant operation, and associated with many organisations. The present climate demands that this effort be maintained, so that the advantages of the nuclear energy route continue to be demonstrated by practical power station operation.

Berkeley Nuclear Laboratories have a most important task in this – by providing research support for the Central Electricity Generating Board in its role as an operator and purchaser of plant. The complexity of modern power stations, the size of the generating system and the costs at stake demand knowledge in such detail, and over so wide a range, that major scientific resources need to be deployed – against operational problems in the short term, and also against longer term objectives. Berkeley Nuclear Laboratories supply this research support for the CEGB's nuclear operations.

The purpose of this booklet is to give the flavour of the Laboratories' work, its objectives, range of interests and methods. No document can give a complete picture, however: one essential ingredient, the staff, can never be properly portrayed. Nonetheless, in addition to the factual information given here, I hope that some indication appears of the energy and enthusiasm of the staff on whom success depends.

B Edmondson
Director, BNL

The Central Electricity Generating Board (CEGB)

The CEGB has a statutory responsibility to develop and maintain an efficient, co-ordinated and economical system of supply of electricity in bulk for all parts of England and Wales. It owns and operates the power stations and the interconnected transmission system, and its operations are on a scale far greater than those of any other single utility in the Western World.

The bulk of the Board's generation is from coal and oil-fired stations, but nuclear plant already contributes about 11 per cent of total output. Under the general co-ordination of the Electricity Council, the electricity generated is sold to the 12 Area Electricity Boards who are responsible for distribution and sales to 20 million consumers in England and Wales.

The CEGB is controlled by a Board of full-time and part-time members. The full-time members work together as a collective Executive under the general oversight of the whole Board. The CEGB has five operating Regions, which run and maintain the power stations, substations and transmission networks in their particular geographical areas; in addition there are two Development and Construction Divisions, responsible for generation and main transmission respectively, and the Research Division. Each Region and Division is headed by a Director-General. A number of specialist departments are located at the Board's Headquarters in London, such as planning and operations.

The Director-General of Research Division is responsible to the Executive for an organisation with almost 2,000 staff and an annual budget of £29 million. Reporting to him are the Directors of the Division's three main laboratories located at Leatherhead, Marchwood and Berkeley, the latter having prime responsibility for nuclear research.

The general objective of the Board's research programme is to provide technical support for the safe and economic operation of existing plant and for the judgements required in the purchase of new plant – in short, to enable the CEGB to be an informed operator and purchaser.

The UK nuclear power programme

Britain launched the world's first commercial nuclear power programme. Stations operated by the CEGB and the South of Scotland Electricity Board have made an important contribution to the nation's energy requirements. The CEGB's first nuclear power stations were commissioned in 1962, and in 1975–76 the Board's eight first-generation stations, each with two reactors, produced more than a tenth of the electricity sold in England and Wales. The average generation cost at these was only 60 per cent of that at contemporary fossil-fuelled stations.

The second generation of nuclear stations is based on the advanced gas-cooled reactor (AGR). The four 1200 MW installations will produce even greater cost advantage as they achieve their expected output.

As to the future, the first CEGB station based on the steam generating heavy water reactor (SGHWR) is under consideration for commissioning in the 1980s, and the potential for the fast breeder reactor is being explored. The sodium-cooled fast reactor is the subject of intensive research and development on a national basis, in parallel with the operation of a prototype plant as Dounreay by the United Kingdom Atomic Energy Authority.

Above
Berkeley Nuclear Laboratories seen from the roof of the adjacent Power Station. The Irradiated Fuel Examination Facility is nearest the camera; the white concrete cube at centre left houses the Critical Reactor Assembly. Oldbury Nuclear Power Station and the towers of Severn Bridge are visible on the horizon.

Berkeley Nuclear Laboratories (BNL)

The Laboratories were set up at the beginning of the 1960s to provide the United Kingdom electricity supply industry, from its own resources, with the research backing to establish nuclear power as an economic means of generating electricity. They stand in pleasant surroundings on the banks of the river Severn, 40km north of Bristol, adjacent to the Board's first nuclear power station at Berkeley. Some 3,500 m^2 of well equipped laboratories serve a staff of 680 including about 280 graduate scientists and engineers. The staff are drawn from a variety of disciplines and provide the broad spectrum of expertise necessary to study the complex technical problems of nuclear systems.

In pursuing its research, BNL maintains close relationships with the Board's laboratories at Leatherhead and Marchwood and with the rest of the power generation industry. Of special importance are the links with other CEGB departments, for example the Development and Construction Divisions, Operations Department, Nuclear Health and Safety Department, Planning Department and the Regions responsible for power generation. As the CEGB does not carry out the actual design and manufacture of plant, its links with the organisations who have such responsibility are vital, embracing the United Kingdom Atomic Energy Authority, British Nuclear Fuels Limited, the Nuclear Power Corporation and the turbine-generator, boiler and other plant manufacturers.

In a wider context, BNL places great weight upon the publication of its work in the professional literature and it has strong links with the universities through the funding of Research Fellowships and programmes of work, provision of access to specialised equipment at the Laboratories, and interchange of speakers for specialist meetings. The Laboratories participate actively in the work of international bodies concerned with nuclear energy and co-operate with many overseas electricity supply utilities and associated concerns. Such activities include information exchanges, participation at conferences, and expert representation on specialist groups.

By all these means, BNL plays a strong role within the utility it serves and also within the wider scientific and technical community at both national and international levels.

Nuclear reactor types

In all types of fission reactors, atoms of the uranium or plutonium fuel are split by neutrons, releasing energy as heat and liberating more neutrons to sustain a controlled chain reaction for example, in a uranium fuelled reactor most of the heat comes from the fission of uranium-235 which constitutes only 0·7 per cent of naturally occuring uranium. Smaller contributions of heat come from the much more plentiful uranium-238 and from the plutonium into which some of this is transmitted in the reactor. To obtain high power densities it is generally necessary to raise artificially the proportion of the fissile component above the natural level, a concentration process known as enrichment.

Thermal reactors require a moderator to slow down the neutrons so that a sufficient number react with the fissile uranium-235. Certain types of reactor depend on graphite for moderation, for example the first generation Magnox plant and the advanced gas-cooled reactor (AGR); in these systems the heat is extracted by a flow of high-pressure gas. Reactors moderated by light or heavy water, for example the pressurised water reactor (PWR) and the steam generating heavy water reactor (SGHWR), use high-pressure water or steam to extract the heat.

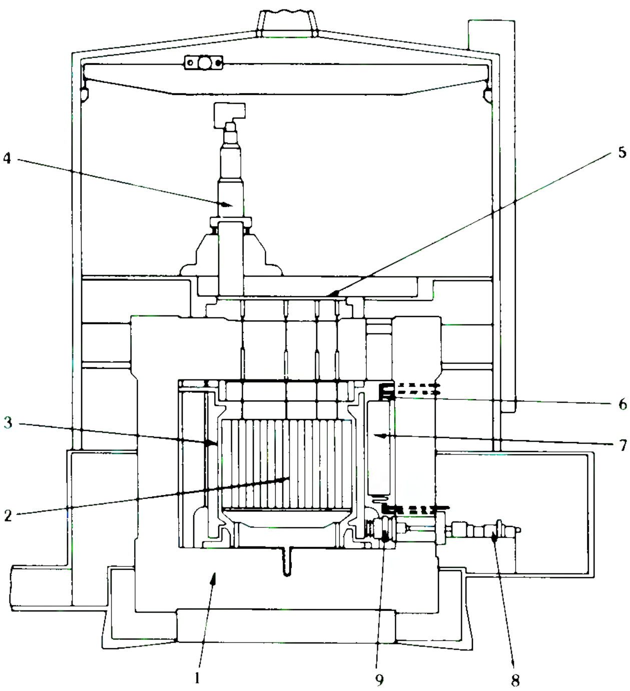
The fuel most commonly used in fast reactors is plutonium, produced initially as a by-product from thermal reactors; a high concentration of plutonium is used so that the fission reaction can be sustained by fast neutrons and no moderator is necessary. The core of the reactor is therefore compact and the resultant high power density calls for a highly efficient coolant such as liquid sodium. The excess neutrons transform the core and uranium-238 in surrounding 'blanket' into more plutonium fuel, the process known as breeding.

In all cases, the final stage of useable power production is similar: the coolant fluid – gas, water or liquid sodium – removes the heat from the fuel elements and itself becomes the source of heat for a conventional steam cycle and turbine-generator.

Details of the different reactor types are given below so that the context of the Laboratory's research programme can be seen more clearly.

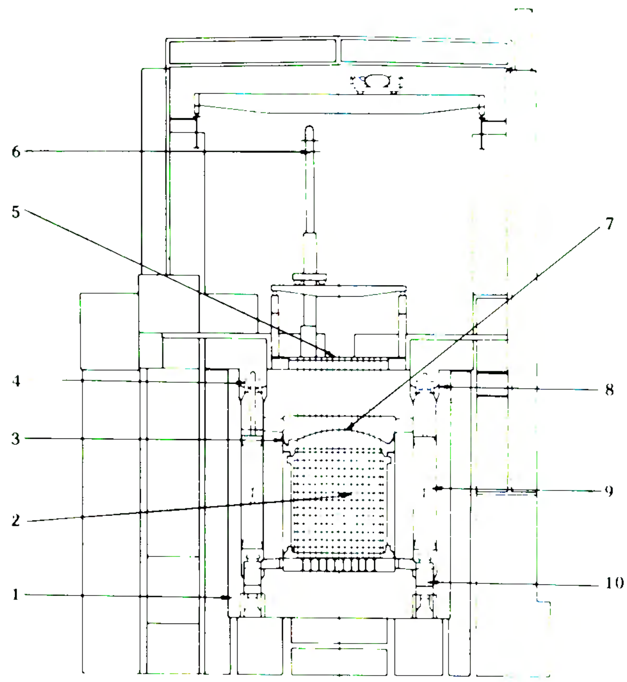
The reactors

Cross-section through a
reactor at Oldbury power station



1 Concrete pressure vessel
2 Core
3 Boiler shield/wall
4 Charge/discharge machine
5 Charge floor
6 Reheater
7 Boiler
8 Turbine for drive to gas circulator
9 Gas circulator

Cross-section through a
reactor at Hartlepool power station



1 Concrete pressure vessel
2 Core
3 Attachment of dome to vessel walls
4 Steam and feed pipes
5 Charge floor
6 Charge/discharge machine
7 Dome
8 Boiler closure
9 Pod boiler
10 Gas circulator

Magnox

Fuel:
Natural uranium metal in cans of a special magnesium alloy (Magnox)

Moderator:
Graphite

Core layout:
Individual fuel elements are stacked in vertical channels in the massive graphite moderator structure

Heat extraction medium:
High pressure carbon dioxide gas

Typical design data for a reactor of 600MW(e) size:
Uranium enrichment: Not enriched
Coolant outlet temperature: 360°C
Coolant pressure: $2 MN/m^2$
Core dimensions: 14m dia. x 8m high

Advanced gas-cooled reactor (AGR)

Fuel:
Uranium dioxide in stainless steel cans; the fuel operates at higher temperature and heat output than Magnox reactor fuel, giving a smaller reactor core and a more efficient steam cycle

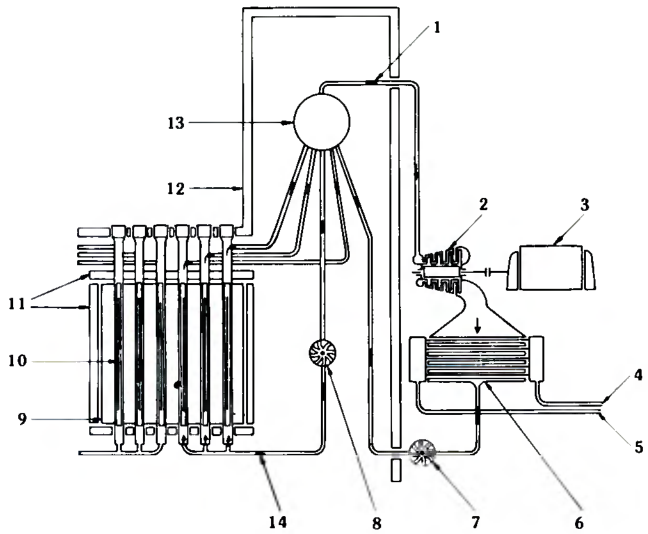
Moderator:
Graphite

Core layout:
Clusters of fuel elements are joined together end-to-end in a stringer and placed in vertical channels in the graphite moderator

Heat extraction medium:
High pressure carbon dioxide gas

Typical design data for a reactor of 600MW(e) size:
Uranium enrichment:
2-3 per cent uranium-235, variable
Coolant outlet temperature: 650°C
Coolant pressure: $4 MN/m^2$
Core dimensions: 9.1m dia. x 8.5m high

Cross-section of the
steam generating heavy water reactor



1 Steam
2 Turbine
3 Generator
4 Cooling water in
5 Cooling water out
6 Condenser
7 Feed water pump
8 Circulating pump
9 Calandria (containing heavy water moderator)
10 Fuel
11 Neutron shields
12 Concrete
13 Steam drum
14 Light water

Steam generating heavy water reactor (SGHWR)

Fuel:
Uranium dioxide in zirconium alloy cans

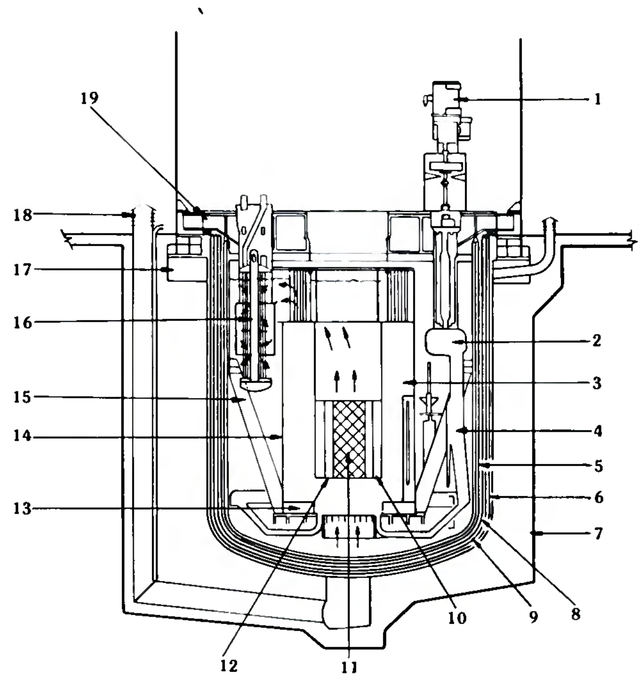
Moderator:
Heavy water

Core layout:
Each cluster of fuel elements is in a separate pressure tube; the pressure tubes are in a tank of heavy water (the calandria)

Heat extraction medium:
Light water at high pressure

Typical design data for a reactor of 600MW(e) size:
Uranium enrichment:
2-3 per cent uranium-235, variable
Coolant outlet temperature: 270°C
Coolant pressure: 6MN/m^2
Core dimensions: 6.5m dia. x 3.7m high

Cross-section of the prototype fast reactor



1 Primary pump drive
2 Primary pump
3 Removable neutron shield
4 High pressure pipework
5 Sodium tank primary vessel
6 Leak jacket primary vessel
7 Structural concrete
8 Vermiculite concrete
9 High temperature concrete biological shield
10 Breeder and breeder reflector
11 'Active' core
12 Core reflector
13 Removable diagrid
14 Reactor jacket
15 Diagrid support structure
16 Intermediate (sodium-to-sodium) heat exchanger
17 Containment hold-down structure
18 Cooling system biological shield
19 Biological shield roof

Fast breeder reactor

Fuel:
A mixture of plutonium and uranium dioxides in stainless steel cans

Moderator:
None

Core layout:
Assemblies of fuel elements are placed inside a tank containing the liquid sodium coolant. The core is surrounded by a 'blanket' in which new fuel is bred

Heat extraction medium:
Liquid sodium

Typical design data for a reactor of 1300MW(e) size:
Fuel enrichment: 20 per cent plutonium
Coolant outlet temperature: 550°C
Coolant pressure: Unpressurised
Core dimensions: 2.3m dia. x 1.1m high
Core dimensions including blanket:
3.1m dia. x 2.1m high

BNL's research programme

The programme is broadly based on the scientific disciplines of physics, mechanical engineering and materials science. The problems studied are very wide ranging, many of them stemming from the generating plant in operation or being commissioned; in such cases the magnitude of both the capital investment at risk and the income involved calls for a high priority response. Even so, half of the total programme is oriented towards plant in the design or conceptual stage and to maintaining a strong fundamental scientific basis.

An outline of the research programme is given below; references to the broad areas described later in this booklet are listed on the left.

This outline shows the breadth of the Laboratories' interests as at February 1977. The detailed sections which follow are not intended to provide a full statement of activities but rather to indicate the scope of the Laboratories' work and the wide range of endeavours and capabilities of its staff.

Fuel and fuel elements (7)
Reactor performance (10)
Structural engineering (12)
Structural materials (13)

Studies are made on the components which are the source of nuclear power, and on some of the factors determining the power output and the extraction of heat from the fuel. Structural adequacy of plant items is ensured by attention to design and materials.

Tribology and mechanisms (15)

Another general area of mechanical engineering given detailed attention is the performance of the mechanisms on which the operation of the plant relies.

Safety studies (16)

Much of the public controversy surrounding nuclear power hinges on the possibility of danger from the release of radioactivity; a significant part of the research is aimed at minimising the problems in this field – for example, work is in progress on factors which might lead to accidental overheating of the core and the consequent spread of radioactivity.

Circuit studies (18)
Health physics (19)

There is also a requirement to understand the behaviour of radioactivity material – both its effects as it circulates in the reactor and associated plant and its ultimate fate and consequences.

Reactor measurements and instrumentation (20)

Spanning most of this endeavour is research into methods of making measurements on the plant itself, supporting both the research workers and the operators in control.

Left
The control console and viewing part of the 1 MeV Transmission electron microscope; this 8 metre high, 20 Tonne machine is used for irradiation studies. Not only does the high accelerating voltage permit the use of thicker more representative specimens, but with suitable adjustment of operating conditions, the electron beam can be used to create radiation damage in a specimen during observation.

Right
This group of steel shielded cells is used for the metallographic examination of oxide fuel from AGRs and water reactors. All the operations inside the cells are carried out using master-slave manipulators, hydraulic or electronic controls. The powerful optical microscopes are fitted for automatic data collection and for optional television viewing.

Fuel and fuel elements

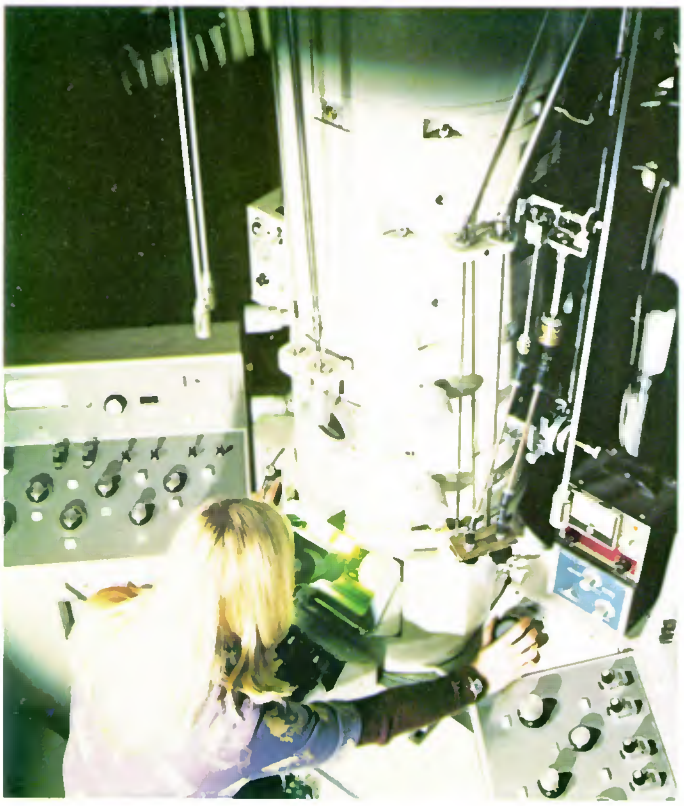
The primary source of power in most conventional generating plant is heat from the combustion of oil or coal. In nuclear plant, the source is heat from the fission of atomic nuclei, generally of uranium-235. In Magnox reactors, for example, the fuel elements are metallic uranium rods 1 metre long, encased in a magnesium alloy can to protect the fuel itself from the corrosive effects of the carbon dioxide (CO_2) coolant. At any one time more than half a million such elements are producing power in the 16 CEGB Magnox reactors. At the end of their period in the plant, a proportion of the elements is examined in the Laboratories to determine the optimum fuel life consistent with the safe and reliable operation of the reactors. For example, close attention is paid to any change in the form of the special fins on the protective can, as this has a vital effect on the efficiency with which the heat is transferred to the circulating CO_2. Changes in the dimensions of the uranium bars themselves are also of special significance; in unfavourable circumstances, volume increases of 14 per cent occur, but studies at BNL have shown that no serious operational difficulty results.

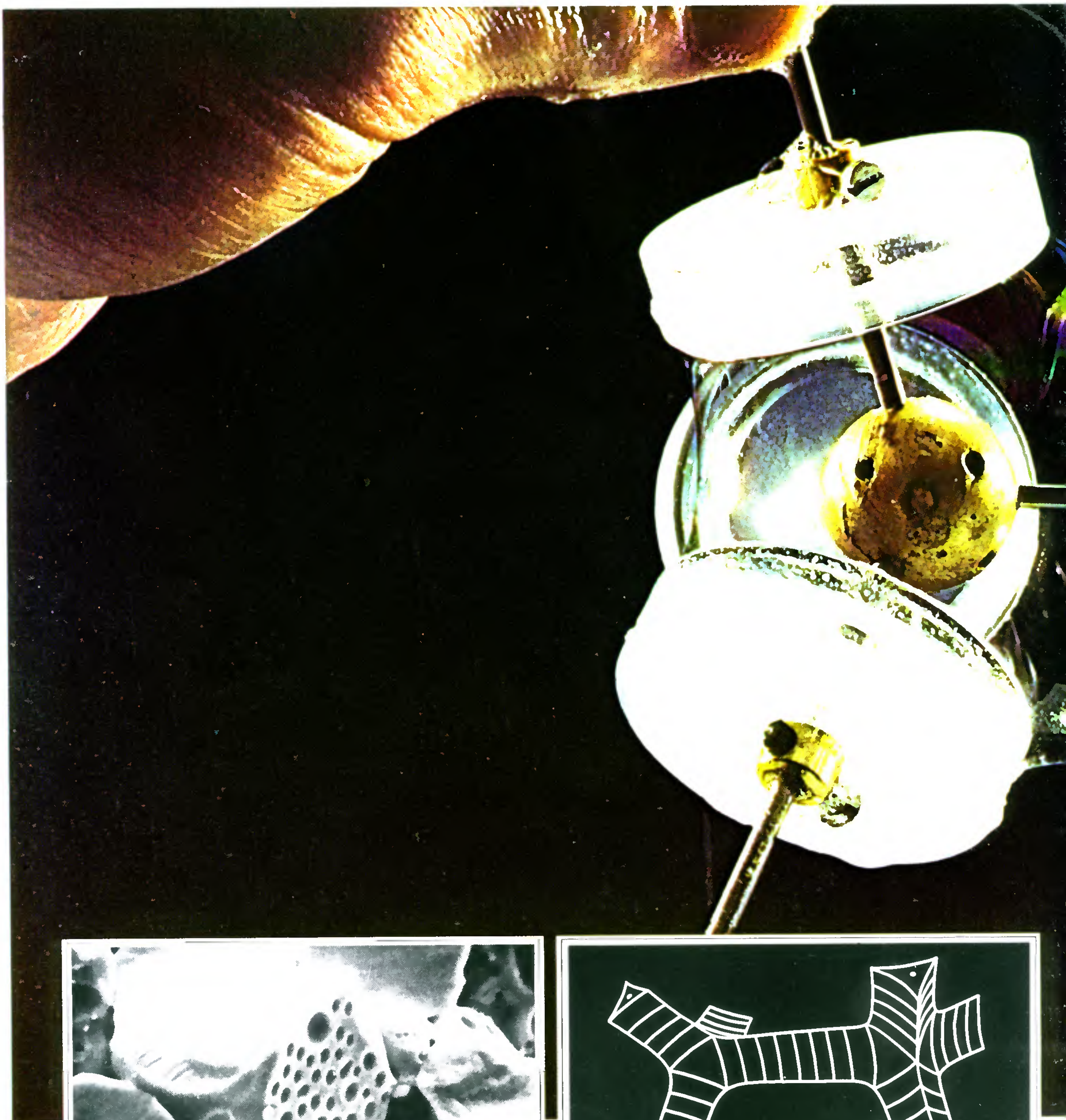
Similar work is in progress on fuel from the more advanced reactor systems, for example the AGR and water reactors, the latter in association with utilities abroad. In these systems, instead of metallic uranium, uranium oxide is used as the fuel to cope with the more severe conditions. Certain by-products of the fission process – the inert gases xenon and krypton – are produced in large quantities and collect to form voids within the fuel itself. The processes involved in the formation and subsequent behaviour of these voids are rewarding and exciting areas of basic study bearing directly upon the operation of the reactor.

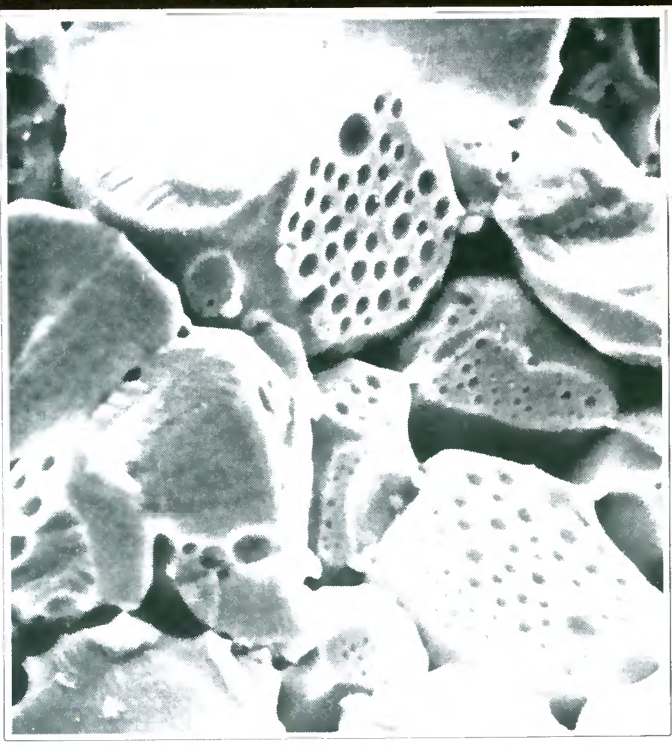
The fuel cans in more advanced plant have to be stronger to resist the internal pressure resulting from the gases generated within the fuel and to resist damage from the intense neutron irradiation. In the fast reactor, for example, the intense bombardment may cause each atom of a fuel to be knocked from its site up to 60 times during its period within the reactor. Whilst most of this damage heals rapidly, there are residual effects with important practical consequences. For study in the laboratory this process can be simulated conveniently by bombarding samples with electrons using the 1MeV electron microscope.

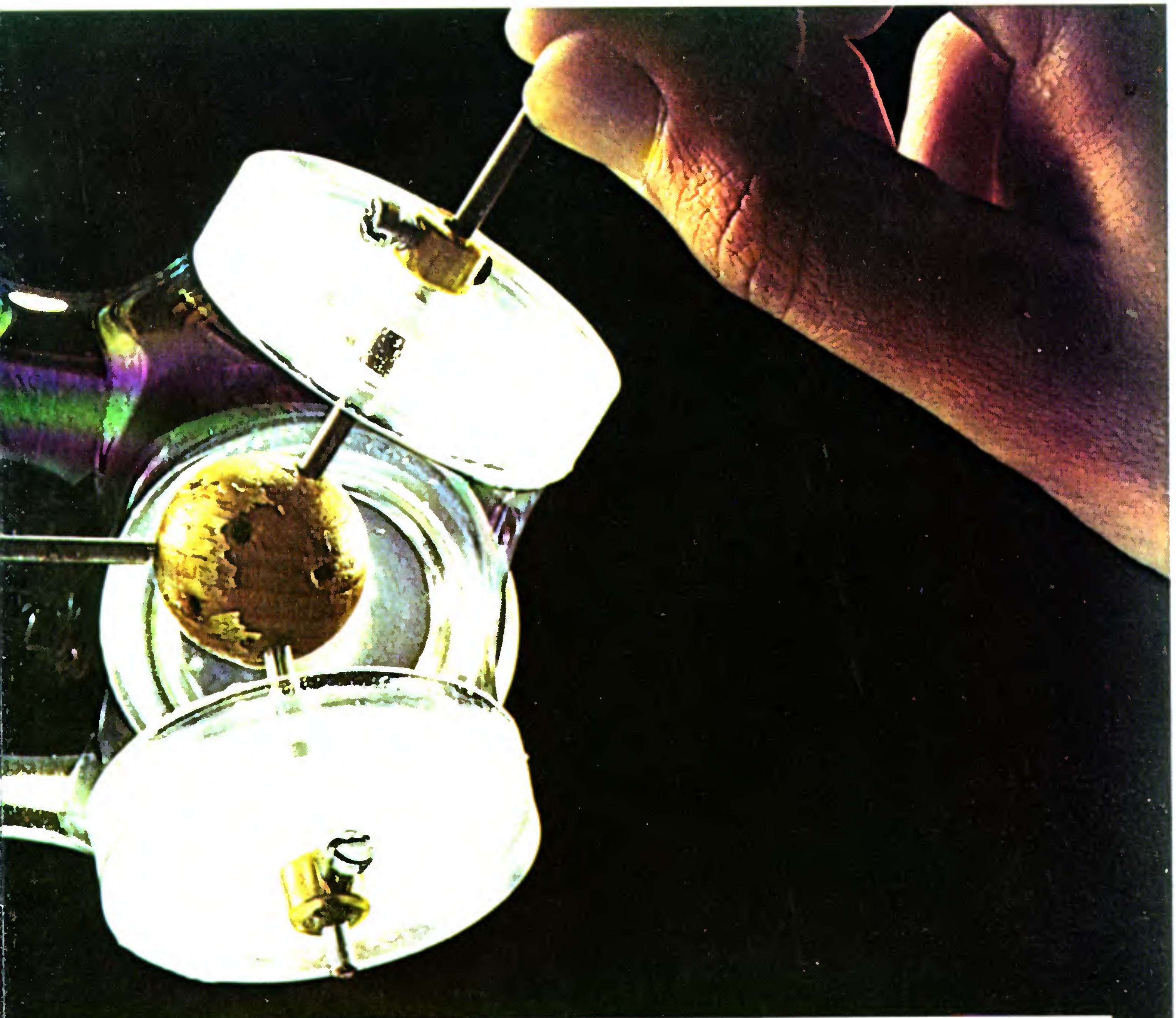
For work involving irradiated fuel and other highly radioactive materials, there is a very extensive facility at BNL. This entirely self-contained unit comprises: a large water-shielded storage pond; nine concrete-shielded 'caves' for operations on highly active components, eg complete fuel elements; lead or steel-shielded 'cells' for work on smaller samples; ten of these are general in application and seven are adapted specially for metallographic studies or chemical analysis; workshops; change rooms, active laundry, and decontamination facilities.

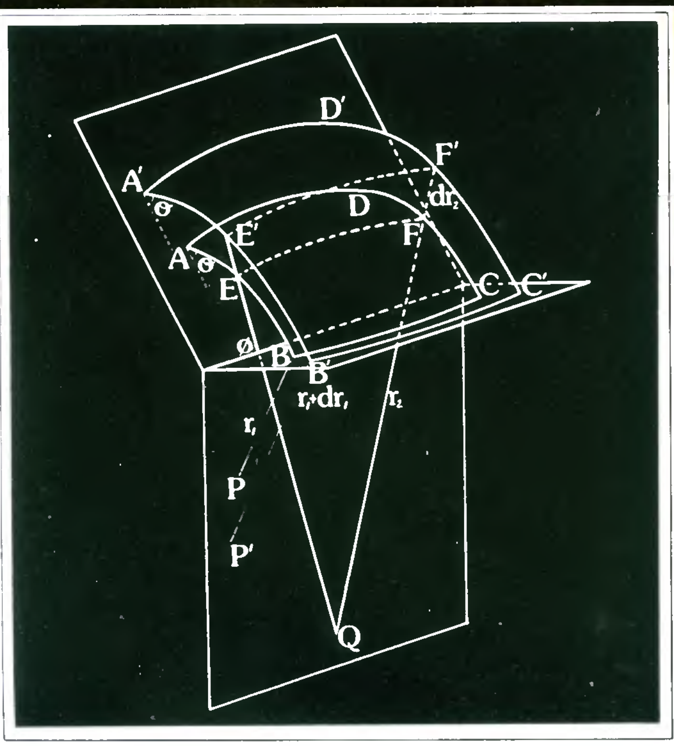
The unit is able to undertake a wide range of work on spent fuel, reactor components and other highly radioactive material.











Bubbles in UO_2

Xenon and krypton are produced by the fission of uranium atoms and diffuse through the fuel to form bubbles, some within the grains and some at grain boundaries. It is important to understand the mechanisms that control the distribution, size and shape of these bubbles, and both theoretical studies and experiments using irradiated fuel are performed at BNL.

Above
Soap film model of gas bubble at intersection of grain edges.

Left
Typical bubbles on the surfaces of grains in a specially irradiated UO_2 specimen as revealed by the scanning electron microscopy.

Centre and right
Computer predictions of bubble shapes at grain corners for dihedral angles of (Top) 15° and (Bottom) 90° respectively. (Right) a surface element used in the calculations.

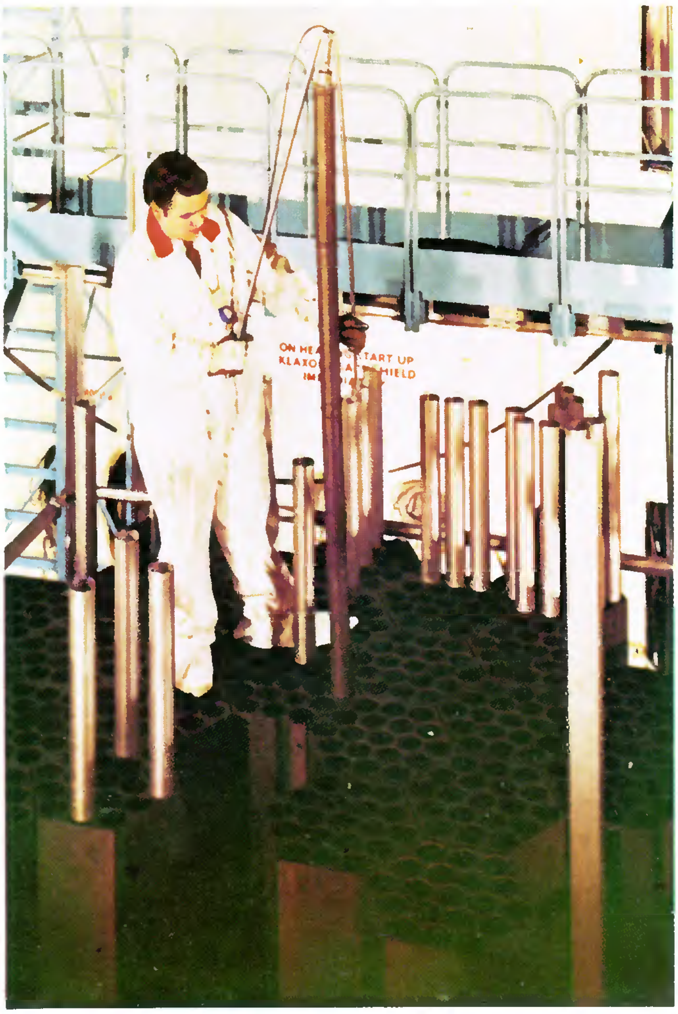
Reactor performance

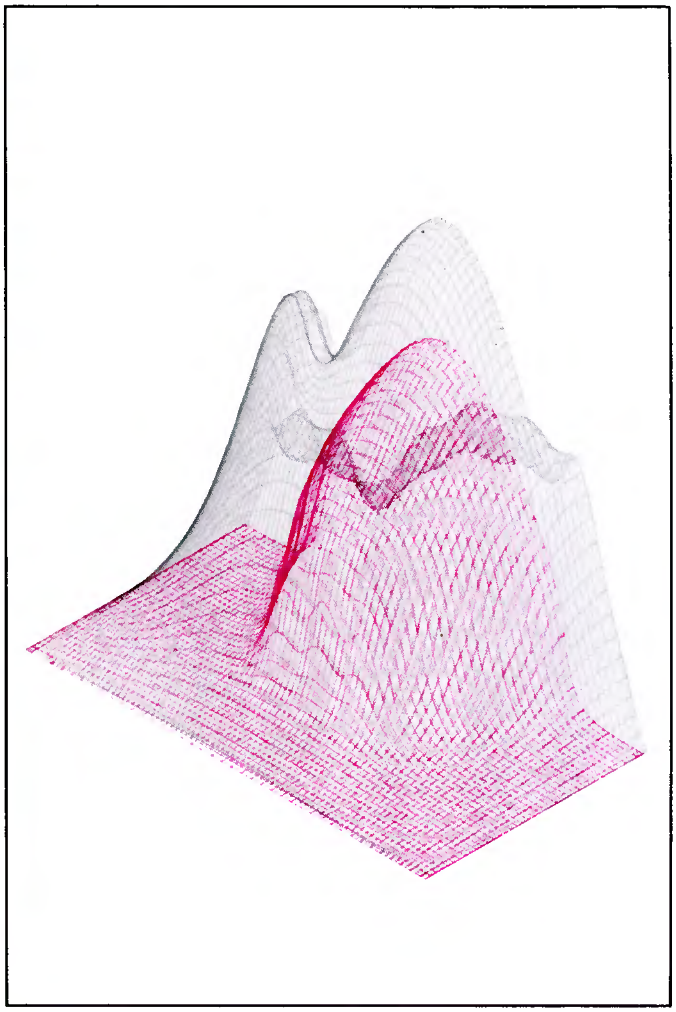
BNL research on reactor performance embraces two major disciplinary lines: reactor physics and heat transfer with associated fluid dynamics. The aim of much of the research is to ensure continuing reliable reactor operation by increasing our knowledge and understanding of the physical conditions inside the cores of nuclear power reactors. In each area, a combination of major experiments and theoretical modelling is demanded.

As an example, a study is being made of the changes in the heat transfer performance of AGR fuel arising from the bowing distortion of individual fuel rods during operation. The research involves basic wind tunnel investigations of turbulence in the pressurised CO_2 gas flowing past the fuel rods; followed by heat transfer measurements on single fuel rods and ultimately on complete fuel assemblies subjected to full reactor conditions in large rigs and in actual reactors. This experimental work is complemented by the development of theoretical models and the computer methods required for their application.

The high power output of the sodium-cooled fast reactor introduces unique research problems. Heat transfer research on liquid sodium systems is needed to determine the stresses imposed on reactor components during rapid temperature changes, so as to avoid the prohibitive cost of full-scale tests in liquid sodium. Work in this area includes experimental investigations of the mixing behaviour of sodium at sudden expansions eg from pipes into a pool, with measurements of turbulence and establishment of the influence of buoyancy. A specially equipped laboratory has been provided to handle major experiments with liquid sodium for this work and for a wide variety of other such studies in the Laboratories' programme. The complementary theoretical work on the application of finite element methods to coupled fluid motion and heat transfer is in the forefront of international development.

Reactor physics research is centred on a series of experiments designed to study special features of the behaviour of neutrons, for example at the interfaces between reactor core components. One of the Laboratories' major facilities is a zero energy reactor in which a wide range of fuel and moderator arrangements can be constructed, each designed to highlight one specific problem and with the capability for appropriate measurements. Parallel theoretical research includes the development and testing of





models to predict the behaviour of neutrons in complex configurations, for example the SGHWR design with calandria and pressure tubes, and the development of generalised Monte Carlo methods to study nuclear particle transport and interactions in detail.

Other performance work related more directly to the operation of plant is aimed at predicting changes in the heat output of individual fuel rods during burn-up in the power generating reactors. This is necessary to provide advice on the most appropriate operating mode. The activities range from basic studies utilising the research reactor to major investigations using the Laboratories' irradiated fuel examination facilities to measure changes in the isotopic composition of fuel elements discharged from power reactors. An extension of the latter technique is being used to infer conditions within the reactor core. The alternative, the detailed direct measurement of the conditions in-core, presents formidable problems because of the hostile environment. In this area, the Laboratories are playing a major role in the development and use of specially instrumented AGR fuel, a task which calls for expert deployment of engineering and scientific skills.

Opposite page left
The BNL zero energy facility – a stage in the construction of a HITREX assembly showing the layers of graphite blocks of different types. Nuclear fuel will be lowered into appropriate holes after completion while other holes will accommodate control rods, experimental equipment and simulate cooling gas channels. This particular assembly will examine fuel management problems associated with the presence of different types of fuel in adjacent zones.

Opposite page right
A theoretical prediction of the neutron distribution in the Hitrex reactor produced by a computer program used in the analysis of the experiments. The plot shows the large variations and gradients of flux which have to be predicted to a high degree of accuracy; the two colours represent neutrons of different energies.

Below
A laser Doppler velocity meter under development for measuring velocity distributions in water models to be used for investigating flow behaviour at junctions between pipes and larger diameter vessels. This is an important problem in fast reactor design assessment.

Structural engineering

BNL is a major centre for structural engineering research on both nuclear and conventional power plant. The development of analytical methods, supported by experimental validation, has had a significant impact on the design, commissioning and successful operation of the Generating Board's plant. Work on this more conventional aspect of stress analysis and design is continuing through the application and development of BERSAFE, a comprehensive and flexible suite of finite element programs. Other computer programs allow evaluation of seismic inputs to buildings and other structures, as well as the response to crashing aircraft, rigid missiles and gas cloud explosions. Soil/structure interaction has been investigated as part of the earth tremor studies.

There is also major research emphasis in other fields. For example, the realisation that all engineering structures contain defects has led to a keen interest in the assessment of the strength of imperfect components and structures. Fracture mechanics is the topic of most significance in this area, and the development and validation of this subject to the point of ready application are important fields of study in the Laboratories.

At high temperatures, the deformation behaviour of materials becomes time dependent, and certain aspects of the design methods developed for lower temperatures are not applicable. Current research at BNL is concerned with the development of analytical methods and material behaviour laws which together will provide the basis for more appropriate design procedures. Of particular concern is the problem of the fatigue loading of fast reactor structural components arising from the severe thermal stressing referred to previously.

In gas-cooled reactors, noise from the circulators and the flow of gas around the circuit give rise to structural vibrations which may produce fatigue or wear problems. The aim of the research programme in this field is to define noise levels and predict the response of structures to noise and flow. The work is a combination of analytical and experimental studies both in the laboratory and at the nuclear stations. Similar studies are being carried out in connection with liquid-cooled reactor systems where the problem is somewhat more complex and model studies have greater importance.

For vibration studies BNL is equipped with large anechoic and reverberation rooms and reactor model test facilities. For more general structural mechanics work, two underground pits are each capable of accommodating vessels up to 7 metres in length which can be subjected to steady or cyclic pressure loading at high temperatures, with a wide range of measuring and data handling methods to hand. The facility is also used for small-scale tests such as the examination of fatigue crack propagation in pressure vessels. For studies on larger vessels and for pressure tests to destruction, an off-site facility is available near BNL.

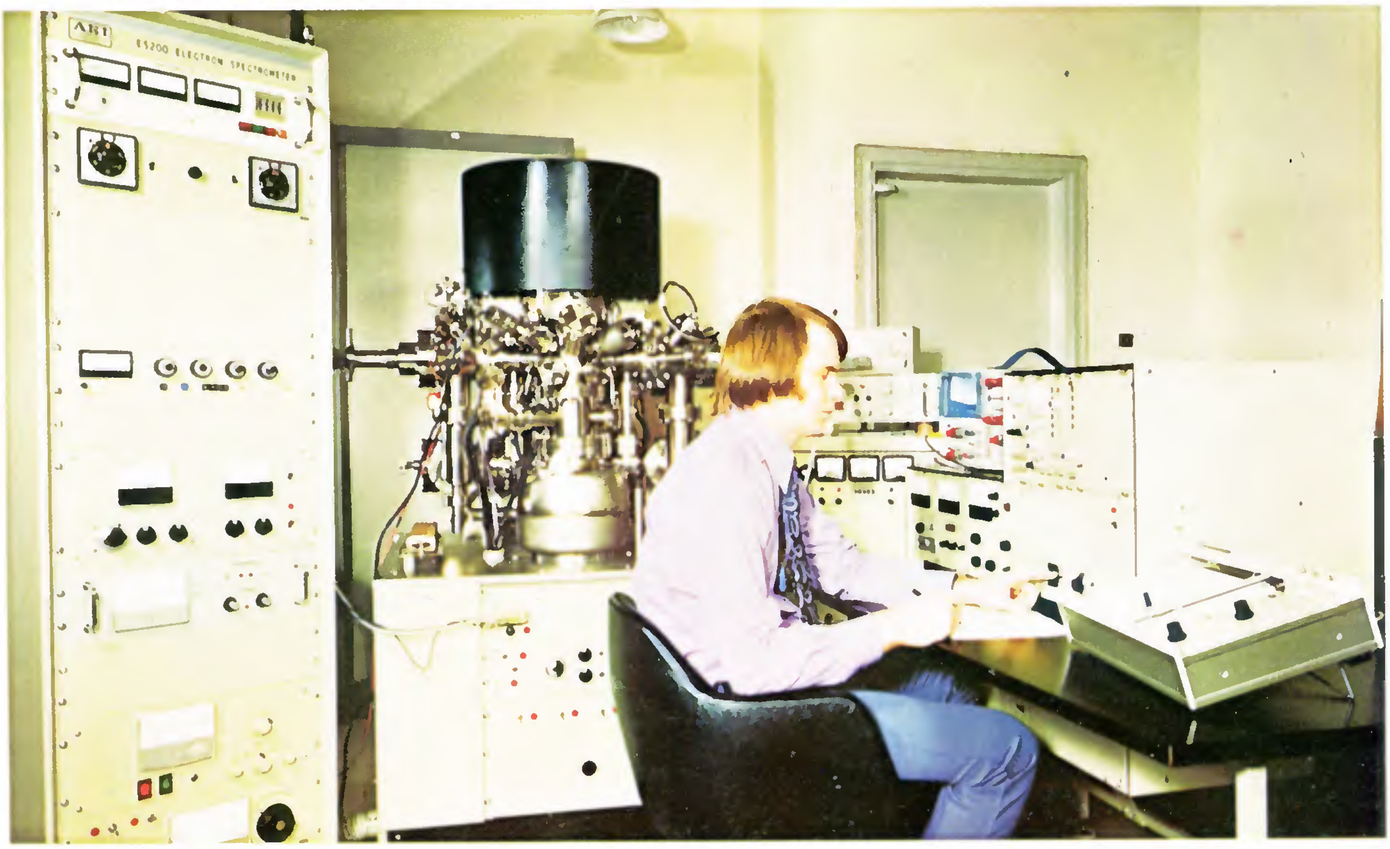
Structural materials

The core of a nuclear reactor presents an extremely hostile environment in which structural materials are required to operate with a high degree of reliability for long periods at high temperatures. Nuclear radiation produces a marked change in the chemical environment in the reactor core, frequently enhancing the rate of corrosion of materials by the circulating coolant. In addition, metallurgical changes result from the neutron irradiation which displaces atoms from their regular sites in the crystal lattice. Fundamental research into these and many other areas is carried out at the Laboratories using a variety of techniques to investigate problems at the ill-defined boundaries between chemistry, physics and metallurgy.

Such techniques provide new insight into a wide range of problems, for example, the chemical nature of the surface of uranium in the early stages of oxidation,

Left
An X-ray energy analyser (left) fitted to a scanning electron microscope. With this equipment, it is possible to determine the chemical composition of very small particles and areas featuring in the microscope image.

Below
This spectrometer is one of several electron beam instruments used for the study of the absorption of gases onto metal surfaces and for the examination and analysis of corrosion products. Chemical reactions at surfaces can be studied as they occur.



the chemical structure of oxide layers initially formed on stainless steels exposed to liquid sodium, and the susceptibility of chromium and iron oxides to surface hydrolysis.

Of immediate and direct application is the work on the corrosion of graphite. The massive graphite moderator structures of the Magnox and advanced gas-cooled reactors are in direct contact with the high pressure carbon dioxide coolant gas. Under irradiation, a reaction occurs between the graphite and the gas, causing corrosion of the moderator. A high intensity gamma-ray source is available at the Laboratories to simulate the reactor environment; at present this is in continuous use for study of the chemical reactions involved. The aim of this work is to reduce the oxidising capability of the carbon dioxide by special additives.

In water reactors, the coolant is subjected to a strong ionising radiation field which decomposes the water and induces chemical reactions. Under some conditions, reactions can take place which may be deleterious to the overall system performance. Research is being carried out on the radiolysis of appropriate aqueous solutions using a pulse radiolysis facility equipped with a source capable of producing several thousand amperes of high energy electrons in controlled pulses of very short duration. This equipment is capable of providing information about reactions occurring on time-scales down to a few nanoseconds.

Outside the reactor core, many key components also depend on the long-term performance of the materials used in construction. It is therefore essential to underwrite the testing of materials and components with basic work which gives confidence in the long-term extrapolation of data. In this field, the liquid metal cooled fast breeder reactor presents new problems – for example, liquid sodium removes the normal protective oxide film from structural alloys, facilitating atom transport between metal and coolant. Materials testing in liquid sodium presents a number of difficulties, and special techniques have been developed at the Laboratories for controlled environment work on corrosion and mechanical properties. Other special techniques available for structural materials studies include:

Transmission electron microscopy (machines include a 1MeV model);
Scanning electron microscopy;
Microprobe analysis;
Auger spectroscopy;
ESCA spectroscopy.

Below
A pulse radiolysis facility used for studying the radiation chemistry of gases and liquids. Each 5-nano second pulse of 0.8 MeV electrons from the field emission source delivers 10^{19} eV of energy to each side of the specimen: the subsequent reactions are followed by kinetic spectroscopy.

Tribology and mechanisms

The aim of the BNL work in this area is to investigate the basic properties of surfaces and interfaces, their influence on the behaviour of reactor components, and means of incorporating basic data into design and assessment procedures.

Interfacial properties may affect the performance of reactor components in a number of ways. High friction or adhesion forces can cause 'seizure' or lead to over-stressing of structural components; wear can be a life limiting factor. In addition, stringent demands are made on seals in the coolant circuit and fuel transport vessels by the need to contain radioactive species and expensive or chemically aggressive coolants.

Such problems are particularly severe in nuclear technology for a number of reasons. Not only is there the need for extremely reliable operation without attention for long periods, but difficulties are further increased by the hostile environment. High temperatures and radiation may preclude the use of lubricants and impose restrictions on the materials that can be employed, while the atmosphere may be chemically aggressive and the components subjected to extreme noise levels.

The Laboratories' basic research in this field covers the topics of surface topography, adhesion and surface deformation. The principal method employed in the surface topography studies is profilometer measurement. Computer analysis of the output facilitates the characterisation of the roughness of manufactured, worn or corroded surfaces; in conjunction with surface deformation studies, these techniques make it possible to understand the way contacting surfaces behave. The adhesion studies are conducted on single crystals in ultra high vacuum, using spectroscopic methods to establish the surface conditions and crystallographic orientation.

Work of more immediate application involves studies of friction, wear and adhesion under appropriate conditions, for example in carbon dioxide, helium and liquid sodium. Particular expertise has been developed in the interaction of wear and corrosion, and in seal technology which involves the properties of elastomers and the hydrodynamics of fluid flow in small passages and cracks.

The greatest benefit can be derived from the work as a whole if the basic and small-scale studies can be employed to predict the performance and reliability of machines. To this end, the applicability of statistics to tribology phenomena is being examined and techniques for reliability prediction from such data are being developed together with computer methods of mechanism analysis. The use of this approach to modelling machine performance, providing a design aid and as a complement to full-scale experiments on plant items, is an exciting new development.

Reactor safety

To ensure that nuclear plant is designed and operated to fail-safe a wide supporting research programme is required to provide a sound understanding of the behaviour of reactors under a range of abnormal conditions. The severity of these conditions depends on the reactor design.

In the steam generating heavy water reactor the most serious event envisaged is rupture of the main pressure circuit, leading to loss of cooling water from the core and overheating of the fuel. The normal reactor power output is in practice limited by the fuel temperatures which would be reached in such an event, so there are economic as well as safety reasons for research to ensure that the details are well understood. To illustrate the nature of this work, the techniques for calculating the coolant flows in the core during the loss of coolant fault are being tested by experiments in which high pressure water in a simple vessel is suddenly vented to the atmosphere. Since the flow during the fault provides some fuel cooling, it is important to judge the efficacy of this; the problem is being studied in detail on electrically heated single fuel rods and on a reactor-scale multi-rod element. From the detailed description thus obtained of heat extraction by vigorously boiling water, calculation methods are being developed to predict the rate of cooling of overheated fuel rods. Parallel studies are being made of the behaviour under these conditions of the zirconium alloy tubes which protect the fuel, so as to ensure that the fuel rod as a whole is not damaged unacceptably.

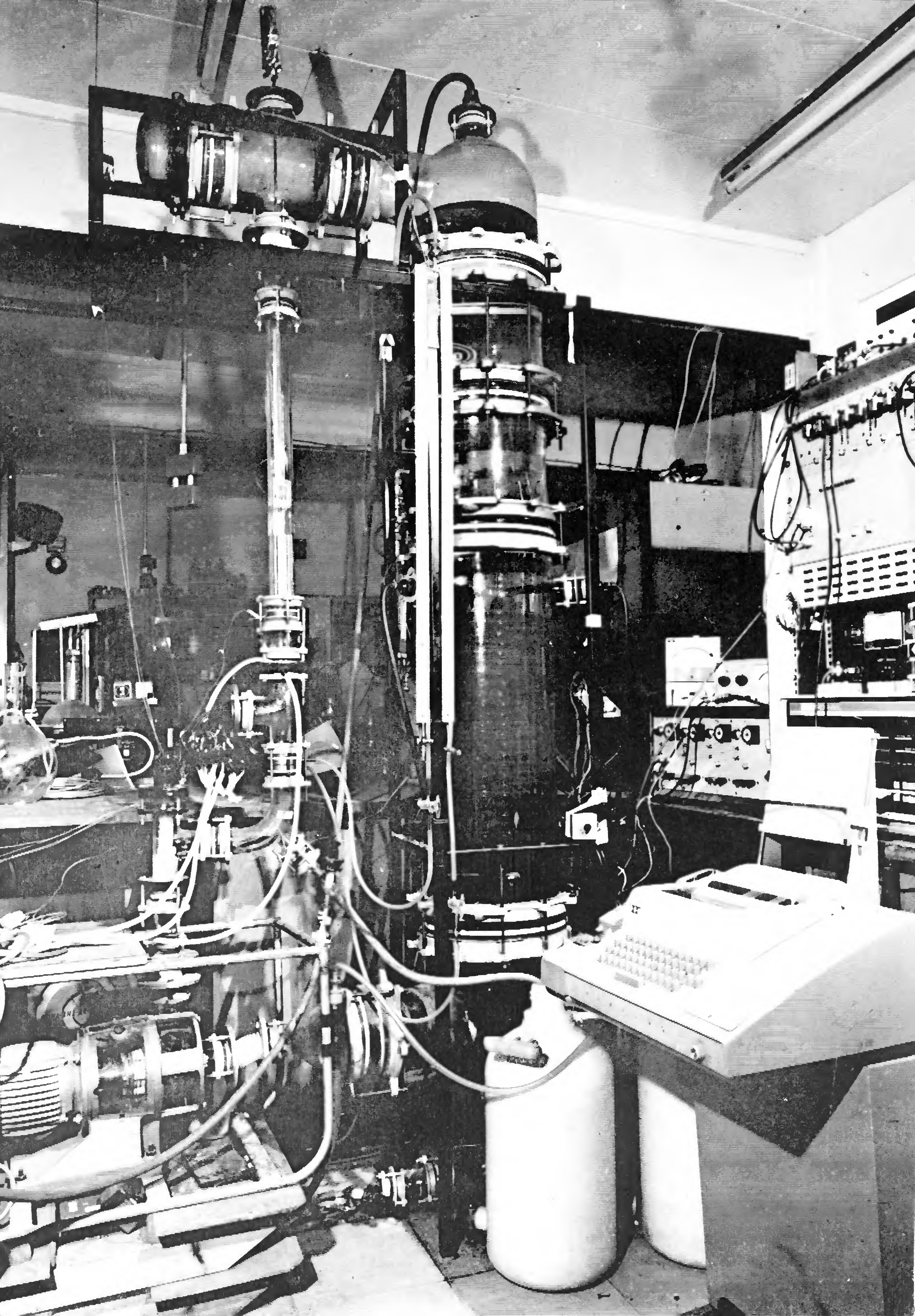
The sodium-cooled fast reactor is likely to become the mainstay of the nuclear programme in the 1990s. The very high power density of the reactor core poses special safety problems, for example possible accidental channel blockages might lead to boiling of the liquid sodium coolant and to damage by over-heating. To study this, a model for the behaviour of vapour bubbles is being developed to be tested in simulation experiments using a multi pin assembly in a large boiling water facility. A further potential stage in such a fault sequence could be fuel melting, with the possibility of a violent thermal interaction between the fuel and sodium coolant. Experimental studies of such explosions are leading to an under-standing of the conditions required. and the nature of the physical processes involved, thus providing a sound basis for assessing the practical likelihood of such events and their consequences.

Methods to detect faults of this kind at an early stage are being developed. For example, in a sodium-cooled reactor the rapid temperature fluctuations generated by turbulence behind a blockage persist to the channel outlet, and this signal can be monitored by a novel fast response electro-magnetic sensor. This and other possible reactor instruments will be tested in the laboratory in a large-scale sodium loop which can provide appropriate flows, temperatures and pressures.

Above
An experiment using electrically heated rods to study the cooling of fuel pins by vigorously boiling water. The experimental results are used to test mathematical descriptions of the cooling processes.

Right
Water loops are used to model the effects of a partial blockage in the core channels of a sodium cooled fast reactor. Cooling water is pumped past electrically heated rods simulating fuel pins and a computerised data collection system reads an array of thermo-couples located around the rods. The temperature distribution thus obtained is compared with theoretical predictions.

This small loop accommodates 30 pins in the 2" diameter working section and dissipates 50 kW. A larger 6" rig takes 150 heated pins which transfer up to 250 kW into the water flowing past at 10 m/sec.



Circuit studies

The transport of radioactive material around the main coolant circuit of nuclear plant is an important topic of study. There are serious issues connected both with the ease of plant maintenance and the external consequences of leaks in the circuit which make it necessary to understand the processes determining the burden of activity in the circulating gas or liquid. Part of the Laboratories' work is directed to the prediction of such activity and to the development of remedial solutions for situations where unacceptably high levels occur.

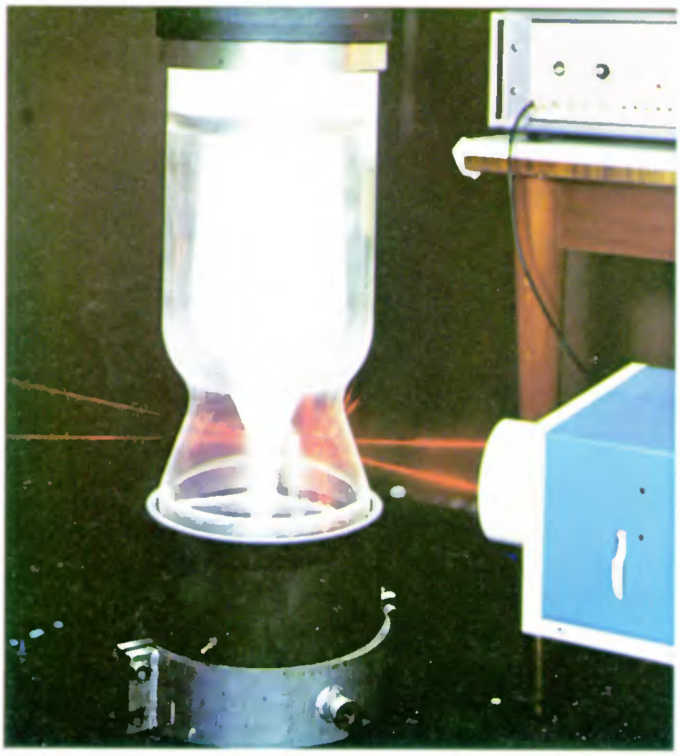
The research covers a number of topics involving theoretical studies and experimental investigations both in the laboratory and on operating plant. For example, a study of the complex manner in which molecules and particles attach themselves to surfaces, and how they may subsequently be detached, is fundamental in the determination of how much material is removed from the circulating fluid by components in the circuit. The adhesion of material to surfaces can be studied experimentally in a number of ways. If the species concerned is molecular, then adsorption and desorption as a function of surface material and carrier gas can be followed readily using the radioactivity of the species as a measure of the material concentration. For particulate material, the methods used are different; for example, an ultra centrifuge is used to measure the forces between surfaces and particles, so as to complement theoretical studies of adhesion.

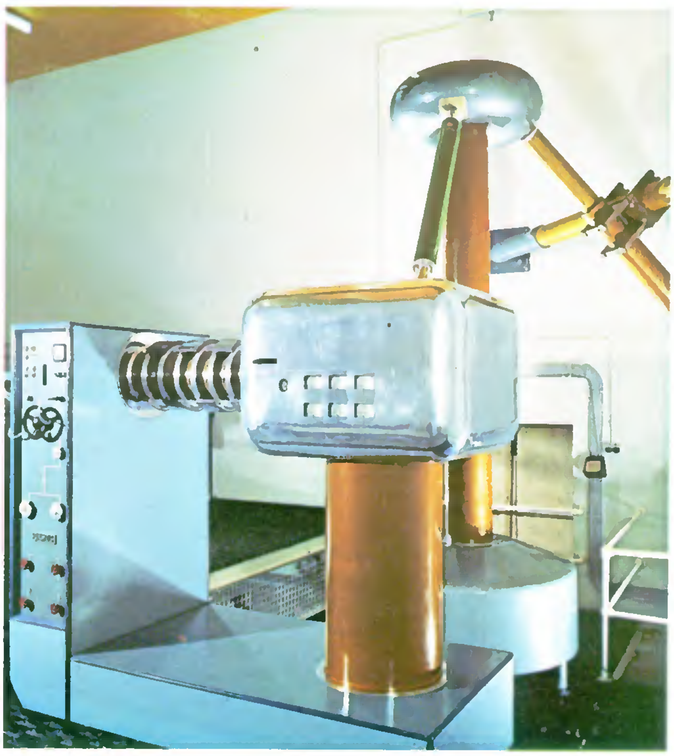
Material transport studies on operating plant have required the development of methods for 'in-flight' measurement and sampling of the particles in the gas circuit. The nature and size of these particles govern their fate in the plant, and purpose-designed sampling probes have readily allowed particle sizing and identification using their self-radioactivity. These techniques enable the consequences of a wide range of events, from fuel failures to changes in coolant flow rates, to be assessed accurately in terms of circuit activity burden.

As an example of a remedial measure, an inertial filter was required to remove particles from the gas circuit of the advanced gas-cooled reactor. The constraints were severe, since the filter had to be designed at a late stage as part of the existing fuel assembly and needed to be installed in such a way that no output penalty was incurred. The design and development work was undertaken at the Laboratories and the extremely successful final design has been incorporated into the operating plant.

Below left
A laser Doppler velocity meter arranged to measure particle and fluid motions within a transparent plastic replica during the development of the central inertial collector. This efficient but compact form of cyclone was designed at BNL to remove particles from the gas circuit of the advanced gas cooled reactor.

Below right
The beams of protons or deuterons from this 400 keV linear accelerator are used to bombard target plates in order to produce neutrons of known energies with which to calibrate dosemeters. Other machines and a range of isotope sources are available so that instruments can be calibrated for response to all types of radiation.





Health physics

In the operation of nuclear plant, constant attention to radiological protection is necessary to safeguard both the public at large and staff operating the plant. The Laboratories have a major influence in a number of such areas.

For example, during the handling of spent fuel and reactor maintenance, it is important to estimate and control radiation doses to the skin and lens of the eye. Working in collaboration with the medical staff of London hospitals, BNL carried out studies which provided significant new radiobiological information. This has been incorporated in the recommendations of national and international standards committees and is now widely used in the establishment of safe exposure levels for operators and members of the public.

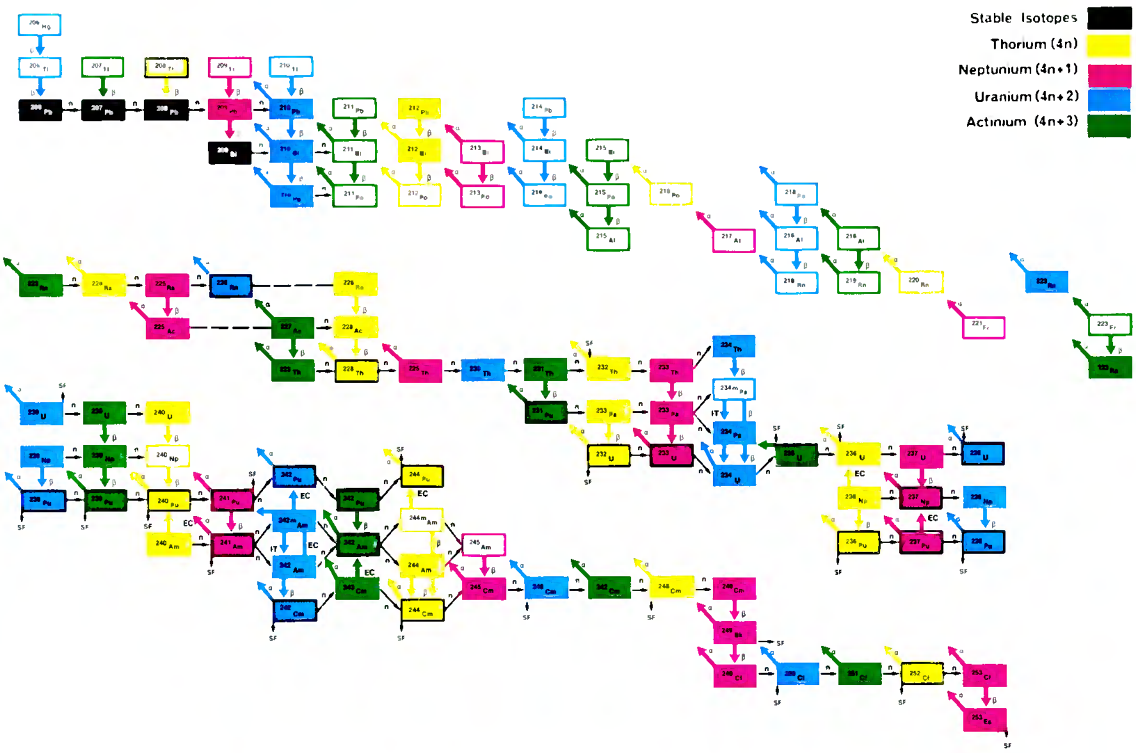
Computer techniques have been used extensively to study the wide range of radionuclides generated within nuclear fuels and the variety of their potential pathways to man. Studies have included the development of mathematical models to predict the isotopic inventory of reactor fuels and the radiation levels resulting from operational and accidental discharges of radioactivity. These models have been used to specify improved emergency monitoring techniques, including those at the Board's Magnox and AGR stations.

District survey work is carried out using equipment installed in a mobile laboratory. Modern gamma-ray spectrometry and data recording equipment are used for environmental measurements to establish base-line data before a new power station begins operation, so that any changes due to nuclear effluent can be properly monitored. Spectrometry has proved extremely valuable in this application, for example in the study of changes in the amount of natural radio-activity from potassium-40 because of variations in seaweed growth.

BNL also plays a central role in the measurement of radiation within the industry, operating personal dosimetry and instrument calibration services. The latter service has established an international reputation through its participation in joint work with radiological calibration organisations in Europe and the USA. The calibration facility is housed inside a large concrete shield and the three exposure rooms are equipped with television monitors and remotely controlled trolleys to position the instruments relative to the appropriate source of beta-radiation, gamma-radiation, or neutrons with energies up to 14MeV. Over 1000 instruments a year are dealt with in this facility, which is unique in the UK.

Below
Hyacinth

The complex build-up and decay chains for heavy isotopes shown in this figure are only a small part of the information which must be included in any computer program used to calculate the precise composition of nuclear fuel as it changes during the operation of a reactor. This information is necessary in order to calculate, for example, the reactivity of the fuel or the levels of associated radioactivity.



Reactor measurements and instrumentation

Spanning the range of the Laboratories' interests is the need to make measurements on reactor plant, both to provide scientific data and to improve the operators' understanding of conditions within the plant.

As part of the work on instrument development, BNL has built miniature detectors cooled by Joule-Kelvin devices and CdTe detectors with miniaturised pre-amplifiers. These have been used to measure the distribution of nuclides within the boilers of nuclear plant, so that the deposition of radioactive material in the gas circuit can be studied. Another successful development, an automatically recording instrument based on a NaI(Tl) spectrometer, is being used to check the enrichment of fresh fuel as it is lowered into the reactor.

The sodium-cooled fast reactor has certain features which demand imaginative efforts on the part of the instrumentation specialists. The purity of the liquid sodium in the cooling circuits has to be controlled because the level of carbon present determines whether the composition of the structural steels changes as a result of exposure to the sodium; furthermore, the level of oxygen dissolved in the sodium controls its corrosiveness to these materials. The Laboratories are developing a series of electrochemical instruments for compositional measurement, so that effective parity control can be achieved.

The corrosion of mild steel components in Magnox reactors has produced some unique instrumentation requirements. For example, BNL staff have developed equipment for determining the amplitude and phase spectra of ultrasonic pulses reflected from steel samples; they have shown that this technique can be used to determine the oxide thickness both on the back face of a component and on the surfaces between mating components.

One of the complications in reactor instrumentation is, of course, the difficulty of access; the requirement to attach such measuring instruments accurately in place at distances as great as 15 metres beneath the reactor operating face illustrates the considerable ingenuity necessary for success in this field.

Top left
Part of the main boiler house
Centre left
The photographic studio
Bottom
Part of the machine shop of Engineering Services Department

Support services

The proper functioning of a large laboratory depends critically on effective support effort. At BNL, the General Administrative Services include the personnel, house services, restaurant, accounting, supply and resource planning functions; specialised facilities are supplied by the Information, Computing, and Health and Safety Services.

The Information Section includes a Library with a stock of some 5,000 books and over 70,000 reports, the majority in microform; in addition it provides an information service to all staff and is responsible for issuing the 300 or more reports produced each year at BNL.

The Health and Safety Services Section is concerned with the radiation and contamination control procedures which protect the health of the staff; it also ensures that nuclear operations at BNL comply with statutory obligations. The Section is also responsible for conventional safety throughout the establishment.

The Laboratories have a major computing capability afforded by two GEC 4080 128k byte multiprocessor terminals which give BNL staff access to the very powerful digital machines at the Board's Computing Centre in London; these terminals provide for local processing and graphical output. Staff also use the large analogue and hybrid computers at the Centre. Twelve smaller machines in the 4k to 32k byte range are also installed at the Laboratories, most of them programmed for control and data processing functions on experimental rigs.

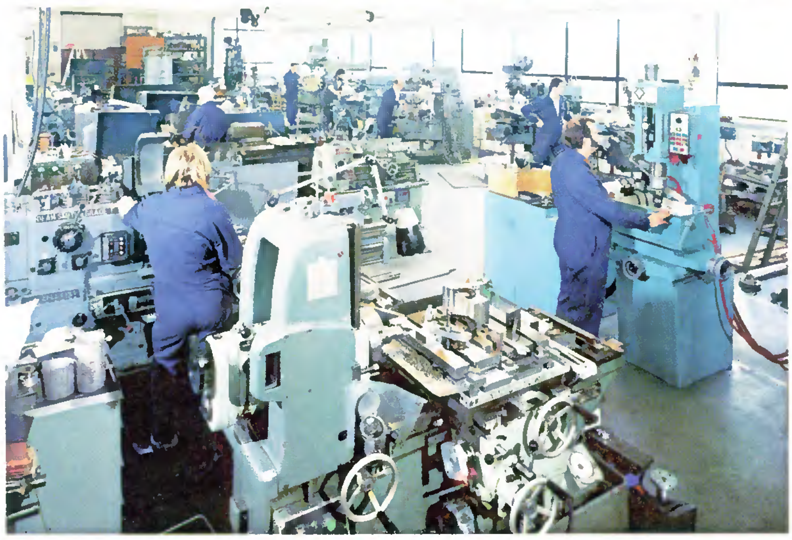
Engineering Services Department also have a vital part to play in providing direct support for research staff. Design and construction of equipment, provision of specialist advice and the supervision of off-site manufacturing of components are all demanded of this service. The Department is also responsible for ensuring the effective performance of a multitude of laboratory plant and services. To cope with this considerable task, BNL has large design offices and workshops manned by engineers, draughtsmen and craftsmen, in total over 100 staff.

The Laboratories thus afford major specialist support in those areas which are generally outside the researcher's immediate experience, leaving him to pursue his prime scientific and technical role.

Top right
Library issuing counter
Above centre right
Main design office of Engineering Services Department
Centre right
This Mural in the Staff Restaurant depicting River Severn Fisheries was designed by a member of the research staff





Conclusion

The following quotations set the Laboratories work in context, without the need for further comment.

"We expect therefore that the Boards should be able to undertake a greater research and development effort than was possible before nationalisation. What we wish to see is a widespread appreciation of the contribution that science can make. Science is not now a thing apart but is initimately associated with all activities and aspects of industry. The electricity supply industry, by its very nature, should be in the forefront of the major industries organising and applying research and development on an extensive scale."

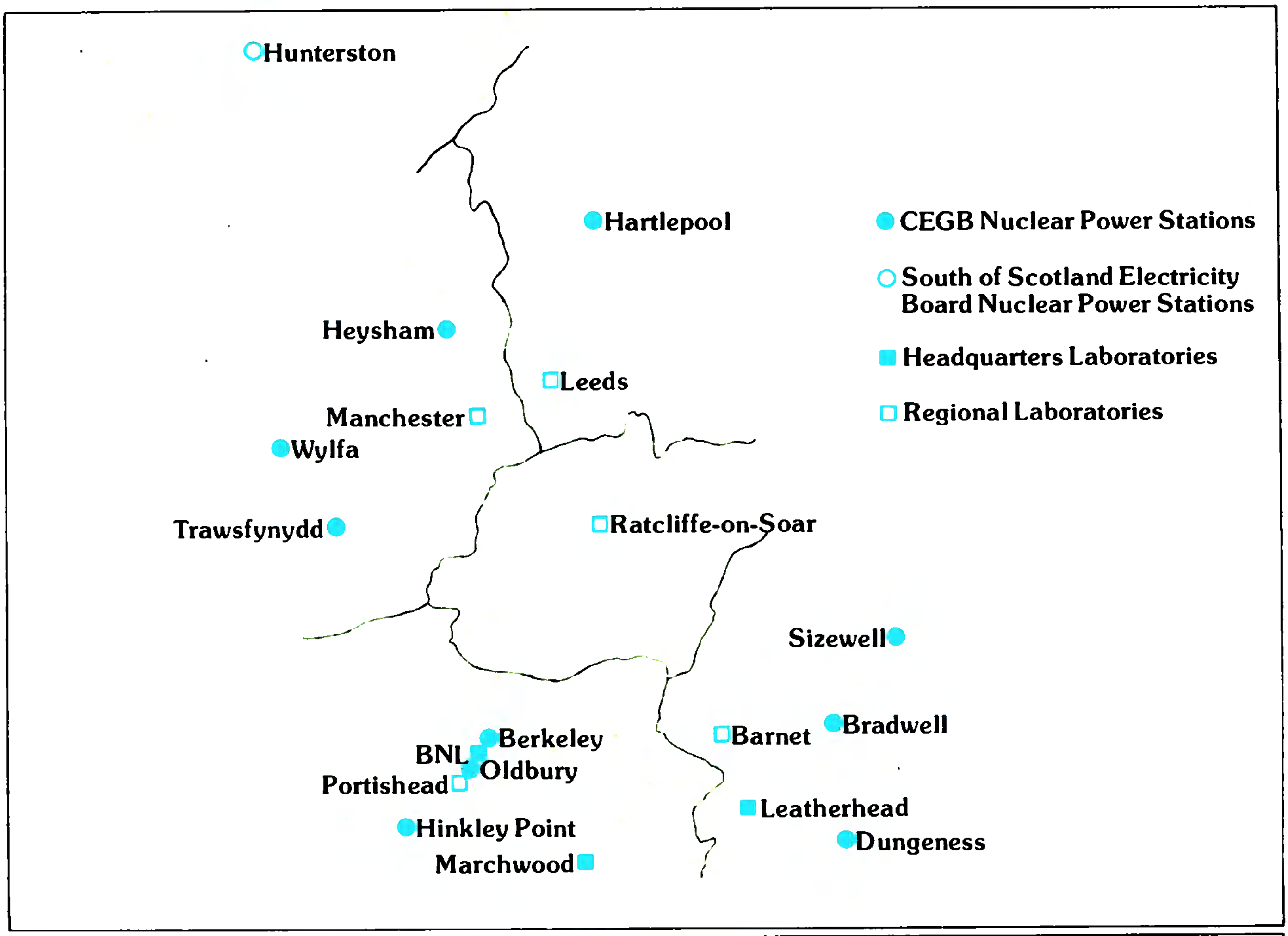
Report of the Herbert Committee of Inquiry into the Electricity Supply Industry Cmnd. 9672. 1956.

"This advice (of the Herbert Committee) was accepted. The CEGB now carries out scientific and technical research on a large scale. A recent investigation undertaken by the industry showed that the savings due to work carried out in its laboratories far exceeded the total costs of the research departments."

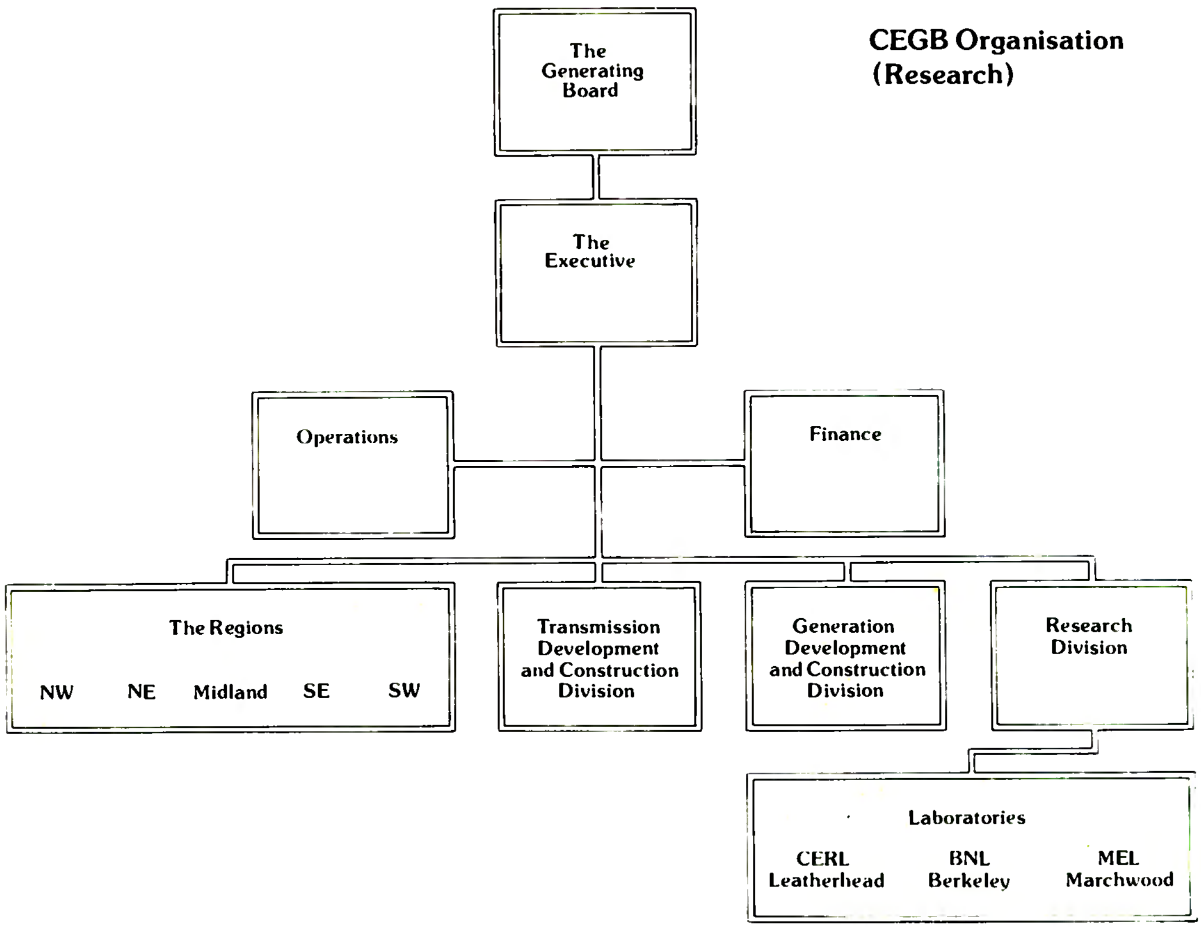
Report of the Plowden Committee of Inquiry into the Structure of the Electricity Supply Industry in England and Wales. Cmnd. 6388. 1976

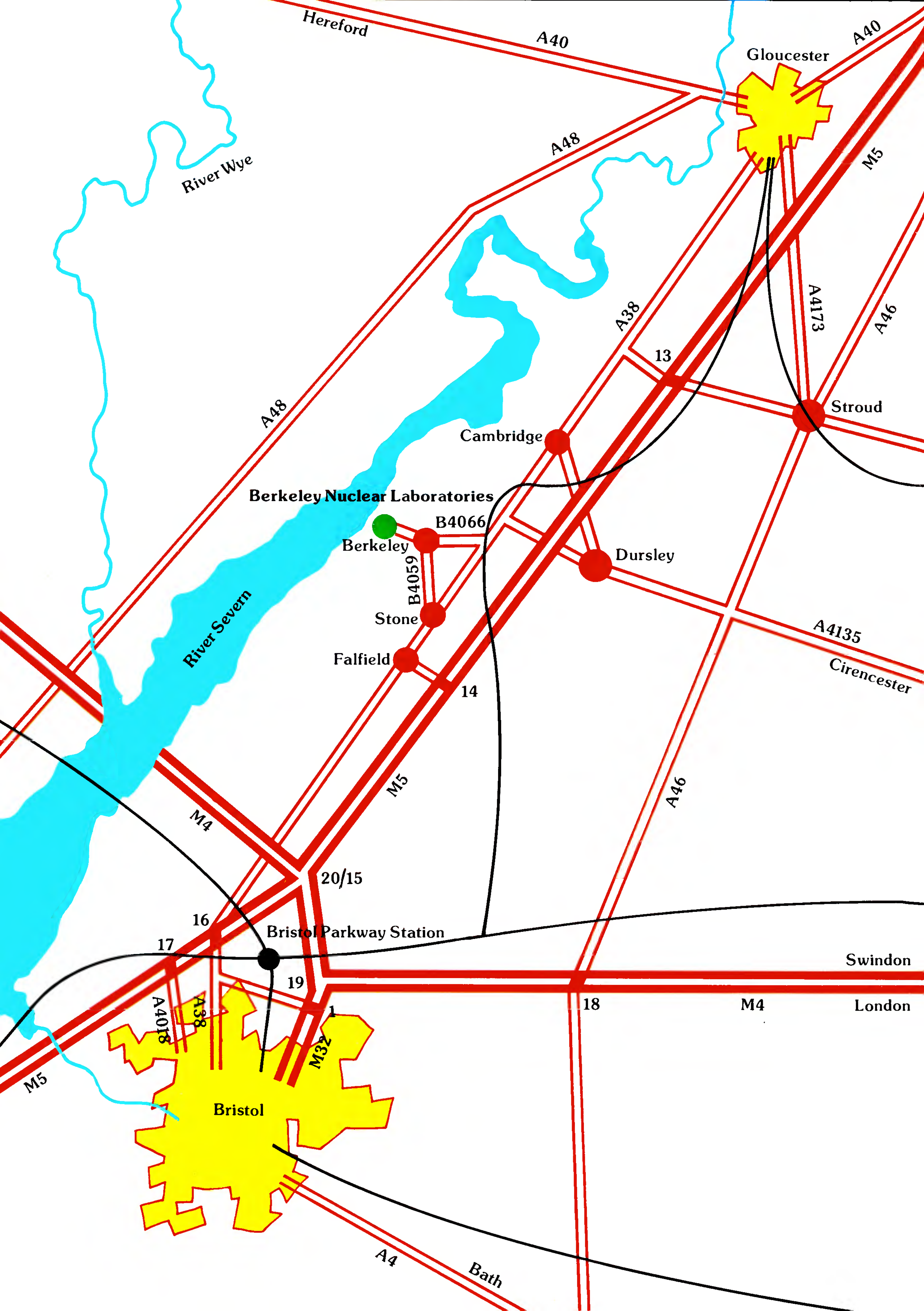
"We have considered whether this country should seek to abandon nuclear fission altogether; we do not think such a strategy would be wise or justified."

Sixth Report of the Flowers Commission on Environmental Pollution. Nuclear Power and the Environment. Cmnd. 6618. 1976.



CEGB Organisation (Research)





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Published by Central Electricity Generating Board
Sudbury House, 15 Newgate Street, London EC1A 7AU

Designed by Guyatt/Jenkins Ltd., London

Printed by Southern Press (Printers) Ltd., Purley, Surrey

G811 April 1977