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THE UNITED KINGDOM ATOMIC ENERGY AUTHORITY

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U.K.A.E.A. PRESS RELEASES

Ninth Dragon Report

The following was issued on behalf of the Board of Management of the O.E.C.D. High Temperature Reactor Project DRAGON, *A simultaneous release was made by the Organisation for Economic Co-operation and Development in Paris.*

A conceptual design study for a 630 megawatt electrical (1500 MW thermal) DRAGON-type nuclear power station with a substantially homogeneous reactor core of low-enriched uranium suggests that building costs around $112 per kilowatt installed should be attainable, with generating costs of just over 4 mills per kilowatt hour (about $\frac{1}{3}$ being fuel cycle costs). This is one of the conclusions of assessment studies reported in the Ninth Annual Report of the O.E.C.D. DRAGON High Temperature Reactor Project which is published today by the European Nuclear Energy Agency.* The Report covers the year 1st April, 1967 to 31st March, 1968 and opens with the statement that during this period "the DRAGON Project has fortified the claims of the high temperature reactor to be an alternative economic source of nuclear power for the commercial production of electricity".

During the year the work of the Project was concentrated on the low-enriched fuel cycle (U-238-plutonium conversion) which now holds the main interest for immediate commercial applications. The Report explains that the previous concept of a "heterogeneous" core layout, with large diameter fuel channels containing clusters of fuelled tubes in a permanent block structure of moderator graphite, has now given way to a more homogeneous design with the core composed of removable graphite blocks, each pierced with a number of coolant channels and containing individual fuelled tubes. Each fuel tube would contain fission-product-retaining coated particles, with porous kernels to accommodate fuel swelling and fission gas release.

This design, coupled with downwards

* The DRAGON Project was set up in April 1959 under an agreement concluded between the United Kingdom, the six Euratom countries (Belgium, France, Germany, Italy, Luxembourg and the Netherlands), Austria, Denmark, Norway, Sweden and Switzerland.

coolant flow through the core—to provide a relatively cool environment at the top for on-load operation of refuelling equipment—should enable the required average power density of 5.8 MWt/cubic metre of core (to give the required 1500MWt output) to be obtained with a maximum fuel temperature not exceeding 1250°C.

The DRAGON Ninth Report covers in considerable detail this latest evolution of the high temperature gas-cooled reactor concept, which would require feed fuel enriched to some 5%. The Report also mentions that the new core design may be adaptable for a highly-enriched uranium/thorium fuel cycle, as originally proposed for DRAGON. If this proves to be the case, the Report states, it will make a truly flexible dual-purpose reactor, capable of operation on either fuel cycle as preferred.

A major section of the Ninth Report is devoted to research and development on the coated fuel particles necessary for the low-enriched fuel cycle. The requirement for higher loadings of heavy metal has led directly to kernels about twice the diameter (700 microns) of those developed for the high-enriched cycle (thorium-U-233 conversion) although coating thicknesses of about 150 microns have been maintained. Long-term heat treatment and irradiation experiments on the larger diameter particles have so far proved highly encouraging.

Development work on "improved" graphite for fuel elements and moderator structures in high temperature power reactors is also reported, including detailed studies of physical, mechanical and chemical properties and of irradiation behaviour. This work has been carried out in particular with the help of Sud-Aviation, Paris (examination of thermal behaviour and mechanical strength at temperatures up to 2000°C), and of Reactor Centrum Nederland, Petten (irradiation tests), as well as in the DRAGON Project itself at Winfrith. In the work at Petten the DRAGON Project has collaborated with Euratom and Kernforschungsanlage Jülich, in a joint programme to study the effects of fast neutrons on graphites and pyrocarbons.

During the year under review the Reactor Experiment at Winfrith, which had begun operation on its second fuel charge in January, 1967, continued until March, 1968 with this charge, which thus achieved an integrated burn-up of 4486 MWD. Reactor availability during this time, in terms of operation at power, was 59%. Analysis of the remaining 41% outage total shows that 33% was due to remedial work on leaking primary circuit tube bundles, 7% due to scheduled fuel changes, and 1% due to trips arising from plant faults (rectifier transformer, mains power supply, variable frequency generating sets, by-pass valves, etc.).

In the 150-day period between mid-October, 1967 and mid-March, 1968 the Reactor Experiment operated on five primary circuit loops uprated in power from 16.6 to 18.0 MWt and, discounting a 5-day fuel change (re-using old first-charge elements to extend running time) reactor availability exceeded 99%.

Besides these technical details, the DRAGON Report contains a section on Administration which deals with budgetary matters, staffing, collaboration agreements, prolongation of the Project to 31st December, 1968 and negotiations for its extension beyond that date. Prolongation to 31st December, 1968 was made possible by the U.K.A.E.A. offering to bear Euratom's financial contribution for this period pending the outcome of Euratom's consideration whether to participate financially in the extension. The offer, accepted by the Board of Management, was conditional on all participants reaching a decision by 31st July, 1968, regarding a further extension, and on Euratom waiving its rights to recover its proportionate share of the written-down value of fixed assets on the reactor site should the Project end on 31st December, 1968.

Although not covered by the Report, it may be noted that agreement in principle was in fact reached by 31st July, 1968, on a formal extension until 31st March, 1970, the total budget for the 11-year life of the Project being increased to £31 million.

Expenditure during 1966/67 totalled £1,939,602 compared with the approved budget of £2,314,000. Revised 1967-68 budgets of £2,100,000 for commitments and £2,105,000 for expenditure were approved during the year, as well as draft 1968/69 budgets of £1,980,000 and £1,987,000 for commitments and expenditure respectively.

Collaboration under the separate agreements with the United States Atomic Energy Commission and the Thorium High Temperature Reactor Association (succeeded on 1st January, 1968, by the Kernforschungsanlage Jülich, GmbH, a former

partner of the Association) included the exchange of visits and information and the participation in cooperative fuel irradiation studies using the DRAGON Reactor Experiment irradiation facilities. Collaboration under the Agreement with Brown Boveri et Cie, Baden (Switzerland) continued during the year and included a number of visits and the provision of information by the Project for B.B.C.'s high-temperature gas-cooled graphite-moderated nuclear power station study.

The total strength of the Project's staff at the end of the year was 90, one more than at the end of the 1966/67 year. There were no changes in senior staff during the period.

Copies of the full report (in English) are available on application to the Public Relations Office of the O.E.C.D. European Nuclear Energy Agency, 38 boulevard Suchet, Paris 16e, France; the Public Relations Branch of the U.K.A.E.A., 11 Charles II Street, London, S.W.1, or the Chief Executive, O.E.C.D. High Temperature Reactor Project, Dragon Project Office, A.E.E., Winfrith, Dorchester, Dorset, England.

4th November, 1968

Uranium reconnaissance

This Press release was issued jointly by the Institute of Geological Sciences and the United Kingdom Atomic Energy Authority.

In March this year the Minister of Technology, The Rt. Hon. Anthony Wedgwood Benn, M.P., announced that the United Kingdom Atomic Energy Authority would undertake a reconnaissance programme for uranium in selected areas of the U.K. through the agency of the Institute of Geological Sciences. This work began in the early summer in two of the areas: North of Scotland and Central England.

The reconnaissance in the two districts has differed somewhat because of the geological and topographical variations between the two areas.

North of Scotland

A systematic survey of the greater part of the area has been carried out; this has involved:

(a) survey of all roads and tracks by car-mounted scintillation counter;

(b) survey on foot of the streams along the eastern seaboard to a distance of approximately 15 miles inland;

(c) collection of some 1500 samples of water from streams in the main catchment areas;

(d) collection of stream sediments, panned concentrates and soil samples over the eastern coastal region as well as in northern Sutherland;

(e) survey of the cliffs along the coast using a scintillation counter mounted on the superstructure of a fishing vessel.

Much analytical work remains to be done, which will be carried out during the winter months, before the results of the investigations in the field can begin to be assessed. However, it can be said that the car-mounted scintillation survey resulted in the discovery of two anomalous areas of radioactivity. The on-foot surveys revealed several other radiometric anomalies* at least two of which merit more detailed assessment.

The next phase—in addition to the analysis of the samples collected—is to undertake a surface examination of the anomalous areas. This has just started and will be continued next season. The work involved is mainly the preparation of detailed geological maps; the preparation of radiometric maps showing the distribution of radioactivity; the analysis of the geological structures of the areas; and pitting and trenching through peat and soil cover. In addition to giving information at shallow depth, the pits and trenches will be used to provide samples of unaltered material for analysis and study the nature of the uranium occurrence. Since uranium is readily leached from rocks at or near the surface, shallow diamond drill holes may have to be put down to ensure that the uranium values at surface are not markedly dissimilar from those at depth.

Midlands of England

The major difficulty in this region is that much of the interesting ground is covered by a layer of barren sandstones and mudstones and this means that normal methods of surveying are inadequate. However, water samples both from streams and from boreholes have been taken. Supplementary work has been done by covering part of this area by car-borne scintillation equip-

* A radiometric anomaly is an area of radioactivity higher than normal revealed by a geiger or scintillation counter.

ment which has revealed minor anomalies.

Future work in this district will thus mean the employment of new techniques, some in course of development, aimed at giving information on the whereabouts of any uranium occurrence in depth. This will involve the monitoring of the ground air in shallow holes by an instrument which measures radon—a gaseous decay product of uranium and therefore a uranium indicator. Other techniques of locating uranium in depth may well be the detection of other elements commonly associated geologically with uranium, but occurring in greater abundance. The presence of such elements at the surface may lead to a decision to put down drill holes, because the most favourable uranium environment in this district may well be tens or hundreds of feet below surface.

5th November, 1968

British team for conference in U.S.A.

(This press release was issued jointly by the British Nuclear Forum and the United Kingdom Atomic Energy Authority.)

A strong team from the nuclear industry and the United Kingdom Atomic Energy Authority will represent Britain at the International Conference on the Constructive Uses of Atomic Energy which is to be held in Washington from 10th to 15th November. U.K. participation has been planned jointly by the Authority and the British Nuclear Forum.

The Washington conference comprises three concurrent events: the Winter Meeting of the American Nuclear Society; the annual conference of the U.S. Atomic Industrial Forum; and an exhibition, "Atomfair '68 International".

Dr. J. M. Hill, Chairman of the Authority, will be guest speaker at an American Nuclear Society luncheon on 12th November.

British speakers will take part in the following sessions of the American Nuclear Society meeting:—

"*Performance and Evolution of Current Generation Power Reactors*" (joint plenary session with A.I.F.):
Mr. R. V. Moore, Managing Director, Reactor Group, U.K.A.E.A., speaking on "Review of Experience with Gas-Cooled Power Reactors";
Dr. J. E. R. Holmes, Chief Physicist, Atomic Energy Establishment, Winfrith, U.K.A.E.A., commentary on "Review of Experience with Heavy-Water Moderated Reactors".
Mr. D. R. R. Fair, Deputy Regional Director, Central Electricity Generating Board, member of an international discussion panel.

"*Problems and Considerations of Power Reactor Siting*"
Mr. W. S. Gronow, Nuclear Inspectorate, Ministry of Power, speaking on "Power Reactor Siting in the U.K."

"*Advanced Thermal Reactors*"
Mr. Compton Rennie, Consultant (and former head of the DRAGON Project), speaking on "High Temperature Gas-Cooled Reactors".

"*Isotope Production and Applications*" (joint plenary session with A.I.F.)
Mr. D. B. Smith, Research Group, U.K.A.E.A. (Wantage), speaking on "Growth Potential for Isotope Applications in Environmental and Ocean Sciences".

"*Recent Criticality Experiments and Nuclear Criticality Safety Data*"
Mr. J. H. Chalmers, Authority Health and Safety Branch, speaker and member of discussion panel.

The following will represent the U.K. at the Atomic Industrial Forum meetings, which have been organised as panel discussions:—

"*Advanced Reactors—Converters and Breeders*"
Mr. R. D. Vaughan, Chief Engineer, The Nuclear Power Group.

"*Nuclear Fuel Enrichment*"
Mr. T. Tuohy, Managing Director, Production Group, U.K.A.E.A.

"*International Aspects of Financing Nuclear Power Plants*"
Mr. G. K. Young, of Kleinwort, Benson, Ltd.

"*Dual Purpose Reactors*"
Dr. H. Kronberger, Chief Scientist, Reactor Group, U.K.A.E.A.

"*Reactor Safety: Licensing Codes and Standards*"
Major Leslie Cave, Atomic Power Constructions, Ltd.

"*Liquid Metal Breeder Reactors*"
Mr. R. R. Matthews, Reactor Group, U.K.A.E.A.

"*Plutonium Utilisation*"
Mr. P. W. Mummery, Director,

Dounreay Experimental Reactor Establishment, U.K.A.E.A.

"*The Atom and the Public*"

Mr. E. H. Underwood, Director of Public Relations, U.K.A.E.A.

Other members of the B.N.F. taking part in the meetings include representatives from Associated Nuclear Services, Babcock & Wilcox Ltd. and Rio Tinto-Zinc Corporation Ltd. Altogether some 35 industrial representatives will attend the meetings.

The Authority and the British Nuclear Forum will have adjacent stands at the exhibition and a combined information bureau, covering in all an area of 3,000 square feet.

The Authority exhibit will describe: the national nuclear power programme in Britain, which has generated more electricity from nuclear power than the rest of the world put together; the Production Group's comprehensive nuclear fuel service, which includes fuel manufacture and reprocessing and transportation to and from any part of the world; the Radiochemical Centre, Amersham, which is a major world supplier of radioisotopes for medical and industrial use; research equipment developed at Harwell and manufactured by industry under Authority licences; and a new process, developed at Aldermaston, for the production of metal powders which have industrial applications.

The British Nuclear Forum exhibitors will be:—

Atomic Power Constructions Ltd.
Avica Equipment Ltd.
Clarke Chapman & Co. Ltd.
Elliott Process Automation Ltd., Reactor Control Division.
The English Electric Co. Ltd., Reactor Equipment Division.
Fairey Engineering Ltd.
Nuclear Engineering International.
Plessey Co. Ltd.
Rolls Royce Ltd.
Twentieth Century Electronics Ltd.

The exhibitors cover a range of products which include gas-cooled nuclear power stations, research and training reactors, a wide range of specialised components for all types of reactors, equipment for sodium cooled fast reactors, and instrumentation and control equipment.

5th November, 1968

IN PARLIAMENT

Nuclear waste disposal

14th October, 1968

MR. EADIE asked the Minister of Technology, what discussions he has had with the European Nuclear Energy Agency on the disposal of nuclear waste.

Mr. J. P. W. Mallalieu: The Department and the Atomic Energy Authority provide the United Kingdom representation on the Steering and the Health and Safety Committees respectively of the European Nuclear Energy Agency.

Discussions in these bodies about scientific and technical co-operation between the Member States have covered the disposal of nuclear waste.

Nuclear propulsion

14th October, 1968

MR. WALL asked the Minister of Technology if he will make a statement about plans for development of nuclear propulsion for surface warships, fleet auxiliaries or merchant ships.

Mr. Cronin asked the Minister of Technology if he will indicate what plans he has for the development of nuclear propulsion for surface ships of the Royal Navy and merchant ships.

The Minister of Technology (Mr. Anthony Wedgwood Benn): Work on the development of nuclear propulsion for naval surface vessels and merchant ships is now under review and I understand that certain shipbuilders may shortly put to me proposals for future development in the merchant ship field.

Mr. Wall: As the Minister has persistently refused to build a nuclear-propelled surface vessel until it becomes economic, would it not be a good idea at least to experiment in the realm of a fleet auxiliary or surface warship?

Mr. Benn: That would be a matter for the Ministry of Defence. The House has accepted that the technical feasibility of building a nuclear surface ship is not in doubt and that what we are waiting for is for the economics to shift in favour of this. With the big container ships and possibly giant tankers, this time may be coming.

Mr. Cronin: In spite of the high capital costs, would my right hon. Friend bear in mind the enormous potential considering the low operational costs? Therefore, will he make sure that we do not lag behind

more than is necessary for economic reasons?

Mr. Benn: It is not only a matter of operational versus capital costs, but the rapidity of turn-round. Traditional merchant ships spend a very long time in port, and they have to pay interest charges on the capital costs while they are in port. Containerisation is important not only because of the larger ships but because more of the time of a ship is actually spent at sea.

Mr. David Price: Does not the right hon. Gentleman agree that we are soon approaching the point at which we cannot resolve this issue further without having an experimental ship at sea?

Mr. Benn: I am not absolutely persuaded of this. If the shipbuilders' proposals, which I am expecting, indicate anything, they might indicate that one would be moving more rapidly towards a ship that had economic operation. I do not want to find that I am committed to a prototype which was not intended for ultimate use.

Nuclear power plant

14th October, 1968

MR. HOOLEY asked the Minister of Technology which countries in Europe have formally indicated to Her Majesty's Government their willingness to co-operate with the United Kingdom in the design and production of nuclear power plant.

Mr. Benn: The design and production of nuclear power plant is primarily now the concern of industrial organisations. British industry is collaborating with firms in Germany, Italy, Belgium and France on gas-cooled reactors, and the United Kingdom Atomic Energy Authority has collaborative arrangements on nuclear fuel manufacture with firms in the first three of these countries.

Mr. Hooley: Is my right hon. Friend satisfied that the proposed re-organisation of the nuclear power plant industry will enable co-operation and collaboration with other countries to continue?

Mr. Benn: I am not only satisfied that it will enable it to continue, but one of the major reasons why the reorganisation proposal was adopted was that we thought it would facilitate it and make it easier.

Mr. Lubbock: Has the right hon. Gentleman studied the information which I sent him shortly before the Recess about the West German plans for a 25 megawatt high temperature reactor coupled to a helium gas turbine at Geesthact, and a 300-megawatt design based on the treble reactor at Jülich? What steps is the right hon. Gentleman taking to make sure that this country stays ahead in gas-cooled reactor technology in which she has excelled hitherto?

Mr. Benn: I think that I wrote to the hon. Gentleman about this. I cannot reproduce everything that I said in answer to his question, but this is one of the aspects which we have very much in mind.

Materials testing

5th November, 1968

MR. MACLENNAN asked the Minister of Technology whether, following the decision to close the Dounreay Materials Testing Reactor, the United Kingdom Atomic Energy Authority will use only the irradiation facilities of Harwell or other authority establishments for materials testing; and if it is intended to invite tenders for this work from abroad.

Mr. J. P. W. Mallalieu: After the Dounreay Materials Testing Reactor is shut down it is the Authority's intention that experiments which would have been mounted in it will be placed in the Authority's Materials Testing Reactors at Harwell. It is not intended to invite tenders from abroad for this work. The Atomic Energy Authority has for some years used facilities in other countries for irradiation work where these facilities are better suited to a particular purpose than their own. They will continue this practice after D.M.T.R. is closed down, but this affects only a fraction of the total work done.

Radiological protection

The latest recommendations of the International Commission on Radiological Protection are included in the revised edition of the Code of Practice for the Protection of Persons exposed to Ionising Radiations in Research and Teaching, H.M.S.O., price 6s. 6d. net.

The principal change in the new edition is in the table listing maximum permissible radiation doses, based on the International Commission's recommendations.

The code is issued jointly by the Department of Employment and Productivity and the Ministry of Health and Social Security, Northern Ireland.

Radioisotopes and the engineering designer

This article, by R. M. Longstaff, Industrial Liaison Officer, Wantage Research Laboratory, U.K.A.E.A., appeared originally in The Engineering Designer, *monthly journal of the Institution of Engineering Designers.*

The term "radioisotopes" covers the whole range of radioactive materials that have become available as a result of the discovery and exploitation of nuclear fission over the last 30 years, and which have proved useful over large areas of scientific research and medical diagnosis and therapy, and in many branches of industry. This article attempts to outline the fields of application of these versatile materials in the engineering industry, particularly in areas where the engineering designer is likely to find himself concerned.

Nature of radioactivity

Radioactive atoms have nuclei with too many neutrons for stability (more rarely, too many protons), and sooner or later undergo a sudden and spontaneous change (disintegration) to a more stable form. This occurs with the violent ejection of a fragment of nuclear material, and in some cases of additional radiant energy. The most important kinds of radioactivity are beta emission, where a fast-moving electron (beta-particle) is ejected, and gamma emission, in which a pulse of radiant energy like X-rays is emitted (often in association with beta-emission). High-energy gamma-rays will effectively penetrate up to several feet of concrete, while ½ in. of plastic will stop any beta-particle. Alpha-particles have negligible penetrating power and are of little direct industrial importance. Neutron emission is not a normal mode of radioactive disintegration but it can be induced by the action of alpha particles on beryllium nuclei and it has industrial applications. Neutrons have widely varying penetrating powers which depend specifically on the material encountered as well as upon their own energy; they are slowed down particularly effectively by collisions with hydrogen nuclei.

Every radioisotope disintegrates in a characteristic manner, producing radiation of a type and energy-distribution which can be used to identify the isotope as clearly as the lines seen in a spectroscope can identify an element. The readiness with which a radioisotope decays is equally characteristic, and can be expressed statistically in terms of its "half-life" or halving time, i.e. the time taken for half of the atoms initially present to change and therefore for the activity to decay to half its initial level. Most radioisotopes have halving times ranging from fractions of a second to tens of years (except for many of the naturally occurring ones, whose halving times range up to millions of years—hence their survival to the present day).

Artificial radioisotopes are produced in nuclear reactors either by direct chemical separation of the medium-weight radioactive elements formed by the fission of uranium or plutonium, or by using some of the hailstorm of neutrons that sustain the fission reaction in order to induce radioactivity in the nuclei of materials put into the reactor for the purpose. Radioisotopes of almost every element (with a few notable exceptions, which include oxygen and nitrogen) are now commercially available in a very wide range of chemical and physical forms. The production and marketing organisation in the United Kingdom is the Radiochemical Centre at Amersham, and the research centre for many industrial and other practical applications (other than in medicine) is the Wantage Research Laboratory; both of these are within the U.K. Atomic Energy Authority.

The energy associated with radioactive decay is vastly greater than that accompanying chemical changes involving similar masses of material, and it is for this reason that radioactivity is both useful and potentially dangerous. Furthermore, radioactivity cannot be "switched off" and there is no practical method, chemical or physical, which can hasten or slow down in any way the process of radioactive decay or restabilise an unstable nucleus.

Beta and gamma radiations interact with

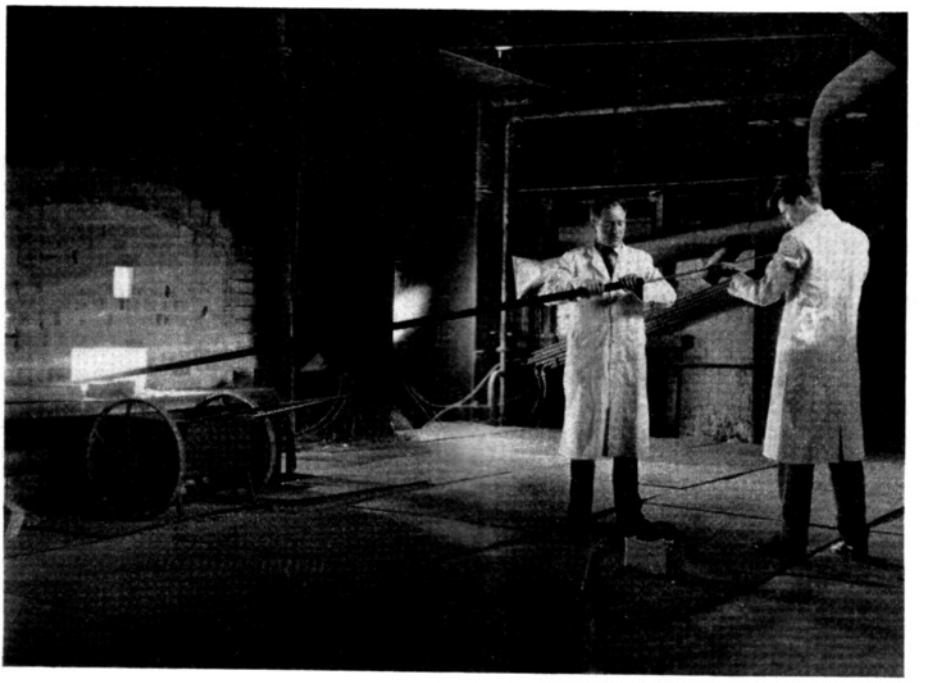

Fig. 1. *Introducing a radioactive tracer into a tank furnace of molten glass to study the efficiency of mixing of the ingredients.*

matter in a variety of ways, depending upon the nature and energy of the radiation and on certain properties of the material encountered, notably its atomic number—that is to say the number of its orbital electrons, which increases progressively with atomic weight. A major overall effect of the interactions is that some of the incident energy is transferred to the matter, where electrons are removed from their normal orbits around the atoms. Complete removal to form a charged atom or ion is known as "ionisation" (hence the generic term "ionising radiation"), while displacement to an abnormal orbit of higher energy-level is known as "excitation"; such atoms return later to their normal state with the emission of light or of X-rays characteristic of the element. Both processes can initiate chemical changes in the irradiated material, and ionisation, by producing charged particles which will move in an electric field, turns gases (which are normally good insulators) into electrical conductors. Living matter, because of its chemical complexity and the delicately balanced reactions taking place in it, is particularly sensitive to ionising radiations; the effects here are complex, and their onset may be delayed for many years. Since ionising radiations cannot be detected by the unaided senses, special precautions are needed in handling radioactive substances. These are reflected in the regulations governing their acquisition and use, which are mostly codified and enforceable (as far as industrial users in the U.K. are concerned) under the Radioactive Substances Act (1960) and under Factories Acts Regulations. Contrary to a rather widespread but erroneous belief, these radiations are in no sense "infectious"—they do not make what they fall upon radioactive, any more than sunshine makes the sun-bather glow in the dark afterwards, whatever other effects it may have. "Contamination" by radioactivity is simply the unwanted physical presence of radioactive material, usually in extremely small quantities, but which can nevertheless be significantly hazardous and which usually needs special cleaning-up ("decontamination").

Measurement of radiation

There are three main ways of detecting and measuring ionising radiations: these depend on (i) the production of electrical conductivity in gases, (ii) the production of light in phosphors such as sodium iodide, and (iii) the blackening of silver salts in

photographic film. These are applied in practice respectively in ionisation chambers and Geiger-Müller tubes or proportional counters, in scintillation counters (associated with photomultipliers), and in photographic films which record the total amount of radiation received at any point. In the first two (electrical) methods the number of radiation events detected over a predetermined period of time is often integrated and expressed as a "count-rate", usually in counts per second or per minute.

In some measurements it is necessary not only to record the amount of radioactivity in terms of count-rate, but also to distinguish between radiations of different energies; this is usually done electronically, using proportional counters or scintillation counters as detectors. Energies are expressed in terms of thousands or millions of electron-volts (keV or MeV), an eV being the energy acquired by an electron falling through a potential difference of one volt.

Radioactive disintegration is a discontinuous process, taking place independently in individual atoms in a manner that is entirely random and is therefore appropriately dealt with by statistical methods. Since the most sensitive types of detector operate by counting single events, it is necessary to count a sufficiently large number of these to ensure the statistical significance of the results. A weak or distant or obscured source of radiation therefore takes longer to measure satisfactorily than a strong one or one that is being measured with a greater degree of efficiency (i.e. more of the radiations are reaching the detector).

There is, and always has been, a background of radiation everywhere from the natural radioactivity in the earth's crust, in the air, in building materials and even in our own bodies, as well as from cosmic radiation. Some of these radiations are bound to be picked up even by a shielded detector, so they must be recorded separately and subtracted from the total reading when making a measurement.

Principles of industrial applications

Three major and inter-related properties of radiation lie at the root of nearly all the industrial applications of radioisotopes. These are their ease of detection and measurement, their penetrating powers, allied with the effects upon them o encounters with matter, and the effect which the radiations (if in sufficient quantity) can have upon matter. Industrial applications can be grouped into three major categories along the same lines:— (i) radioactive tracer studies, where a small amount of a suitable radioactive substance is used as a "label" to follow the movement and distribution of some constituent of a process (eg.. distribution of a component in an industrial mix, or the movement of silt on a river bed); (ii) instruments for studying some physical quality in a material or system (e.g. thickness or level gauging, elemental analysis, or flaw-detection by gamma-radiography); and (iii) radiation processing (e.g. polymer cross-linking or the sterilisation of medical supplies). Other applications include the ionisation of air to prevent build-up of static electricity, the excitation of phosphors in self-luminous devices, and the supply of energy for remote automatic signalling equipment.

Radioactive tracers

Radioactive materials are available in very wide variety, so it is usually possible to choose one that is physically, chemically and radiologically suitable for labelling any selected constituent of a process; alternatively, it is sometimes more appropriate to activate an actual constituent of the process directly by neutron-bombardment in a reactor. For safety reasons it may occasionally be necessary to use an inactive tracer which is activated in the samples afterwards. Precautions must be taken to ensure that whatever tracer is used is homogeneously mixed with the material to be labelled, and does not become segregated or removed during the process, e.g. by adsorption or selective chemical action. Since the tracer will usually be the only significantly radioactive substance present in the system, the activity measured at any later stage in the process will be directly related to the amount of the labelled constituent that is present. Background radiation must be measured and deducted, and in the case of short-lived tracers a simple correction may have to be made to allow for loss of tracer by radioactive decay during the time of the experiment. Particular account must be taken of radiological safety and the associated legal requirements, and it is

necessary for a user to be familiar with these or to be guided by someone having the necessary experience—for example staff from the U.K. Atomic Energy Authority or a local University or College of Technology. In particular, the Ministry of Housing and Local Government and in the case of a factory the District Factory Inspector, must be notified beforehand and approval obtained. Generally speaking radioactive tracers are not used for routine control purposes but the techniques are applied in the course of specific operational investigations or comparative studies. There is virtually no limit to their application to industrial or geophysical problems on any scale from the microscopic to the global, and it is only possible to give here a few representative examples selected for their potential interest to engineering designers.

In the constant-rate isotope injection technique for flow measurement (described fully in British Standard 3686, Part 2C, 1967), a few litres of solution of a suitable radioisotope (usually sodium-24 as bicarbonate dissolved in acetic acid) are injected at a steady and accurately known rate into the process stream; a sample is then withdrawn at a point downstream and its radioactivity compared with that of the injected material. The total flow-rate will bear the same ratio to the injection-rate as the activity-concentration of the injection bears to that of the diluted sample. Complete mixing across the stream is essential, and if a sufficient "mixing distance" is not available other measures must be taken to achieve it. In a straight pipe a mixing distance equal to about 100 pipe-diameters is usually required, but this is reduced by bends, constrictions or other causes of turbulence. Pumps or turbines are extremely efficient mixers and when they are included in a section very little addition pipe-length is required. One of the most valuable applications is in the measurement of the very high rates of flow in power-station cooling-water systems and hydro-electric stations, and in other installations where large amounts of power are involved and where the measurement of flow—and therefore of pump or turbine efficiency—is extremely important. Radioactive tracers are being used with great success in acceptance-testing and commissioning of pumps and turbines and in calibrating installed flow-meters. Accuracies of + or − 0.5% (at 95% confidence) are obtainable at flow-rates of 500,000 gallons a minute and of + or − 0.2% at 50,000 gallons a minute, giving a real improvement over other methods. In installations where accurate measurement of fluid flow is likely to be of critical importance either in commissioning or in operation, it is an advantage to make provision at the design stage for injection and sampling points, preferably on either side of positions of high turbulence; the injectors at these points can often be single nozzles introducing the tracer at the axis of the pipe, whereas in the absence of natural mixing multiple or high-pressure nozzles may be needed.

Where the cross-section of a pipe is accurately known a single rapid injection of tracer may be made, and its time of passage measured between two points a known distance apart downstream; complete mixing is still needed, but the radiation is detected externally and there is no need for sampling. Similar techniques are being developed and used for the measurement of gas flow, including town gas in mains, using radioactive krypton-85 gas as a tracer.

Many other aspects of the kinetics of operation of process plant can be studied by single-shot or continuous injection of radio-tracers. For example, a single injection into the input of a mixer, combined with a record of the activity in the outgoing mix over a period, can be used to obtain detailed and quantitative information on mixing efficiency, residence time, hold-up, recycling or other characteristics of the plant, under any chosen conditions of operation. The technique is especially useful in commissioning new plant, studying process variables, establishing optimum operating conditions and investigating malfunctions. In scaling up from pilot-plant to full-scale production radioactive tracers can be used to make very accurate comparisons between both plants, thus determining precisely the effects of size on operating characteristics. This kind of information can be of great value in later scaling-up operations, and has in fact been used by chemical plant designers to dispense altogether with pilot-scale plant and to design to full scale directly from the laboratory bench. Again, to take full advantage of the methods, it is useful to construct the plant in the first place with suitable injection and sampling points and

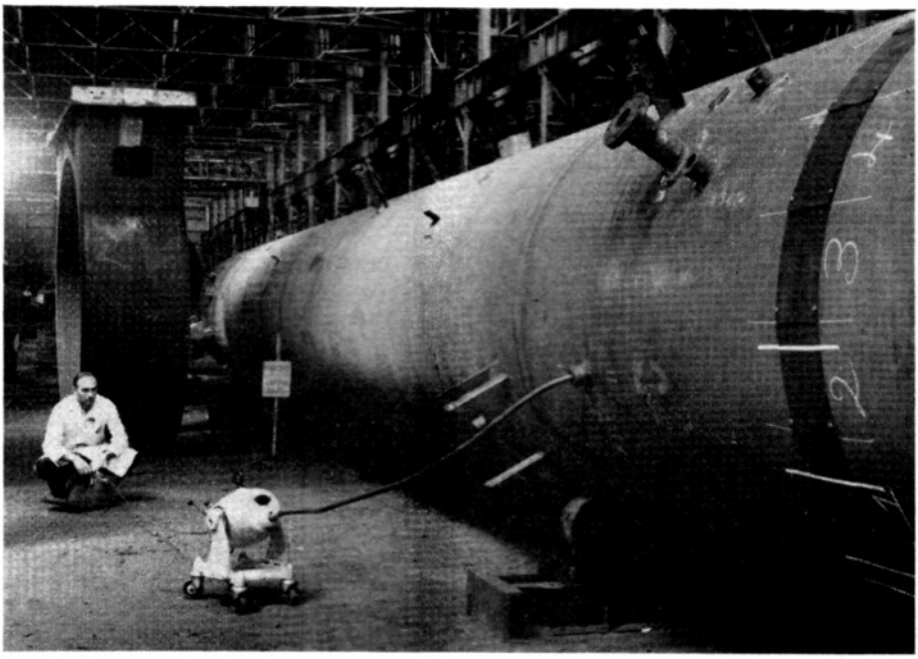

Fig. 2. *Gamma-radiographing a circumferential weld in a pressure vessel. The radioactive source is introduced by remote operation through the small opening to a central exposure position. The films can be seen over the weld to the right of the picture.* (Photo: courtesy Nuclear Engineering Ltd.)

positions of access for instruments to measure radiation externally. Radioactive gases can be used as tracers for studying ventilation problems etc., on line similar to the above.

Radioactive tracers can sometimes be used very successfully to locate leaks in pipes and plant. The principle here is to charge the suspected vessel with a dilute radioactive solution under pressure, or to pass a "slug" of radioactive solution through it, and then to flush out and examine the vessel, internally or externally, for any traces of residual activity that may have leaked out. In the case of buried pipes the detector can be pulled through the pipe by a cable which also carries the electrical signals and at the same time indicates the probe's position; or it can be mounted in a "go-devil" piston along with a self-contained recorder which is played back afterwards. Alternatively, if leak-points are already suspected (e.g. at joints in newly-laid watermains) bar-holes can be made and probed for activity from the surface. For finding substantial leaks in pipes of near-uniform bore, the tracer may be carried captive in a rubber ball which fits the pipe snugly and is carried by the current as far as the leak, where it will lodge and can be detected externally. This technique has been used successfully in industrial and domestic water systems, through up to 4 feet of soil or the equivalent in brick or concrete. Refinements of these techniques may be used to locate leaks in engine-fuel systems, between concentric pipes, etc. Here, too, their application can be simplified by incorporation at the design stage of injection points, hatchways and other means of access at appropriate places, and by avoiding siting critical parts in inaccessible positions. Small sealed electronic components etc. can be checked very sensitively for integrity of sealing using radioactive krypton gas as a tracer.

Other useful radioactive tracer techniques include the labelling of interfaces between successive batches of liquid in a common pipeline, testing the integrity and efficiency of filters, and studying hydrological problems such as the movement of ground-waters and the siltation of rivers.

It is worth recording that many disappointments would be avoided if it was realised that in any tracer study the tracer must be added at a point in the process upstream of the system being investigated, whether this is a leaky pipe or a complete process unit: an added tracer can aid in

following a process material in its subsequent movements, but it can be of no help in elucidating its previous history. It is, therefore, not possible to add a tracer to a noxious effluent in order to find its origin any more than it is possible to identify an unknown piece of luggage by tying a label onto it afterwards—the label must be attached before the luggage is lost.

Gamma-radiography

Gamma-radiography does the job of X-radiography, using a radioisotope instead of an X-ray tube as a source of radiation. The main advantages are the portability, dependability and independence from electricity supplies of the radiation source, and an added benefit is the possibility of taking all-round or multiple-object radiographs in a single exposure. Also, an isotope source with its shield is very much cheaper than an X-ray machine of similar capacity, particularly in the higher energy-ranges. The main disadvantages are the longer exposure times required, the need to replace the source at intervals depending upon its rate of radioactive decay rather than the extent of its use, and the problems of safeguarding a radioactive source that cannot be switched off. The small size and manoeuvrability of a radioisotope source as compared with an X-ray tube are worth bearing in mind when designing structures or products that may require acceptance or maintenance testing by radiography; for example, an isotope source (unlike an X-ray tube) can be used under water or inside a 1 in. pipe. At the same time it should be remembered that radiography of any kind will not normally show up laminar flaws that lie in a plane at right angles to the path of the radiation beam.

Radioisotope instruments

A radioisotope instrument consists of a radioactive source and a radiation detector arranged so as to determine some characteristic of a material or system, in rather the same way that a person might use light to examine something visually. The source and its associated measuring equipment can be selected to carry out any one of a wide range of determinations, from a simple indication of the presence or absence of an object in the path of the radiation-beam to the accurate assay of a particular element in a mineral sample. The simplest of these instruments is the "yes-no" indicator (of which the so-called "gamma-switch" is one type), which merely reveals whether or not something is stopping the radiation-beam from reaching the detector; alternatively, it may be arranged to detect an object which scatters some of the radiation into the detector, which it cannot normally reach. Instruments of this kind are very useful where a robust and dependable signal source is required needing a minimum of maintenance, or where optical methods are ruled out by reason of dust, smoke or physical obstruction. Examples include position-indicating alarms for furnace doors, mine cages or the covers of reaction vessels, but the major use of the principle is for level gauging (often associated with automatic control) in circumstances where other methods are unsatisfactory—for example, on large silos and storage hoppers for solids, on vessels containing hot, corrosive, turbulent or otherwise troublesome materials, on glass tank-furnaces and on pressure-vessels. Special portable gauges are made for cylinders of gases liquefied by compression which otherwise have to be checked by weighing. Isotope level-gauges are often fitted to package-filling machines, for high-speed monitoring of containers such as beer-cans, soap-powder cartons, etc. Accuracies as good as $+$ or $-$ $\frac{1}{16}$ inch are usual with isotope level gauges. If necessary, a continuous range of levels can be covered by using a sloping radiation path or extended or multiple sources or detectors. Alternatively, automatic "hunting" gauges can be used to follow the surface level continuously.

Of even greater industrial importance are the gauges used for measuring the mass per unit area of continuously-produced materials—e.g., basis weight of paper, thickness of sheet or strip metal or of plastic sheet or film, or the thickness (by subtractive measurements) of the coatings on treated materials such as linoleum or rubberised tyre fabric. These gauges operate by measuring the proportion of radiation that succeeds in penetrating the material intervening between source and detector, a figure which can be made dependent only on the mass per unit area of the absorber; to interpret this in terms of thickness it is essential that density remains constant, or that any variations are ascertainable by independent measure-

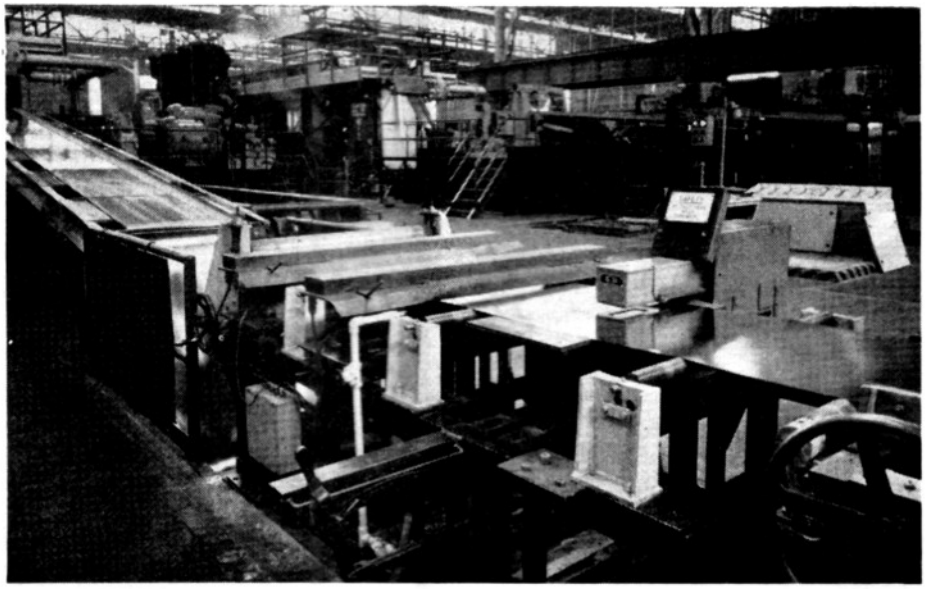

Fig. 3. *A beta-gauge in operation on a steel rolling mill.* (Photo. courtesy Steel Company of Wales).

ment: for example the moisture content of paper will significantly affect its density and must be measured by micro-wave absorption or other means if basis weight is to be converted to thickness. The converse measurement, of density where thickness is constant, is used for measuring fluid or slurry density (and hence composition) in pipes or vessels, or the packing of tobacco in cigarette manufacture; here there are physical constraints on the effective thickness of the materials measured. Accuracies of measurement by thickness or density gauges usually lie between + or − 0.1% and + or − 5%; one of their major practical advantages is that no direct contact need be made with the materials measured, which can thus include hot, easily damaged or rapidly moving products. Further, as with all radioisotope instruments, the outgoing signal is an electrical one which can be made compatible with any type of system for automatic or manual control; indeed, the suitability of these instruments for incorporation into automated or computer-controlled systems is one of their major advantages.

It is not always possible to obtain access to both sides of a specimen to be measured, in which case back-scattered radiation can sometimes be used, but these measurements are usually rather less accurate, less rapid and more dependent upon composition than those making use of radiation transmitted through the specimen, and the range of thickness that can be measured is more restricted. However, instruments (some of which are portable) are available for measuring by back-scattered radiation the thickness of continuously-produced sheet or strip materials, for detecting the contents-level of closed vessels, or for the external checking of internal corrosion of the walls of vessels or pipes. Bulk density of solids can also be measured by back-scattered radiation. Because the amount of scattering depends among other things upon composition, and in particular upon atomic number, it is sometimes possible to use radiation of suitable (comparatively low) energy to determine mean atomic number. This can be interpreted in terms of the composition of binary alloys or of the thickness of thin coatings (eg., zinc on galvanised steel or gold on printed circuitry); it can also be used, for example, to distinguish coal from shale in automatic coal cutting, to measure the ash-content of crushed or powdered coal at washeries or blending plants, or for production-line measurement of calcium in cement. Preferential absorption of radiation can be used similarly for determining sulphur in kerosene, lead in motor spirit, mineral fillers in paper, etc.

When the atoms of an element are

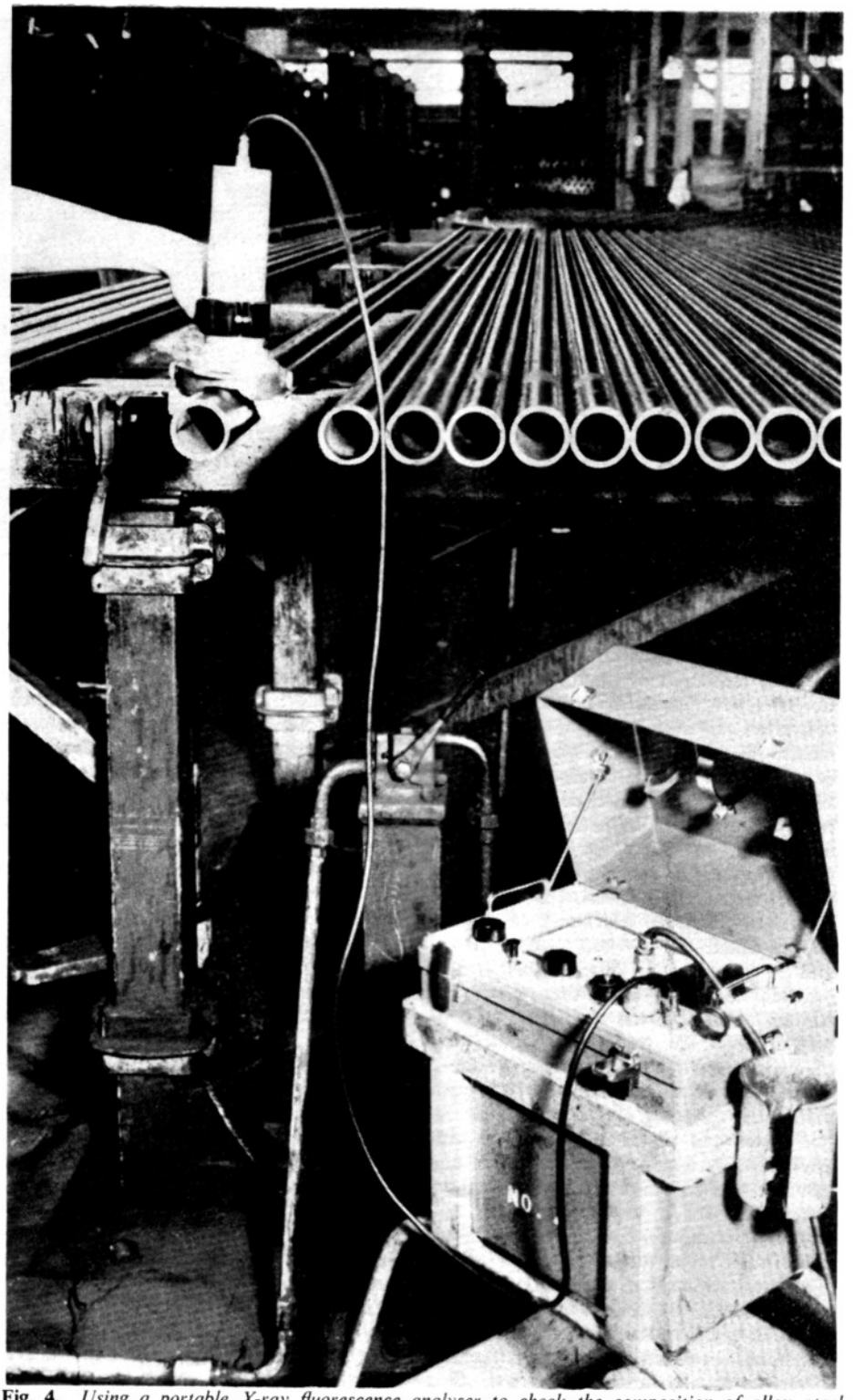

Fig. 4. *Using a portable X-ray fluorescence analyser to check the composition of alloy steel*

excited by radiation of a suitable energy their orbital electrons are displaced to higher energy levels, from which they drop back with the emission of fluorescent X-rays characteristic of the element; the intensity of these X-rays is a measure of the percentage of the corresponding element in a specimen. This is the basis of X-ray fluorescence spectrometry, a well-established analytical technique of great versatility usually carried out with an X-ray machine and a crystal diffractometer. By using radioisotope sources and suitable X-ray filters it has been possible to develop compact and comparatively inexpensive analysers for laboratory or factory use, as well as battery-operated portable instruments for field and rock-face work; in suitable cases elements can be measured at concentrations of less than 1% in a few seconds, without special preparation of the sample. The same technique and instruments can be used to measure coating-thickness in many different systems, by measuring either the intensity of X-rays characteristic of an element in the coating, or the attenuation of X-rays characteristic of an element in the substrate as they pass through the coating.

The water-content of non-hydrogenous bulk materials such as soil, foundry-sand, clay, or concrete can be measured on-line or *in situ* by bombarding the specimen with neutrons (see above) and counting the numbers slowed down by collision with the hydrogen nuclei. Accuracies of + or − 1% are claimed in measuring times of a few minutes and no special sample preparation is required, although a bulk density measurement may also be needed for interpretation; this is easily obtained with a gamma-ray density gauge.

A few radioisotope devices rely directly upon ionisation of the air or gas in the immediate neighbourhood of the source. A well-known smoke-alarm system operates independently of temperature or visibility by detecting changes in ionisation properties of the air due to the presence of combustion-products, and a gas-flow meter that causes no restriction to the flow measures conductivity due to the residual ionisation of the gas a short way downstream of a source fixed inside the pipe; this is directly related to the gas flow-rate.

Light and power sources

A wide variety of low-intensity self-luminous signs and markers make use of the beta-decay energy of radioactive substances to excite light in phosphors such as zinc sulphide; they are particularly useful for instrument dials, exit-signs, warning-markers on obstructions and low-level emergency illumination. For larger self-contained power requirements with outputs up to a few watts, a range of RIPPLE's (radioisotope-powered prolonged life equipment) is being developed by Harwell and evaluated practically for use in navigational lights, remote radio beacons, submarine cable repeaters and other situations where reliable unattended operation for up to 10 years is more important than low initial cost.

Safety

Statutory regulations have to be observed in the installation and use of radioisotope instruments and devices of all kinds, although many of these have sources small enough for exemption from special radiological safety measures. The manufacturer (or in appropriate cases the Factory Inspector) can advise on this aspect. The Radiological Protection Service, operated jointly by the Ministry of Health and the Medical Research Council, also gives advice on this and on other questions relating to radiological safety and associated legal requirements. The regulations to be observed are seldom very onerous and should never be thought of as *prima facie* grounds for rejecting the use of radioisotope techniques.

Radiation processing

The industrial application of ionising radiations to the processing of materials, as distinct from the use of radioisotopes in instruments or as tracers, is confined to relatively few specialised fields. In the United Kingdom by far the most important of these is the sterilisation of pre-packed disposable medical equipment by gamma-rays from cobalt-60. Four large plants are operating commercially and several millions of items are sterilised each week, the largest single line being hypodermic needles and syringes. Very large doses of radiation are required for sterilisation against microbial infection (equivalent weight for weight to some 3,000 times the lethal dose to man) and stringent precautions have to be taken in the design and operation of the plant. Radiation has many advantages over con-

ventional sterilants such as steam-heat and ethylene oxide: heat-sensitive materials (e.g., polyethylene) can be used, sealed wrappings and intricacies of construction offer no obstruction to the radiation, and a very high bacterial inactivation factor is achieved. Prior wrapping of the product ensures the maintenance of sterility until use, the process itself is not expensive and comparatively cheap materials, e.g., injection-moulded plastics, can be employed so that the products can be discarded after use instead of being sterilised again for re-use. This greatly reduces the risks of cross-infection between patients. The introduction of gamma-sterilised disposable products has, in fact, brought about a minor revolution in the production, handling and use of a wide range of medical stores.

The treatment of food to prolong storage life or to safeguard public health has not yet reached the stage of practical application in this country (and only to a very limited extent elsewhere). However, the technology and the necessary administrative machinery already exist for the process to be applied as soon as sufficient commercial interest has been aroused.

Chemical processing by gamma-radiation is used on a limited industrial scale, particularly in the Dow process for making ethyl bromide. In the U.K. it is at present mainly confined to the treatment of small batches of polyethylene to improve its heat-resistance when used as an electrical insulator, and to the manufacture of a new type of composite wood-plastic material. The latter is being used initially for the handles of high quality table cutlery, where it has many advantages in appearance and durability, and there are many other potential domestic and industrial applications. An allied process on the threshold of industrial exploitation uses electron beams from accelerating machines for the ultra-rapid curing of factory-applied paints —a process which in a few years may very well bring major reductions in industrial finishing costs together with improvements in the finish obtainable, particularly on heat-sensitive substrates. Electron accelerators are also used in the production of heat-shrinkable plastic films and tubing.

Economic advantages

It will be clear that radioisotope techniques of the types described above have made it possible to carry out difficult measurements with a new order of accuracy and speed, and have opened up new possibilities in product and plant design and in process operation. For example, the improved accuracy with which sheet-metal thickness can be controlled by isotope gauges means that designers can safely specify thinner gauge material with consequent reduction in overall cost and weight. The exploitation of radioisotope techniques by industry has already resulted in direct savings in the U.K. of tens of millions of pounds a year, largely by increased productivity and reduced wastage. Many individual firms have found that the cost of installing radioisotope instruments has been more than made up by the savings achieved by their use within a few months, or that a few hundred pounds spent on a tracer investigation has resulted in an annual saving of thousands through increased output. If the installation of radioisotope instruments and the provision of facilities for using radioactive tracer techniques are considered in the early stages of the design of new plant, and if full advantage is taken of radiation processes and products even greater benefits will accrue to British industry.

Suggestions for further reading

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Irradiation experience with isotropic graphite

This paper was presented to a Symposium on Advanced and High Temperature Gas-cooled Reactors, organised by the I.A.E.A. at Jülich, Germany, from 21st-25th October, 1968. The authors are P. T. Nettley, J. E. Brocklehurst and W. H. Martin, of the Reactor Materials Laboratory, Culcheth, and J. H. W. Simmons, of A.E.R.E. Harwell.

Abstract

The use of isotropic graphites with high coefficients of thermal expansion for the moderator of an AGR was first recommended just over five years ago. Since that time wide experience of the irradiation behaviour of such graphites has been gained from experiments performed mainly in the Dounreay Fast Reactor (DFR) and in the Belgian reactor BR-2. This paper summarises the data, obtained for five isotropic graphites, on dimensional changes, irradiation creep, changes in thermal conductivity, thermal expansion, Young's modulus and strength. The effect of radiolytic oxidation in CO_2 coolant on these properties is also discussed.

Linear dimensional changes induced by fast-neutron irradiation in an AGR moderator, made from any of the isotropic graphites studied here, would be less than 3.5% during the lifetime of an AGR of the Dungeness B type. Moulded isotropic graphite exhibits less shrinkage than extruded isotropic graphite. The irradiation creep behaviour of the isotropic graphites ensures that internal stresses in AGR bricks resulting from the irradiation induced dimensional changes will be small. The strength of the AGR moderator graphite is increased by fast-neutron irradiation and decreased by radiolytic oxidation. The strength of the moderator at the end of life will not be less than the original value if radiolytic weight losses are less than 13%. At neutron damage doses slightly higher than the expected peak lifetime dose of an AGR moderator of the Dungeness B type, a marked temperature dependence is observed in dimensional changes in the temperature range 370-550°C in DFR, and a rapid growth is observed at these high doses in all materials investigated at temperatures of 500-550°C.

Introduction

The graphite moderator in an AGR of the Dungeness B type[1] experiences changes in properties due to two main processes:

(a) Graphite crystal damage due to carbon atom displacement by fast neutrons; the effect of the resulting defects on the bulk properties has led to the development of an irradiation damage model which has recently been reviewed[2].

(b) Radiolytic oxidation of graphite by the CO_2 coolant; this does not affect the crystal properties but changes the bulk properties[3] by alteration of the structure.

The problems posed by these processes and the programmes of work to solve them have been discussed previously [4, 5]. During the last five years these programmes have been pursued vigorously, and full use has been made of the very high fast neutron fluxes in the Dounreay Fast Reactor, DFR[6]. These high fluxes have enabled us to expose graphite to equivalent fast neutron doses which are well in excess of those expected during the lifetime of the Dungeness B reactor.

The reactor designer needs to know how fast neutron damage and radiolytic oxidation will alter the properties of the moderator during the life of an AGR, and in this paper, the changes in the properties of isotropic graphites resulting from fast neutron damage and radiolytic oxidation are described. The data cover fast neutron doses and weight losses which exceed those which are expected during the lifetime of the Dungeness B type reactors.

Only near isotropic graphites with high coefficients of thermal expansion are discussed. The use of such graphites in the AGR system was initially recommended in 1963[4] and confirmed in 1966[7]; the early manufacturing development of the materials has also been discussed previously[8]. Production of this type of graphite in kiloton quantities has been completed

satisfactorily for the Dungeness B reactor and good progress is being made in the production of materials for the Hinkley B and Hunterston B reactors (see, for example, Nuclear Engineering 1967).

Experimental

Types of graphite

The behaviour of four extruded isotropic graphites and one moulded isotropic graphite are discussed. All these graphites were manufactured from cokes and binders which yielded well-graphitised materials when they were heat treated at about 2800°C; their typical properties parallel and perpendicular to the forming direction are listed in Table 1. One of the extruded graphites and the moulded graphite were made from the same coke. Detailed manufacturing information on these two graphites has not been published but examination by the methods of Knibbs[9] shows that they are virtually identical in structure to graphites which have been manufactured from gilsocarbon coke.

The same coal tar pitch binder was used for the manufacture of graphites PH, PO and PR and the materials were impregnated with a special impregnant to obtain high density and low open porosity; this impregnant yielded a hard carbon when it was graphitised. Previous work[10] has indicated that a poorly graphitised impregnant has little effect on the irradiation behaviour of the parent graphite. Examination of the materials PI and NA, using the methods described by Knibbs[9], has shown that the impregnants and binders used in these materials yield soft carbons on graphitisation.

Equipment

Most of the irradiations have been performed in uninstrumented specimen holders in the core of DFR. The techniques used to determine temperatures and neutron doses in these experiments have been described previously[11,12]. Specimens have also been irradiated in inert atmospheres in instrumented rigs at 700°C in the Belgian MTR BR-2 and in the range 390-550°C in DFR. Irradiations in CO_2 have been performed both in DIDO and in the high γ-flux of BR-2 to produce specimens oxidised to high weight losses. In these latter irradiations the neutron dose was small and the fast neutron effect was removed by post-irradiation annealing[3] at about 2000°C, thus enabling the effect of radiolytic oxidation to be isolated. Neutron doses were measured by nickel activation and they are expressed as equivalent doses in DIDO (i.e., the nickel dose required in the materials testing reactor DIDO at A.E.R.E., Harwell to produce the same number of primary displaced carbon atoms). The conversions from DFR and BR-2 nickel dose scales to the DIDO equivalent dose have been described previously[11,12,13], and so have the techniques used for determining physical and mechanical properties before and after irradiation [14, 15, 16]. Irradiation creep experiments were performed in BR-2[17,18].

Results

Dimensional changes

The dimensional changes observed in the directions perpendicular and parallel to forming in the isotropic graphites are presented in Figs 1-4. The maximum dose achieved is well in excess of that which would arise in a current AGR (e.g., Dungeness B) after, for example, 35 years life assuming an average load factor of 75%. All the graphites contract initially in both directions. The contraction rates are similar in all the extruded materials with somewhat more contraction parallel than perpendicular to extrusion. The moulded

TABLE I. *Typical physical properties of the graphites before irradiation*

Reference code	Extruded				Moulded
	PH gilsocarbon coke	PO petroleum coke	PR coal tar pitch coke	PI unspecified coke	NA unspecified coke
Thermal expansion coefficient ∥ ..	3.5	3.0	4.2	3.5	3.8
(20 to 120°C) (10^{-6} deg C^{-1}) ⊥ ..	3.9	3.6	4.4	4.1	3.7
Thermal conductivity ∥	0.32	0.38	0.26	0.36	0.29
(cal cm^{-1} sec^{-1} deg C^{-1}) ⊥ ..	0.28	0.36	0.23	0.33	0.30
Young's modulus ∥	17	17	17	14	14
(10^5 lb/in^2) ⊥	15	14	15	12	14
Average tensile strength (10^3 lb/in^2)	2.0	2.0	1.7	2.0	2.0
Density (g/cm^3)	1.85	1.8	1.8	1.8	1.8

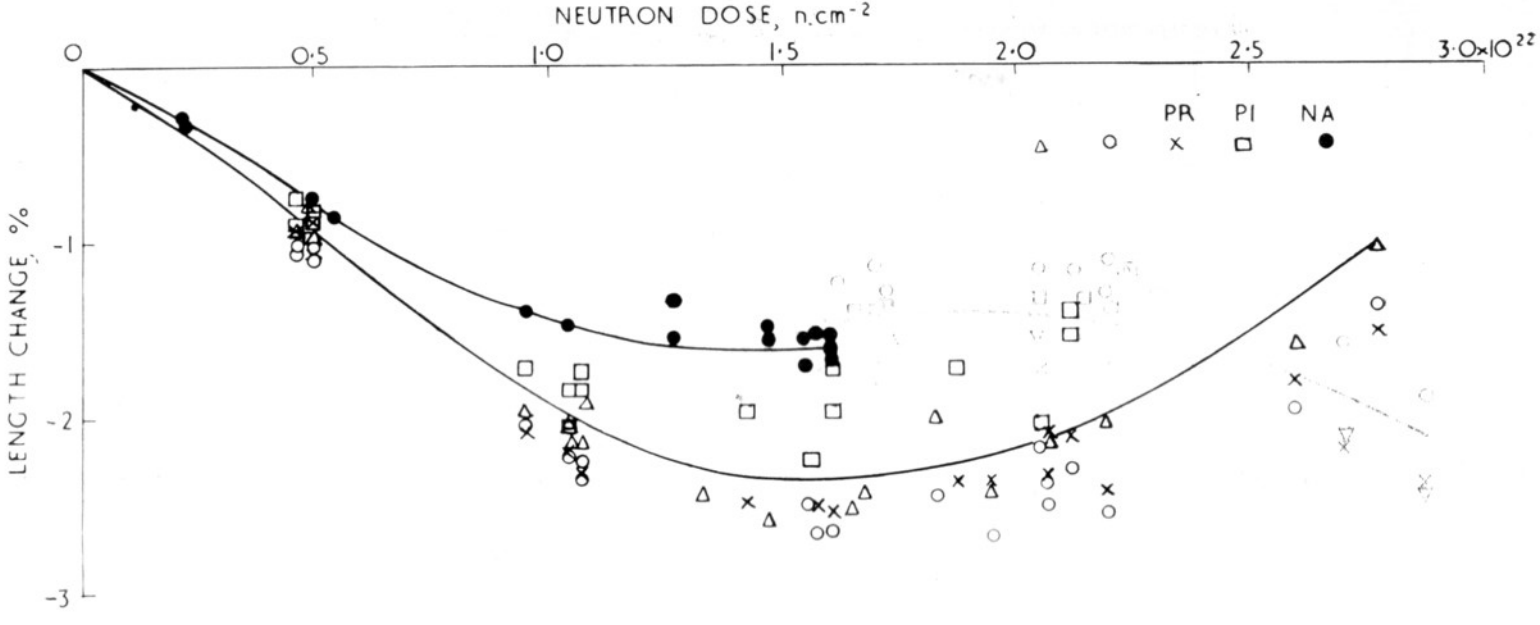

Fig. 1. *Dimensional changes of isotropic graphites, perpendicular to extrusion or parallel to moulding, at DFR temperatures in the range* 370 *to* 440°*C.*

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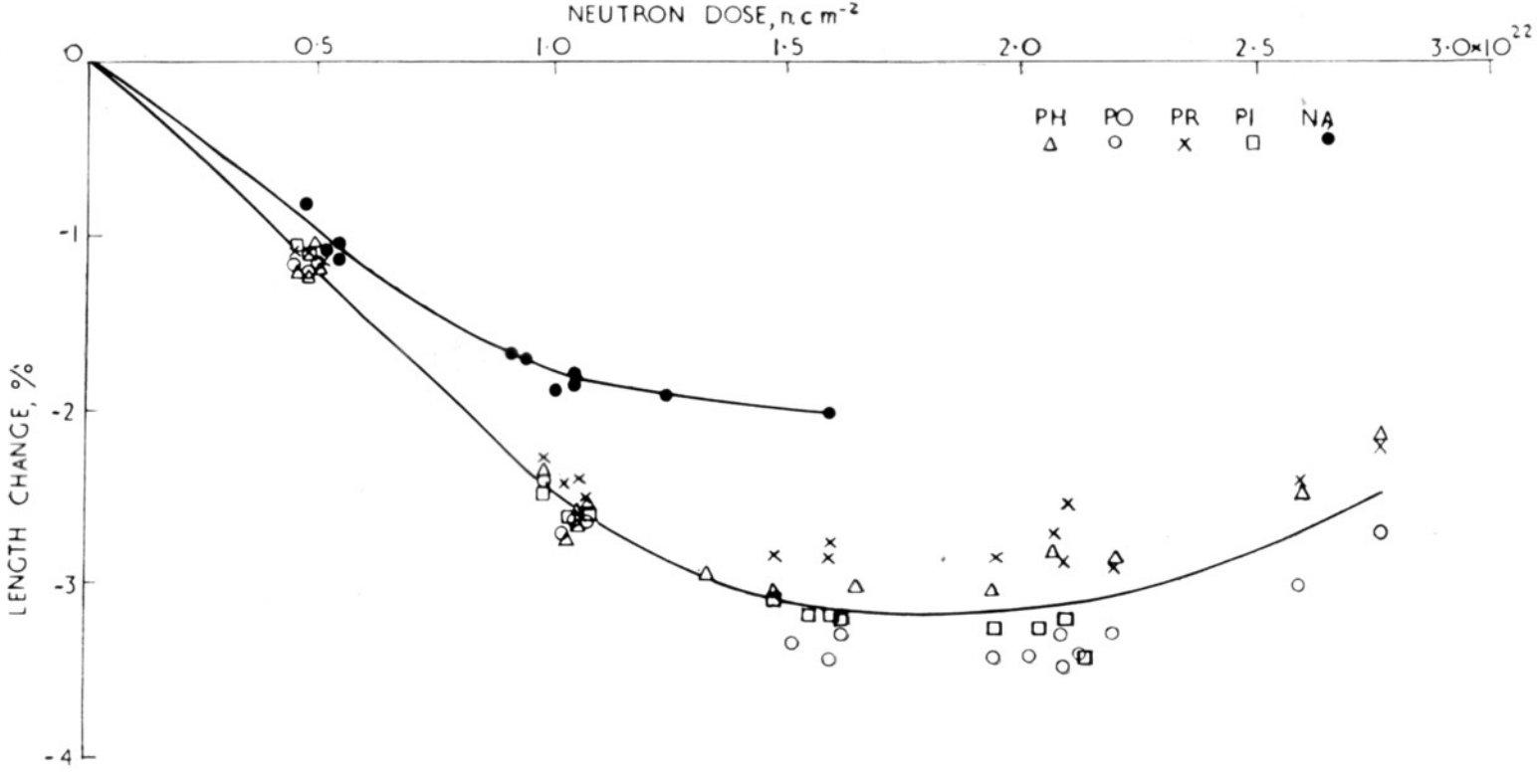

Fig. 2. *Dimensional changes of isotropic graphites, parallel to extrusion or perpendicular to moulding, at DFR temperatures in the range* 370 *to* 440°*C.*

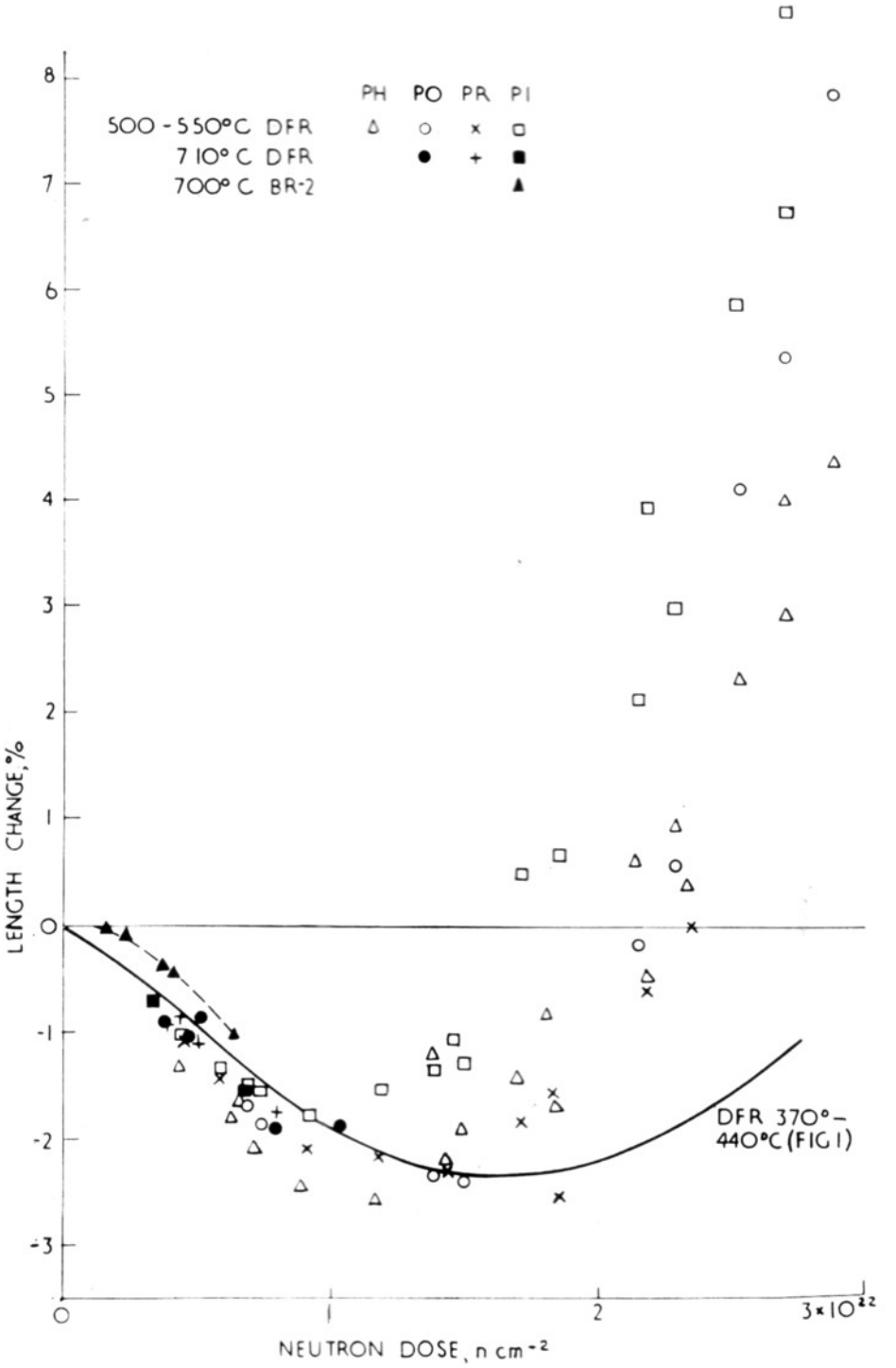

Fig. 3. *Dimensional changes of isotropic graphites, perpendicular to extrusion, at temperatures of* 500-550°*C and* 710°*C in DFR and* 700°*C in BR-2.*

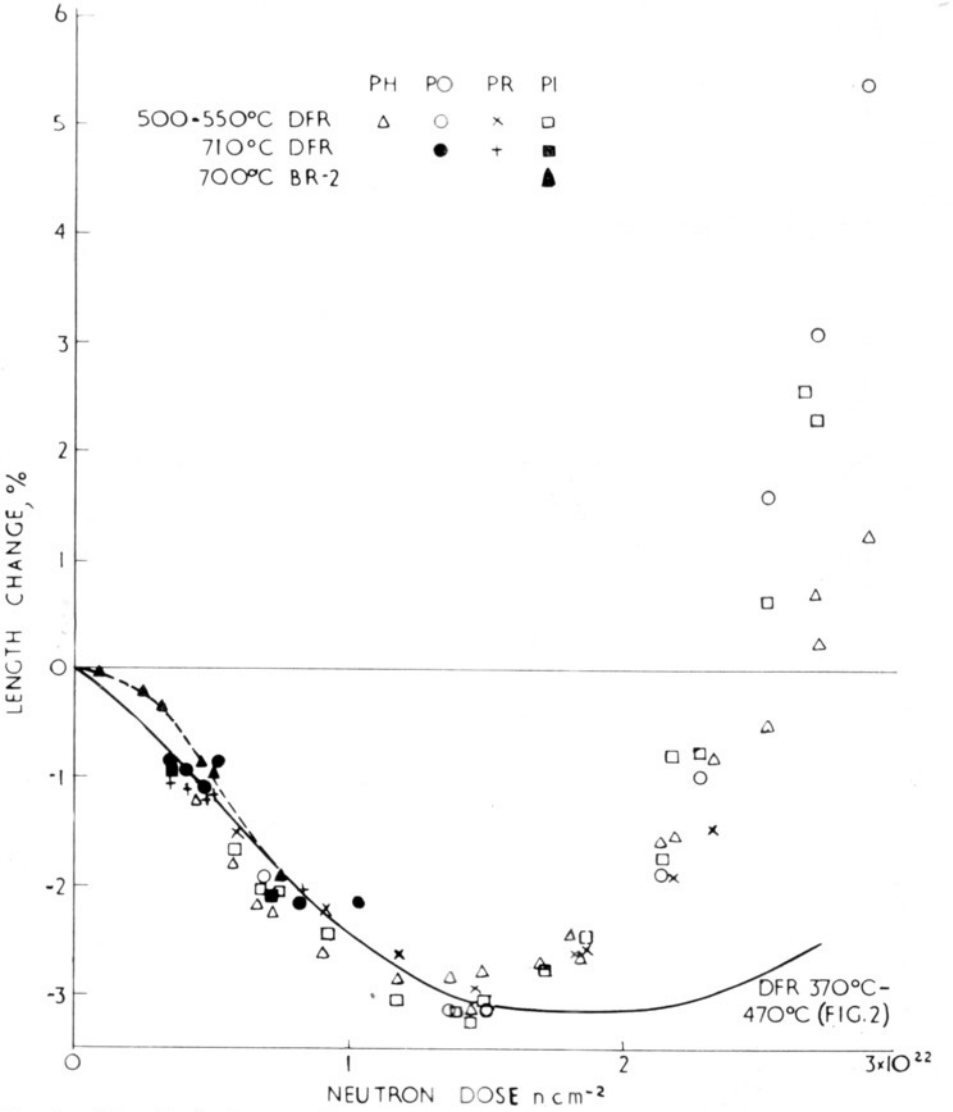

Fig. 4. *Dimensional changes of isotropic graphites, parallel to extrusion, at temperatures of 500-550°C. and 710°C in DFR and 700°C in BR-2.*

material has a lower shrinkage rate than the extruded materials.

At doses up to about 1.5×10^{22} n cm^{-2} little temperature dependence is observed in the dimensional change behaviour of graphites at DFR temperatures in the range 370 to 550°C. In addition the BR-2 data show that at doses up to 0.8×10^{22} n cm^{-2} there is little temperature dependence in the range 370-700°C in DFR because a BR-2 temperature of 700°C should be equivalent to a higher temperature in DFR when the dose rates are taken into account[12]. However, at doses higher than 1.5×10^{22} n cm^{-2} a marked temperature dependence is observed in the DFR data and, at temperatures in the range 500-550°C, a rapid growth rate is observed in all materials which have been investigated at high doses. At the same time, whereas all the extruded graphites had shown similar dimensional changes up to doses of about 1.5×10^{22} n cm^{-2}, at higher doses significant differences in the growth rates of different materials are observed in the temperature range 500-550°C. At lower temperatures (370-440°C) expansion rates at the high doses, although they are

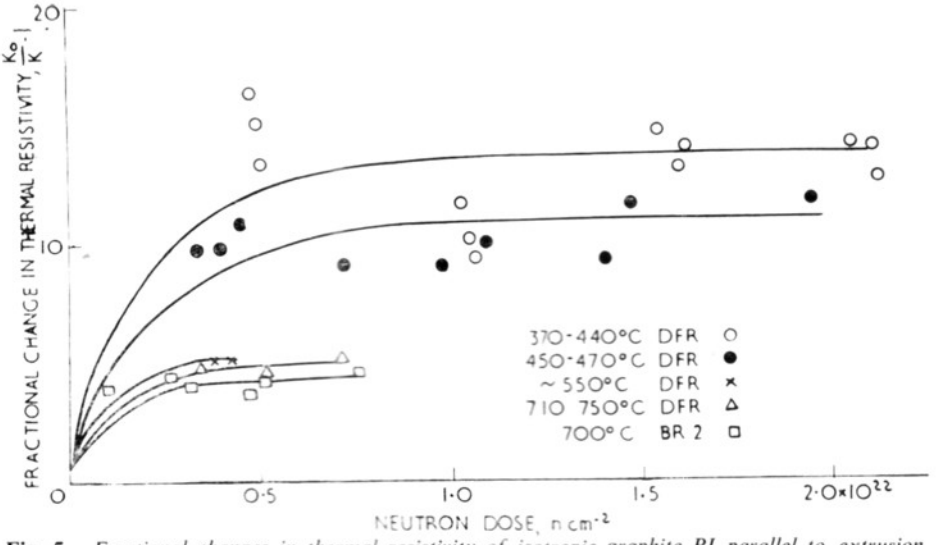

Fig. 5. *Fractional changes in thermal resistivity of isotropic graphite PI parallel to extrusion.*

significant, are much less marked than those observed in the higher temperature range and the differences in behaviour of the different graphites do not seem to be particularly important. The reason for the temperature dependence at high doses is not yet understood. It could result from a temperature dependence in crystal volume change rates with volume increases occurring at the higher temperatures due to vacancy clustering. Alternatively, it could be due to the development of additional porosity at high temperature although the mechanism for such an effect is not very clear at present.

Thermal expansion

It has been reported previously[2] that the thermal expansion coefficients of isotropic graphites increase up to a dose of about 0.5×10^{22} n cm^{-2} at 370-440°C in DFR and then decrease at higher doses. A continued decrease is observed to a dose of 2.1×10^{22} n cm^{-2}, when the thermal expansion coefficient is about 1×10^{-6} deg C^{-1} below its initial value. Measurements have also shown no significant effect of radiolytic corrosion on thermal expansion coefficient up to at least 20% weight loss.

Thermal conductivity and stored energy

Changes in the thermal conductivity of isotropic graphite, measured at 30°C, are shown in Fig. 5. Data are only given for graphite PI in the direction parallel to extrusion, because all five materials exhibited similar behaviour in both directions.

The data show that the thermal conductivity changes saturate at doses of about 0.5×10^{22} n cm^{-2}. Therefore changes in the properties of the crystals rather than structural changes dominate the thermal conductivity behaviour.

Thermal conduction in graphite is mainly due to propagation of phonons in the layer planes; in polycrystalline graphite, heat flows from one crystal to its neighbours and the conductivity is determined by the tortuosity of the heat path. Therefore, in-pile oxidation which would be expected to increase the tortuosity of the heat path should reduce the thermal conductivity. The magnitude of this effect is shown in Fig. 6, which shows the relationship between thermal conductivity at room temperature and radiolytic weight loss in carbon dioxide. Fig. 6 shows that the effect of in-pile oxidation on thermal conductivity, even after a weight loss of 15%, is small compared with that produced by fast neutron irradiation. In addition all the isotropic graphites exhibited the same relation between thermal conductivity and weight loss.

The combined effect of irradiation damage and in-pile oxidation can be determined in the following way. The irradiation-induced change in the thermal conductivity at 30°C is determined from Fig. 5. The corresponding value at the irradiation temperature can be determined from the known temperature dependence of thermal conductivity[19,4]. The factorial reduction in this value due to radiolytic oxidation is

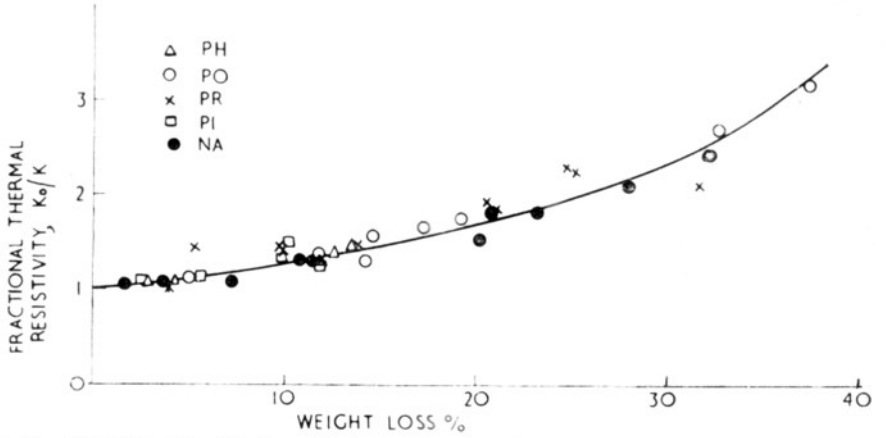

Fig. 6. *The effect of radiolytic oxidation on the thermal resistivity of isotropic graphites.*

then obtained from Fig. 6. This approach is justified because neutron irradiation, which has little effect on the tortuosity factor, determines the temperature dependence, whereas oxidation, which only alters the tortuosity factor, does not affect the temperature dependence of irradiated graphite because the latter is determined by the properties of the crystals.

Porosity generation due to crystal shape changes at high dose can increase the tortuosity factor, thus decreasing thermal conductivity. As yet there are insufficient data to determine if this effect will be significant at very high doses at the higher temperatures of Figs. 1-4 where the high growth rates suggest that porosity generation exists. Since porosity generation at doses less than 1.8×10^{22} n cm^{-2} in the DFR temperature range 370-550°C is small, this effect will be unimportant in Dungeness B type reactors.

Experiments have shown that the relationship between the accumulation of stored energy and the change in thermal conductivity observed at low irradiation temperatures[20] is still valid after 10^{22} n cm^{-2} in DFR at temperatures up to 425°C. Thus the accumulation of stored energy saturates at a low value and under Dungeness B conditions, the rate of release of stored energy with temperature, dE/dT, should not exceed 0.1 cal g^{-1} deg C^{-1}. This is a much lower value than that existing in the Calder Hall reactors[21].

Young's modulus and strength

Fast neutron irradiation increases Young's modulus by pinning dislocations with interstitial atoms and by closing microporosity with crystal strain[22,23]. Fig. 7 presents fractional changes in Young's modulus and tensile strength in samples of isotropic graphite irradiated in the range 350-440°C in DFR and includes modulus data from BR-2 irradiations at 700°C. The relative strength changes are obtained by diametral compressive tests on small graphite rings[24] and by tests on tensile specimens.

The results clearly show the steady increase in Young's modulus at high doses; this is believed to be due to closure of microporosity. Strength increases are less than the modulus changes and the results suggest, as first proposed by Losty[25], that the strain energy to fracture remains constant during the irradiation. A constant strain energy to fracture suggests that the elastic strain to failure decreases by the factor $\sqrt{E_0/E}$, and limited data support this deduction. Deterioration in strength and modulus at high doses due to porosity generation has not yet been observed.

Fig. 8 shows the results obtained from experiments in BR-2 and DIDO on the reduction in strength of isotropic graphites by weight loss due to radiolytic oxidation in carbon dioxide. The factorial reduction in modulus with weight loss is only marginally lower than that in strength, giving little effect of oxidation on breaking strain (about 20% reduction in failure strain at 35% weight loss). All the isotropic materials investigated exhibit a similar relation between relative strength and weight loss. Even at a weight loss of 30%, about 20% of the original strength is retained. It is interesting to note that the results show that the fast neutron effect

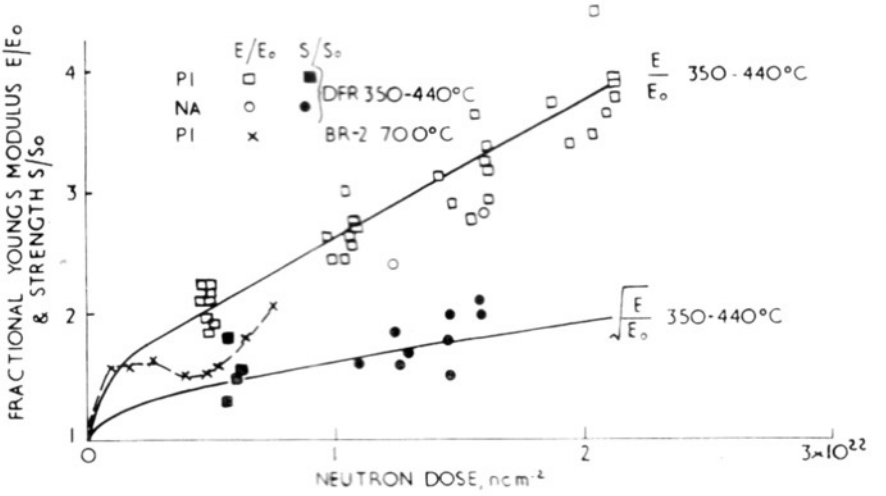

Fig. 7. *Fractional changes in dynamic Young's modulus E and tensile strength S of isotropic graphites at temperatures of 350-440°C in DFR and 700°C in BR-2.*

doubles the strength after a dose of about 2×10^{22} n cm^{-2}; therefore a graphite which has experienced such a dose will be as strong as unirradiated material even when the graphite has experienced as much as 13% weight loss in-pile in CO_2.

Internal stresses and irradiation creep

The dimensional changes in graphite are dependent on dose. Thus the flux gradients which exist in reactor bricks will result in differential strains and internal stresses in the bricks. It has been shown that in isotropic graphites, tensile creep strains of well over 1.0% can be obtained without fracture during irradiation[11]. In addition it has been shown[18] that the creep constant of these isotropic graphites, at temperatures between 300 and 650°C, is 0.20×10^{-6} per lb in^{-2} per 10^{20} n cm^{-2} and is the same in compression and tension in all directions. These data can be used with dimensional change data in the stress analysis of reactor bricks and such analysis shows that, in reactors of the Dungeness B type, the peak stresses generated by differential shrinkage

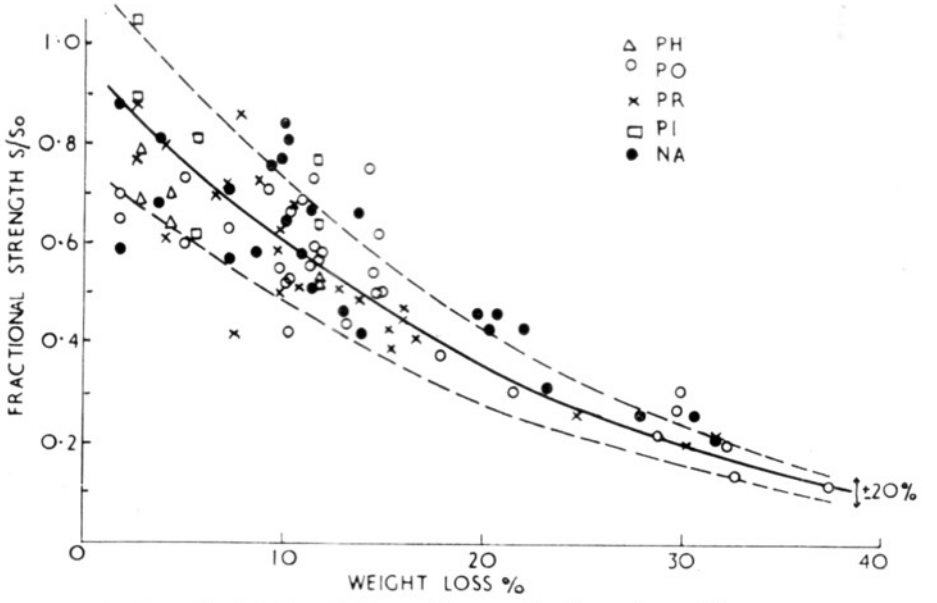

Fig. 8. *The effect of radiolytic oxidation on the strength of isotropic graphites.*

are only a small fraction of the breaking stress and that the required creep strain is well below the value that has been demonstrated. It has also been shown[17] that the creep rate per unit dose per unit of elastic strain is independent of graphite type; thus in-pile oxidation, which decreases Young's modulus, will lower the internal stresses but will not affect internal elastic strain significantly provided that the oxidation throughout the brick is reasonably uniform.

Most of the data on fast neutron damage described in this paper are obtained from experiments in DFR where the dose rate is about fifty times that in Dungeness B, twenty-five times that in DIDO and four times that in BR-2. Lattice parameter changes have been observed in instrumented and uninstrumented rigs in DFR and controlled temperature instrumented rigs in DIDO[26]. Comparison of these has enabled us to correct for the effect of dose rate. The lattice parameter changes show that in order to get equivalent damage as a function of DIDO equivalent dose in DFR and DIDO, DIDO temperatures are related to DFR temperatures by the curve given in Fig. 9. Since the dose rates in DIDO and Dungeness B type reactors are similar no significant correction is required in relating DIDO temperatures to Dungeness B conditions.

Summary and conclusions

It has been shown that isotropic graphite in Dungeness B type reactors will exhibit linear shrinkages of less than 3.5% in any direction and that moulded material appears to be more dimensionally stable

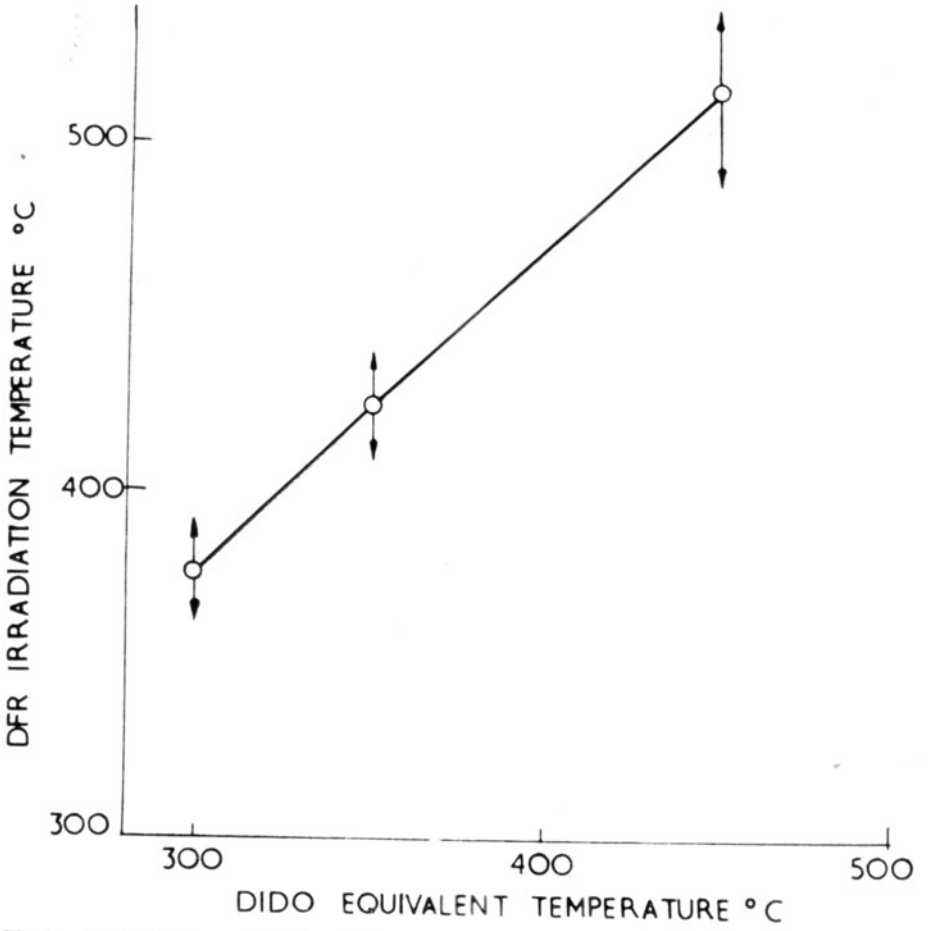

Fig. 9. *Relation between DFR irradiation temperatures and* DIDO *equivalent temperatures obtained from measurement of lattice parameter changes.*

than extruded material. The character of the shrinkage is such that no serious design difficulties arise in its accommodation. Internal stresses in the bricks will be very small because an efficient irradiation creep process is operative. Thermal conductivity changes due to fast neutrons saturate at modest doses and the effect of radiolytic oxidation can be determined reliably; the changes in thermal conductivity will not lead to excessive temperature gradients in the AGR graphite. Moderator strength at the end of life will be greater than the original value if radiolytic weight loss is less than 13%.

Acknowledgment

The work has been supported by co-operation between various members of the Metallurgy and Research Reactors Divisions Harwell, the R.M.L., Culcheth, the D.E.R.E., and the C.E.N. at Mol, Belgium. The authors are particularly indebted to their colleagues at R.M.L. Culcheth, and Metallurgy Division, Harwell, who undertook the detailed measurements described in this paper.

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A.E.A. Reports available

THE titles below are a selection from the November, 1968, "U.K.A.E.A. list of publications available to the public". This list is obtainable free from the Librarian, A.E.R.E., Harwell, Didcot, Berkshire. It includes titles, of all reports on sale, translations into English, books, periodical articles, patent specifications and reports which have appeared in the published literature. It also lists the Depository Libraries in the U.K. and the countries with official atomic energy projects which receive copies of U.K.A.E.A. unclassified reports.

AEEW-M 801
The Measurement of Personnel Neutron Dose in the Energy Region 0.15eV to 10 MeV with Thermoluminescent Lithium Fluoride. By H. E. Preston. August, 1968. 9 pp. H.M.S.O. 2s. 6d.

AEEW-M 825
GMS 3. A Users Manual for an Improved Generalised Multigroup Scheme Using W.D.S.N. Mk.2 for the KDF9 Computer. By M. R. Barnett and J. A. Ward. August, 1968. 34 pp. H.M.S.O. 5s.

AEEW-R 243
MOCUP. A Monte Carlo Programme for Estimating Resonance Escape in Complex Geometries. By G. W. Bannister, J. C. Basher and I. C. Pull. August, 1968. 65 pp. H.M.S.O. 9s.

AEEW-R 603
Further Optimization Studies of Experimental Dynamic Responses Measured on the HTGC Dragon Reactor. By J. D. Cummins. April, 1968. 17 pp. H.M.S.O. 8s.

AERE-M 2072
Improvements to Liquid-Nitrogen Lines of the Dido Liquid-Nitrogen Loop. (Job No. 90593). by V. L. Fontaine. May, 1968. 17 pp. H.M.S.O. 3s.

AERE-R 5766
Blood Counts on Radiation, Non-Radiation and New-Entry Employees, Research Establishment, U.K.A.E.A., Harwell. By C. Sanders, R. G. Orr and R. J. Evans. August, 1968. 6 pp. H.M.S.O. 3s. 6d.

AERE-R 5815
An Advanced Modular System of Electronic Equipment for On-line Computer Applications. By H. Bisby. August, 1968. 17 pp. H.M.S.O. 4s. 6d.

AERE-R 5818
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A Small Computer Used as a Multi-channel Analyser. By A. Lewis. July, 1968. 10 pp. H.M.S.O. 2s. 6d.

AERE-R 5867
Studies of the Liquid State Using the Inelastic Scattering of Slow Neutrons. By S. J. Cocking. August, 1968. 126 pp. H.M.S.O. 19s.

AERE-R 5870
The Use of Thick Steel Wrapper Plates for Large Lead Filled Flasks, which could Obviate the Need for Special Thermal Shields. By F. E. Dixon and A. J. Brook. September, 1968. 21 pp. H.M.S.O. 9s.

AERE-R 5871
A New Standard Series of Packaging for Loads up to 40,000 Curies of Cobalt-60 or Equivalent. By F. E. Dixon and L. R. Cohen. August, 1968. 12 pp. H.M.S.O. 3s.

AERE-R 5878
The Determination of Oxygen in Silicon Nitride by Inert Gas Fusion. By I. M. Griffin and A. P. Mead. August, 1968. 8 pp. H.M.S.O. 2s. 6d.

AERE-R 5896
An Evaluation of Time of Flight and Conventional Diffraction Techniques at Harwell. By D. H. Day and R. N. Sinclair. September, 1968. 14 pp. H.M.S.O. 2s. 6d.

AERE-R 5897
A Position Sensing Detector Array for a Charged Particle Magnetic Spectrograph. By D. L. Allan, G. V. Ansell and R. K. Jolly. September, 1968. 10 pp. H.M.S.O. 3s.

AWRE O-33/68
Compton Cross Section. By A. Warham. July, 1968. 28 pp. H.M.S.O. 4s.

AWRE 0-41/68
Map, Time Series and Other Plotting Routines for Use With the Stromberg-Carlson 4020 Plotter. By J. B. Young and A. Douglas. July, 1968. 76 pp. H.M.S.O. 11s.

AWRE O-42/68
The Effects of Sampling and Sample Pretreatment on the Determination of Carbon in Uranium Metal. By K. Aldersley, F. H. Cripps and A. E. Sawyer. July, 1968. 21 pp. H.M.S.O. 4s.

AWRE O-48/68
Spline. A Fortran Computer Program for the Evaluation of Sets of Experimental Data Using Cubic Spline Curve Fitting and a Statistical Theory of Unknown Systematic Errors. By A. Horsley and J. A. Price. September, 1968. 63 pp. H.M.S.O. 9s.

AWRE O-52/68
Electron Metallography of Uranium and Some Uranium Alloys. By I. T. Porter and J. C. Ruckman. September, 1968. 19 pp. H.M.S.O. 4s. 6d.

U.K.A.E.A. SCIENTIFIC AND TECHNICAL NEWS SERVICE

HTGCRs for urban siting

The high temperature gas-cooled reactor, one of the possible successors to the AGR, could be developed for urban siting.

Concluding a paper at a Symposium on Advanced and High Temperature Gas-cooled Reactors at Jülich, Germany (from 21st-25th October), Mr. F. R. Farmer, Head of Safeguards Division, U.K.A.E.A., stressed that safety standards could be ensured provided existing engineering techniques were developed and vigorously applied.

Earlier he had outlined the areas of development needed to achieve the satisfactory safety standards:

Methods for detecting marked aberration in fuel behaviour, for good management as well as safety.

Chemical compatibility of fuel, core and coolant.

Emergency cooling—coated particle fuels appear to tolerate high temperatures and thermal stresses and offer scope for core designs which can accept loss of cooling for some time after the reactor is shut down, but this requires confirmation for any particular design.

The effect of temperature on reactivity, which varies widely with the type of fuel cycle employed.

There may be a demand for still higher coolant gas pressures, which would require thicker concrete pressure vessels.

Achieving the standards required for siting in populous areas may take years of further development, and in his final paragraph Mr. Farmer stated,

"There will undoubtedly be a continuing conflict between the demands imposed by economy and those imposed by safety. Some of the improvements and investigations will cost money; they may not be pursued energetically unless the requirements of safety are fully accepted, not solely as a penalty on HTGC reactors but on all systems."

22nd October, 1968

Calibration service

The British Calibration Service (B.C.S.) has authorised the instrument test laboratories at Harwell to issue B.C.S. certificates for electrical instruments used in d.c. and low frequency a.c. measurements.

The laboratories are now part of a national network sponsored by the Ministry of Technology to provide this service to industry.

The instrument test laboratories are in the Instrument Services Section of Harwell's Engineering Support Division. They were established in 1951 to determine uncertainties in the Section's test equipment and to carry out quality control over instrument work performed by the Section for scientific divisions engaged on research work associated with the U.K. atomic energy programme.

This service is now available to other organisations requiring the certification of accuracy of instruments used to measure d.c. resistance, voltage and current, inductance, capacitance, a.c. voltage (r.m.s.) and frequency. The values of Weston type standard and reference cells, certain values of "S" class resistors and Grade I resistors of moderate dimensions can be determined with an uncertainty of 0.001% over the temperature range 15°C to 25°C.

The calibration service does not include repairs or adjustments outside the requirements of the setting up procedure.

Further information on charges and the measurement capability over the various ranges and of the services available, is obtainable on application to U.K.A.E.A. Instrument Test Laboratories, Building 388.1, A.E.R.E., Harwell, Didcot, Berks. Telephone No. Abingdon 4141, Ext. 4819 or 4535.

23rd October, 1968

Earthquake-proof A.G.R.s

Earthquake-proof A.G.R.s have been studied by the U.K.A.E.A.

They were described this week in a paper presented to a Symposium on Advanced and High Temperature Gas-cooled Reactors at Jülich, Germany, organised by the I.A.E.A. from 21st-25th October. The authors were Mr. K. H. Dent and Mr. I. Davidson, of the U.K.A.E.A.'s Reactor Group.

The studies presented in the paper are based on a 500 MW(e) plant, designed to withstand vibratory motions and differential movements of the ground.

Two types of sites were considered in the paper, one in which the seismic activity was unlikely to be exceeded anywhere in Europe, and one which was unlikely to be exceeded anywhere in the world.

For the European site, all major features of the ordinary A.G.R. design are perfectly satisfactory, and only minor modifications to details are required.

On the site of extreme seismic activity, the 27,000 ton concrete pressure vessel has favourable characteristics, in that it minimises the accelerations transmitted to the 4,600 tons of equipment which it contains and also provides it with lateral support. The stresses produced in the vessel are insignificant. Stability is ensured by tying the vessel down with rock anchors, and tying the internals too.

The integrity and alignment of control rod holes is assured under maximum potential earthquake conditions, but a separate secondary shutdown system can be supplied, possibly using boron steel balls which would be released electromagnetically to fall by gravity through semiflexible tubes into the core.

The fuel can be cooled under all conceivable fault conditions and complete fuel elements have been tested mechanically. These tests included impact loadings equivalent to horizontal decelerations of 100g.

The authors concluded that the A.G.R. can be made satisfactory for any seismic site likely to be needed: indeed its characteristics make it particularly suitable for earthquake countries. *24th October, 1968*

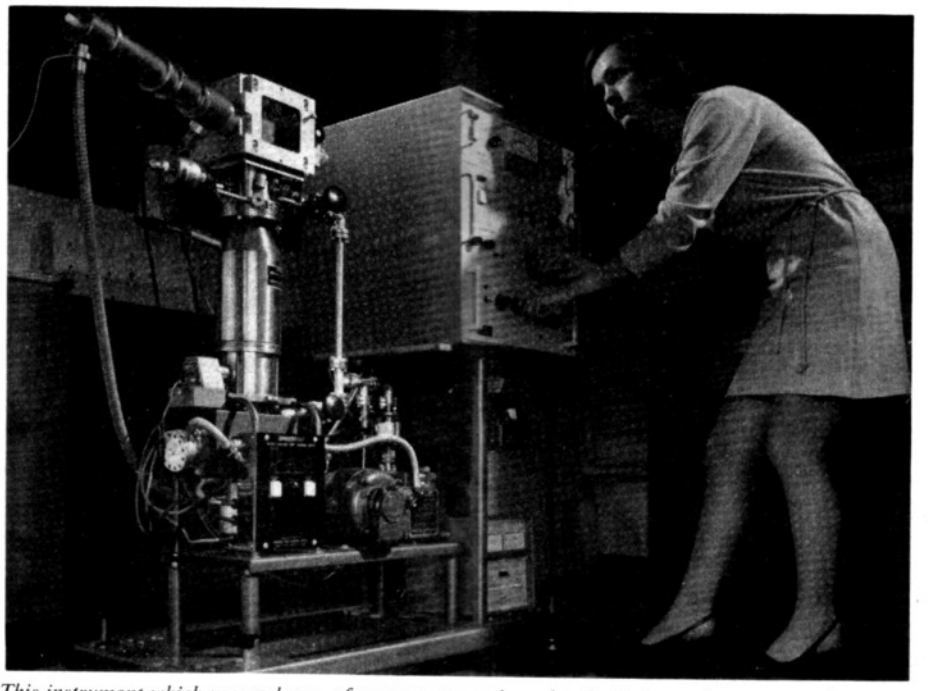
Proton microscope

A British instrument which speeds up and simplifies the study of single crystals and crystalline films is being introduced to America.

Called the Proton Scattering Microscope, it was shown by Edwards High Vacuum International Ltd., at the American Vacuum Society Convention, 29th October to 1st November, the Hilton Hotel, Pittsburgh, Pennsylvania, and on the U.K.A.E.A. stand at Atomfair, 11th-14th November, at the Sheraton Park Hotel, Washington, D.C.

It can be used to:

- Orientate single crystals to about 1° accuracy.
- Observe the structures and orientation of large grain (about 0.5 mm) polycrystalline materials.
- Examine the structure and orientation of thin crystalline films (perhaps only a few tens of atom layers thick).



This instrument which uses a beam of protons to produce detailed information on crystal structure has been developed at Harwell. It works by scattering a beam of protons from a specimen of material to produce a magnified image on a fluorescent glass screen.

Study single crystal structures including crystal perfection and the effects of surface treatment (e.g. polishing methods) on crystal perfection.

Study changes in crystal structure during phase changes.

The advantages of the method are:

The instrument is simple to operate and requires no specially trained staff.

Results are obtained rapidly (a pattern can be obtained in about 5 minutes from first placing specimen inside vacuum chamber).

Interpretation of patterns is very simple.

Vacuum requirements are not rigid—results can be obtained at pressures as high as 10^{-4} torr or greater.

It is not necessary to remove a thin film specimen from its substrate.

The instrument works by scattering a beam of protons from a specimen of material to produce a magnified image on a fluorescent glass screen. When the protons strike the specimen, those travelling close to the densely packed rows or planes of atoms have their trajectories blocked so that a reduction of intensity occurs in the directions of the rows or planes. The image on the fluorescent glass screen corresponds to the crystal lattice structure and its orientation.

The technique is complementary to electron and X-ray diffraction for the study of crystal structures.

The proton scattering microscope was developed at Harwell and is being further developed and manufactured under licence by Edwards High Vacuum International Ltd., Manor Royal, Crawley, Sussex.

29th October, 1968

Atomfair 1968

The United Kingdom Atomic Energy Authority had an exhibition of 1,900 sq. ft. at ATOMFAIR 1968. This Fair was associated with a concurrent international conference on the constructive uses of atomic energy, which was co-sponsored by the American Nuclear Society and the American Atomic Industrial Forum and at which several senior scientists from the U.K.A.E.A. gave papers. The exhibition was held at the Sheraton Park Hotel in Washington, D.C., from 10th-14th November inclusive, and the A.E.A.'s stand was adjacent to the British Nuclear Forum's display.

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Great Britain—an alternative economical source of enriched uranium fuel
Dr. N. L. Franklin to the Swiss Association for Nuclear Energy, in Zurich.

Radioisotopes in food processing—Part 1 Radioisotope instruments
By R. M. Longstaff.

February

The design of the Steam Generating Heavy Water Reactor
H. Cartwright to the I.A.E.A. Symposium on Heavy Water Power Reactors in Vienna.

Radioisotopes in food processing—Part 2 Analytical and tracer techniques
By R. M. Longstaff.

March

Power to fulfil
Article by Lord Penney, originally published by the Indian Council of Scientific and Industrial Research.

Isotopic thermoelectric generators
Colloquium at the Washington Hotel, London.

April

Winfrith S.G.H.W.R. opening ceremony.

Fast reactor development in the United Kingdom
Dr. Hans Kronberger, F.R.S., Scientist-in-Chief, U.K.A.E.A., to the Institute of Atomic Studies, Bucharest.

May

Nuclear fuel cycle services in the United Kingdom
Dr. N. L. Franklin to the Japan Atomic Industrial Forum, Tokyo.

Depleted uranium in industry
By K. G. Seedhouse.

June

Economics of plutonium utilisation in an integrated system of thermal and fast reactors
C. E. Iliffe to an I.A.E.A. symposium on the economics of nuclear fuels in Prague, Czechoslovakia.

July

Nuclear power conference in Copenhagen

Commissioning and operating experience with the Winfrith S.G.H.W.R.
D. Smith, D. English and J. McCrickard to the B.N.E.S. Conference on Steam Generating and other Heavy Water Reactors at the Institution of Civil Engineers, London.

August

Press visit Harwell

Integrated gas turbine plants using Co_2-cooled reactors
Dr. H. Kronberger, E. Maillet and G. Coast to an E.N.E.A. Symposium on the Technology of Integrated Primary Circuits for Power, in Paris.

September

Prospects for nuclear energy in Western Europe: illustrative power reactor programmes
Some comments by P. J. Searby.

October

Biomedical technology
By F. E. Whiteway.

Carbon fibres
By Dr. J. B. Morris.

An 'S' curve to forecast electricity demand
By L. G. Brookes.

November

Fourteenth Annual Report and Press Conference

A broader approach to benefits from nuclear power and associated social and other costs
By M. Phillips.

December

Radioisotopes and the engineering designer
By R. M. Longstaff

Irradiation experience with isotropic graphite
P. T. Nettley, J. E. Brocklehurst and W. H. Martin to an I.A.E.A. Symposium on Advanced and High Temperature Gas-cooled Reactors, in Jülich, Germany.