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MONTHLY INEORMATION BULLETIN OF

THE UNITED KINGDOM ATOMIC ENERGY AUTHORITY

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MONTHLY INFORMATION BULLETIN
OF THE UNITED KINGDOM
ATOMIC ENERGY AUTHORITY

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Contents

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New Year Honours 1973

The Authority are happy to record that Her Majesty the Queen has been pleased to award New Year Honours to the following:

C.B.E.
Dr. W. Marshall, F.R.S., Member and Director of Research Group, Harwell.

B.E.M.
E. R. Staniland, Non-Technical Class Grade IV, Technical Services, Process Technology Division, Research Group, Harwell.

O.B.E.
Mr. M. T. Kavanagh, Deputy Director (Sales), British Nuclear Fuels Ltd., Risley.

U.K.A.E.A. PRESS RELEASE

Extension of DRAGON Reactor project

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.

The O.E.C.D.'s DRAGON High Temperature Reactor Project at Winfrith, Dorset, is to continue for a further period of three years from 1st April, 1973 to 31st March, 1976. This has been announced following a meeting in Paris of the Board of Management of the Project at which the Prolongation Agreement was signed by representatives of the United Kingdom, the European Communities (for EURATOM), Austria, Sweden and Switzerland. The Agreement increases the overall budget of the Project by £9.4 million to some £47 million.

Although the new Agreement will take effect after the entry of the United Kingdom into the European Communities on 1st January, 1973, a separate U.K.A.E.A. contribution will continue as in previous years, the contributions of the various Signatories being as follows:

	£
U.K.A.E.A.	4,066,500
Austria	174,000
EURATOM	4,427,500
AB Atomenergi, Sweden	419,000
Switzerland	313,000
	£9,400,000

The position of the Norwegian Institute for Atomenergi, which has been a participant in the DRAGON Project since its initiation, is still under consideration.

The new three-year programme will include continued development of the special coated-particle fuel, and fuel elements which are major features of the DRAGON Reactor concept, together with evaluation of the behaviour in service of fuel elements, core and primary materials and other components. Emphasis will be given in this work to industrially-produced items specially developed for high-temperature power reactors.

The operational characteristics of such reactors, including safety aspects, will also continue to be investigated on the basis of experience obtained with the DRAGON Reactor Experiment and other installations available to the Project. In addition, the new Agreement provides for the Project to continue its consultancy and other technical services, on terms agreed by the Board of Management, to organisations promoting high-temperature reactors. Finally, the new programme will give attention to possible uses of high-temperature reactors for the production of industrial process heat.

The new Agreement includes a provision that the Signatories shall consult together regarding a further possible extension beyond 31st March, 1976, and that this shall be determined not later than 30th June, 1975.

Background note

The DRAGON Project was set up in April 1959 under an Agreement concluded between the U.K. Atomic Energy Authority, the Austrian and Swiss Governments, the National Atomic Energy Authorities of Denmark, Norway and Sweden, and the former EURATOM Commission*. Originally for five years, this Agreement was extended in 1962 to eight years with an increase in the overall budget from £13.6 million to £25 million. In 1966, 1968 and 1969 further extensions were agreed, bringing the total overall budget up to £37.935 million for the period to 31st March, 1973.

12th December, 1972

Note: The thirteenth annual report of the DRAGON Project covering the period from April 1971 to March 1972 was issued in December.

* Representing Belgium, France, Germany, Italy, Luxembourg and the Netherlands.

Future prospects for energy supply and demand

In November, members of the Reactor Group Board of Management and guests from the Generating Boards, Department of Trade and Industry and the Design and Construction companies heard a presentation on future prospects for energy supply and demand from the New Systems Forum of the U.K.A.E.A. The Forum has been considering the prospects for long-term alternative nuclear power systems with a view to advising on the most appropriate reactor research and development programmes in the U.K.

Forward forecasts point to the conclusion that between 1985 and 1995 nuclear energy will cease to be simply an option to fossil fuels and will become essential to maintaining world energy supplies at a sufficiently high level to meet even the most modest rates of economic growth. This conclusion arises from analyses and projections of the relationship between energy consumption and economic growth; and the likely changing pattern of fossil fuel supply, demand and price.

If fast breeder reactors, and subsequently fusion reactors, prove commercially successful, nuclear fuel supplies at acceptable prices seem adequate for many centuries, and in the long-term the world should be able to adjust to meeting a high proportion of its total energy demand from nuclear sources. But in the medium term there is danger that nuclear energy may not be introduced fast enough, or industry converted to new patterns of energy consumption quickly enough, to prevent serious rises in fossil fuel prices.

Consequent electricity price increases may damp down the demand for electricity, along with other forms of energy and, paradoxically, reduce nuclear's prospects by reducing the demand for power stations of all types. A nuclear installation rate high enough to keep electricity prices stable in the face of rapidly rising fossil fuel prices therefore becomes a necessity.

In their early years of operation, conventional and nuclear power stations commissioned around 1976 are expected to have roughly equal generating costs, in the region of 0.5 p/kWh under base load generating conditions. Fossil fuel prices—e.g. fuel oil, may well rise in real terms in future years whilst nuclear fuel prices should fall as existing fuel plants reach their design outputs and larger, more efficient, new fuel plants are built.

For later power stations the specific capital costs of the thermal reactor power stations are expected to approach more closely those of conventional power stations as nuclear design and construction experience accumulates and as individual nuclear station outputs approach the outputs of conventional power stations. Combining possible new capital costs and the fuel cost changes mentioned above means that by 1990 the generating cost of an A.G.R. power station would be only two thirds that of an oil-fired power station.

The increase in maximum demand for electricity in Britain has been falling steadily during the last decade from around 10 per cent to the present 2 per cent per annum. New generating plant has, however, been installed such that the output capacity has grown at a steady rate of about 7 per cent per annum.

This has resulted in a larger plant margin than is normally planned, i.e. 34 per cent instead of, say 20 per cent. The argument for continuing high plant margins rests on the poor availability which has so far been obtained with new large turbine-generator units.

The anticipated present power station commissioning programme 1975 to 1980 is about 12,000 MW. If the growth rate for electricity demand was to stay as low as 2 per cent per annum the result would be an even greater plant margin, so there is apparently little immediate incentive for the electricity generating boards to order additional new capacity.

New plant will therefore be ordered in the immediate future as a result of the need to meet special situations rather than load growth. Increasingly substantial nuclear orders will, however, be needed from about 1975 onwards if the requirement for new capacity in the decade 1980-90 is to be met economically.

A commercial fast breeder power station programme commencing with a lead station coming on line in 1981 and further stations in the mid 1980s appears to be a reasonable assumption on the basis that P.F.R. know-how and experience will be adequate for a first order to be placed for around 1976.

The commissioning of new capacity at the beginning of that decade should be at around 5,000 MW per annum of which 2,500 MW per annum could be nuclear thermal reactors and the introductory fast reactor, whereas at the end of the decade 6,000 to 7,000 MW per annum of new capacity will have to be commissioned, within which 5,000 MW could be nuclear—mainly fast reactors, with generation costs below even those of A.G.R. and half those of oil-fired stations.

A point to recognise is that between 1980 and 1990 the thermal reactor programme is limited to at most 2,000 MW per annum, which will be an important determining factor when considering the place of the designs other than A.G.R. which might be included.

The continuing requirement for fossil-fuel stations to supply low-merit short duration needs leads to a capacity at the end of the century more than double that at present. This capacity will consume about the same amount of fossil fuel as now, but less of it as coal and more as oil.

The nuclear capacity to supply cheap base load must, however, increase 10 to 15 fold between now and the end of the century—a quite formidable objective in view of the present slow rate of progress.

Siting of approaching 200,000 MW of generating plant by the year 2000 will present some severe problems, probably leading to a few large power/generating centres of, say 20,000 MW located around the coasts to obtain adequate condenser cooling water.

Consideration is already being given to this and to the most appropriate end-of-century reactor unit and turbine generator sizes. It appears that a reactor size of 4,000 MW or so could be acceptable, 10 per cent of the minimum summer night load. The 400 kV electricity grid transmission system would probably suffice, although eventually a higher grid voltage may be required, or alternatively the network would need to be sectionalised with limited inter-connectors.

Looking beyond the end of the century, oil is likely to become increasingly scarce and costly. There is however a prospect that a new nuclear system such as fusion will give costs lower than might be achieved with fast reactors. By that time the costs incurred for electricity generation will be those of established nuclear power and so a measure of our success will be the extent to which energy, including electricity, has become plentiful and cheap.

If the near future mix of power station types is allowed to continue with a high non-nuclear content, the burden will be so much the heavier with serious implications for our balance of payments and rate of economic growth in the event that fossil fuel prices rise steeply as scarcity develops.

If nuclear power is to fill the energy gap and be economically effective it must be installed to supply a substantial part of our national needs before fossil fuel prices start to rise, as otherwise demand for energy will be inhibited and the country's economic growth regressively reduced.

Quality technology

In November the Harwell Nondestructive Testing Centre announced the introduction of its QUALTIS service. Apart from many other benefits, subscribers to the service receive copies of a Year Book, "Quality Technology". The aim of this Year Book—and the wider objectives of QUALTIS—are summarised in the following extract from the introduction to this new publication:

Quality '73 is the first of a planned series of Year Books designed to provide a handy directory for those with a responsibility for the maintenance of product quality in industry. It is also intended as a reference source of background data for those more intimately involved in designing and applying inspection and testing procedures to monitor quality in a manufacturing process.

The idea for the Year Book arose from the widespread use that is made of the unique information store built up by the Harwell Nondestructive Testing Centre over the past six years. This store now contains well over 10,000 items of technical information carefully classified by content for ready access in order to satisfy industrial enquirers. It is from this working experience of dealing with practical problems that the scope and content of the Year Book has naturally developed.

Because of the nature of the prime source of data, the contents of Quality '73 might be criticised for being heavily biased towards nondestructive testing. This, however, is perhaps not inappropriate since nondestructive testing techniques can be regarded as forming one of the fundamental frameworks around which the wider concept of Quality Technology or Materials Evaluation is built. However, to have called it NDT '73 would have tended to focus attention on the methods that one uses rather than on the objectives of the tests; the economic importance of achieving product quality and reliability might then have been inadequately emphasised.

In future editions of the Year Book, it is intended, not only to maintain a constant up-dating of the directory entries, but to broaden the coverage into other allied areas of Quality Technology, beyond the rather narrowly interpreted limits of conventional nondestructive testing.

In the directory sections emphasis in this first edition is centred on British organisations and contacts and those overseas companies with agencies or branches in the U.K. It is realised, however, that the wider coverage of overseas interests planned for future editions will increase its value to those in this country manufacturing for export or wishing to extend their technical contacts overseas.

The technical data section of the Year Book is a feature which is intended to include published and unpublished material which individuals have assembled or collected over the years and found useful for day-to-day reference or guidance. Here, again, it is hoped to be able to expand this section.

The Year Book, itself a valuable source of information in its own right, also forms an integral part of the wider QUALTIS service offered to industry by the Harwell Nondestructive Testing Centre. Subscribing members of QUALTIS (Quality Technology Information Service) not only receive regular pre-publication issues of the Year Book, but also have direct access to the whole of the NDT information store at Harwell and a personal advisory service to help find solutions to their specific materials testing problems.

Further information about this new Harwell service can be obtained from: QUALTIS Manager, The Nondestructive Testing Centre, Atomic Energy Research Establishment, Harwell, Didcot, Berks. OX11 0RA. Tel: Abingdon 4141, ext. 2470.

The changing role of Harwell

The following article, by R. M. Longstaff (Group Marketing Unit, Harwell), was published in the December issue of Scientific Era *and is reproduced by courtesy of the Editor.*

Any organisation that is to survive through changing times must itself accept and undergo change. This applies particularly to those organisations that have been specifically created to foster change—the research organisations. For by its very nature research, like exploration, tends to be self-frustrating—the more it succeeds in its aim the nearer it comes to bringing about its own termination. Nor is it in the nature of a research organisation to hold back on its own productivity in order not to glut the market or exhaust the demand for its services. Therefore, to survive it must look for fresh fields in which to do its research, or fresh ways of exploiting the results of what it has already done. The latter can at best be a temporary expedient.

Harwell is no exception to this broad generalisation: it is indeed a classic example. For Harwell, or more correctly, the Atomic Energy Research Establishment situated outside the Berkshire village of that name, was founded in 1946 to carry out research into all aspects of atomic energy and to furnish the scientific and technical information needed to exploit it. For much of this time Harwell has been concerned mainly with the science and technology of reactor materials (rather than reactor systems as such), and has employed the skills predominantly of chemists, physicists and metallurgists. Now, after twenty five years of research and development and industrial exploitation, the cheapest electricity to be produced by any power station in the C.E.G.B. network comes from a nuclear station, and Britain has produced far more nuclear power than any other country in the world (indeed until recently, more than all the rest of the world put together). Britain exports nuclear fuel (though not nuclear power stations) to many countries, and reprocesses fuel from many more. Our exports of radioactive materials—by-products of nuclear reactors and related operations—are the world's greatest.

So one might be tempted to think that Harwell's work on materials should be near to completion except for dotting the i's and crossing the t's of the present reactor systems, and completing the work on those advanced concepts such as the high temperature and fast breeder reactors that have not yet come to full fruition, but which promise even greater economies for the future. But this would be to under-rate gravely the determination of Harwell's scientists to continue to be at grips with new and exciting problems, and the collective vitality of the laboratory itself with its will to survive into the new era which it has helped to create.

From early days Harwell was already working closely with many industries unconnected with atomic energy in the exploitation of the useful properties of radioactivity. Applications included the use of radioisotope "tracer" techniques for investigating geophysical phenomena and process plant operations, the development of instruments such as beta-gauges for product quality control in the paper, plastics and metal industries, and the use of heavy radiation doses for the sterilisation of prepacked disposable medical supplies.

Partly through initiatives arising from within Harwell, and partly as a result of the activities of enlightened men in Westminster, Whitehall and the City, Harwell as part of the U.K. Atomic Energy Authority became empowered—indeed, required—under the Science and Technology Act of 1964, to undertake industrially oriented work in specified fields outside atomic energy. At first this work was mainly undertaken for the national benefit and under Government funding. For example, the development of industrial non-destructive testing techniques, the desalination of water and the design of plant for making carbon fibres on an industrial scale were among the first major commitments. Later an increasing amount of work was undertaken for individual firms, or groups of firms, on a direct repayment basis, or under some arrangement for sharing risks and profits between Harwell and the client—for example, by licensing Harwell patents to industrial exploiters on a royalty basis.

These and other activities clearly demonstrated that Harwell's work was not only relevant to industry but that Harwell's scientists were by no means confined to the ivory towers of "pure" research but were in effective touch with the organisations and ways of thought of hard-headed business men.

As this industrial work, with or without a nuclear connotation, grew in significance at Harwell, so the work connected directly with the increasingly successful exploitation of atomic energy diminished somewhat, but the major reduction came about in the "fundamental research into all aspects of atomic energy" which was originally Harwell's principal *raison d'être*. This "underlying research" as we now prefer to call it still goes on, though at a reduced rate: continually breaking new ground is the very life-blood of any research laboratory that is not to degenerate eventually into a mere service establishment. From occupying 53 per cent of Harwell's effort in terms of scientifically qualified manpower in 1966/7 it now takes only about 27 per cent. At the same time work for industry on a repayment basis has leapt from 6 per cent in 1966/7 to 38 per cent now, and by 1974/5 we expect it to reach 50 per cent of our total effort. During the same period our annual cash receipts from R and D work for industry can be expected to have risen from under £0.2 million to over £2.5 million. There has been a fairly substantial decline in the total numbers employed at Harwell, from a peak of about 6,000 (1,500 of them professional scientists or engineers) in 1960 to 4,560 (1,070 professional) now. This has been brought about almost entirely by natural wastage without resort to redundancy procedures.

In considering these changes we must bear in mind that the major shift has been from research of a fundamental nature, without directly formulated objectives or a firm time-schedule for completion, to very closely defined and tightly scheduled work often under strict financial control. The people involved, however, are the same and it is their work, and above all their motivation, that has had to change. That they have made this change successfully is evidenced not only by the growth of the work itself consequent upon industry's acceptance of its value, but also by the atmosphere of purposeful commercial activity that pervades Harwell.

Let us now look at the kinds of industrial activities that Harwell is undertaking and see how these have arisen naturally from existing skills and facilities developed for atomic energy matters. A few examples, taken from widely differing fields, will suffice to show the diversity and flavour of Harwell's current programme of industrial work.

First, however, it must be made clear that Harwell is still very active, and is likely to remain so, in the field of nuclear energy. Our reactors, particle accelerators and specialised laboratories are all in continual demand for work connected directly with Britain's nuclear power programme and forming part of our basic commitments. This demand extends also to other countries: for example, Harwell designs and fabricates experimental nuclear fuels to the specifications laid down by official atomic energy research bodies in other countries. We then expose them to speeded-up operational tests in our own nuclear reactors or particle accelerators and finally put them through detailed "hot" laboratory examinations to assess and report on their performance—all with the maximum of direct collaboration with our clients.

Materials Science and Technology

Our very extensive work on graphite (one of the vital materials of nuclear energy, second only in significance to uranium itself) led naturally to our involvement in developing the production technology of carbon fibre and materials made from it. This remarkable substance forms the basis of composites that can have the strength and stiffness of steel at a fraction of the weight.

Carbon fibre is expensive at present, but as its value becomes established so production will rise and prices will fall. Harwell is engaged in furthering this cycle of advance both by improving production technology of the fibre and its composites and by developing, in conjunction with industrial clients, new uses in fields as diverse as skis and highly stressed machinery parts.

Our work on non-metallic nuclear fuel materials such as the carbides and oxides of uranium or plutonium, gave us an insight into the nature and properties of ceramic materials in general. The Ceramics Centre at Harwell is now the focal point for work in this field. It is concerned with many aspects of the technology of industrial ceramics, for example, in partnership with an industrial firm (G. R. Stein Refractories Limited) we have developed a method of fabricating unusually large and complex blocks of very high density refractory materials for the steel industry using a process known as "vibro-compaction". On a smaller scale we have designed and licensed (to Energy Beams Limited of Cheltenham) the manufacture of a machine for the semi-automatic welding of, e.g. zirconium oxide thermocouple sleeves 1mm in diameter.

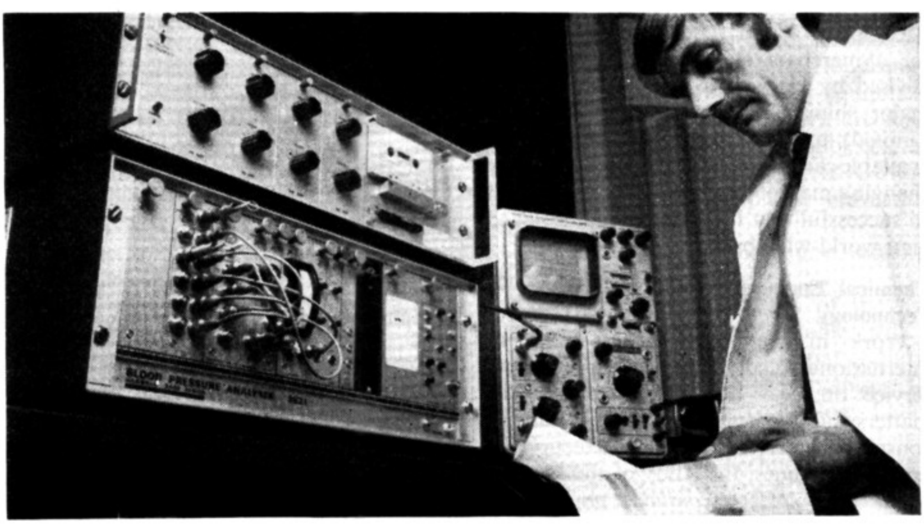
Arising from our work on the effects of nuclear radiations on materials, we have developed a process for the treatment of wood by impregnation and irradiation, to give a product that combines the appearance of wood with the hardness and impenetrability of a high quality plastic. This is already being used in cutlery and brush handles, and at the other extreme as a flooring material in a chemical plant. Related composites based on fibreboard, concrete, etc. show promise as novel constructional materials.

Quality Control

Analysis of materials and the testing of components (particularly by nondestructive methods) are of prime importance in atomic energy work. Our experience in these fields led to the setting up here in 1964 of the NDT Centre, and later of the Analytical Research and Development Unit and the Physico-Chemical Measurements Unit. The NDT Centre develops test methods of many kinds and encourages their application in industry. Two examples must suffice to illustrate these activities. It is well known that some materials—tin for example—"squeak" when bent sharply. This noise can give a clue to the internal crystalline structure of the metal. The NDT Centre is doing research on this phenomenon of "acoustic emission" with a view to developing it as a routine technique for industrial use, particularly for the nondestructive testing of structures and new materials. The other example is more specific. The Bristol Engine Division of Rolls-Royce (1971) Limited asked the NDT Centre to help them to develop a system for the radiographic examination of aero engines during test-bed running. After successful preliminary experiments with a small engine and an irridium gamma-ray radiation source, a portable installation was built that uses a Vickers electron linear accelerator to produce radiographs, in a five-second exposure time, showing the internal clearances in the largest jet engines during the full gamut of test-bed running and shutdown conditions.

In the field of analysis, new methods are developed to meet specific needs: e.g. a fully automated boron-in-steel analyser that cuts the time per sample from 8 hours to a few minutes was developed in conjunction with Marconi Elliott Avionic

The Harwell Blood Pressure Analyser



Systems Limited for a particular use, and is now marketed commercially. Special analyses are carried out at Harwell on samples ranging from mouthwash to moon dust, and a special quick-turn-round postal service is available for comprehensive spectrometric analysis of organic samples. Clients' materials can also be examined and characterised by a range of physical methods, including optical and electron microscopy, X-ray or electron diffraction, ion-beam analysis, etc.

Instrumentation and control systems

Arising from the need for accurate measurement of nuclear radiations in reactor operation and allied fields, Harwell has built up considerable expertise in electronic measuring, data handling and control systems. This is being exploited industrially in partnership with instrument making firms and potential users. One example, in the medical field, is the Harwell blood pressure analyser for automatic analysis of electrocardiogram and blood pressure records from patients undergoing continuous cardiac monitoring. The first such instrument, which is in operation at the Radcliffe Infirmary at Oxford was built with the joint support of the Medical Research Council, The British Heart Foundation and the Department of the Regius Professor of Medicine at Oxford.

Computer applications

Harwell is one of the world's largest users of computers for scientific purposes and as such is well placed to help industrial and other outside organisations. Perhaps the most striking example is the introduction of a computer based scheduling programme for a merchant shipping fleet. This was devised by Harwell in conjunction with a major shipping firm (Seabridge Shipping Limited) to help ensure the best use of available cargo-carrying resources in rapidly changing market conditions. It has proved so successful that it is now being marketed on a world-wide basis.

Chemical Engineering and Process Technology

Work in this field ranges from an international subscription information service on heat transfer and fluid flow matters (supplemented by experimental and consultancy services) to the detection of leaks in pipelines, the study of the kinetics

(*continued on page 63*)

Reliability assessment

For the past two years the Systems Reliability Service of the United Kingdom Atomic Energy Authority has been running a series of courses for industry to provide a basic introduction to reliability assessment. The techniques that have been developed and applied for the assessment of systems in both the nuclear and non-nuclear industry are covered. The Systems Reliability Service is part of the Authority Safety and Reliability Directorate based at Culcheth and it is running its sixth course "An Introduction to Reliability Assessment—Theory and Practice" in conjunction with the University of Liverpool from the 2nd to 13th April, 1973.

The course is intended for engineers and technologists of all disciplines who are concerned with the problems of achieving adequate standards of reliability in complex equipments and systems. It is of equal interest to designers, operators and managers as well as their support staff. By the end of the course participants should have acquired a fundamental understanding of the principles evolved in achieving reliability and should be able to undertake the solution of practical engineering and operational reliability problems.

Since its inception the course has been attended by over 90 people from the public and private sectors of industry. In addition to the U.K. all the major European countries have been represented with a wide spectrum of interests from the following industries:

Aerospace
Atomic Energy, design, operation and regulation
Chemical
Civil aviation
Computers
Consultancy
Defence
E.E.C.
Electricity generation and distribution
Fire protection
Glass
Manufacturing
North Sea gas
Oil
Shipping, war ships and merchantile
Steel
Universities

The numbers attending each course are limited to approximately 20 so as to achieve an adequate balance between group participation and tutorial attention.

The first part of the course is devoted to reliability and probability concepts followed by lectures on the techniques by which these concepts are applied to practical situations. The second part of the course is a series of tutorial examples during which reliability techniques are applied to simple problems in electrical and mechanical engineering. The lecturers are drawn mainly from the Systems Reliability Service and the University of Liverpool, with specialist contributions from the staff of the Universities of Birmingham, Bradford and Manchester. The topics covered include:

Mathematics of probability
Basic definitions, combination of probabilities.

Probability distributions
Particular emphasis on the exponential, mean variance, standard deviation.

Reliability testing and maintenance
The application of probability theory and probability distribution on the testing and maintenance of equipment.
Queueing Theory and application to plant availability and stock levels.

Markov processes and Monte Carlo method Correlation and regression analysis
The use of these mathematical tools as an aid to the solution of reliability problems.

Reliability considerations for technological systems
The reliability parameters that are of interest in typical technological systems. Reliability models for evaluating these parameters.

Equipment failure rate prediction techniques
Assessment of equipment failure rate by consideration of component failure rates.

System synthesis
The modelling of a system. Determination of overall system reliability and availability. Parallel series systems.

Electrical networks
Methods for evaluating the reliability of electrical networks. The application of system synthesis and system reliability models.

Mechanical system analysis

High integrity protective systems on hazardous plant

Computer techniques of analysis
Computer services used in Reliability Engineering and in particular the NOTED programme.

Data bank services
The use of S.R.S. Data Bank in the derivation of Mean Time between failures, confidence levels in data, etc.
Additional project work will lead to assessments of the reliability of electrical and mechanical equipment and finally a complete system assessment.

The course list is now open for nominations and acceptances will be limited to approximately 20. The fee is £150 (£125 for associate members of S.R.S.) exclusive of VAT and accommodation. Applications should be sent to Mr. A. C. Wilson, Systems Reliability Service, United Kingdom Atomic Energy Authority, Wigshaw Lane, Culcheth, Warrington, Lancashire, Tel. Warrington 31244, Extension 208.

Health Physics Summer School 1973

The fourteenth annual Summer School in Health Physics (Radiation Protection) will be held at Imperial College from 2nd to 13th July, 1973.

Topics covered will include basic physics, biology, radiobiology and genetics; an assessment of the hazards to the worker and the population; derivation of safe working levels; medical supervision of radiation workers; legal and administrative aspects; physical and biological monitoring; principles of radiation and contamination hazard control; application of radiological protection in large and small establishments, nuclear power stations, factories and hospitals; transport of radioactive materials; disposal of radioactive wastes; accident and emergency conditions; and organisation of radiological protection services.

A visit will be arranged to laboratories in which radioactive materials are handled and an opportunity will be given for using a range of portable monitoring equipment.

The lecturers, most of whom are international authorities in their subjects; are drawn from the senior staffs of Government departments, hospitals, universities and the U.K.A.E.A.

The tuition fee for the course, which is non-residential, is £42.

A brochure giving details of the programme, lecturers and timetable, will be available in March 1973. Initial enquiries should be addressed to the organiser, Dr. H. D. Evans, Nuclear Technology Laboratories, Department of Chemical Engineering and Chemical Technology, Imperial College, London SW7 2AZ.

Nuclear power—the future

The following article is based on a paper presented by Dr. T. N. Marsham, Deputy Managing Director, Reactor Group, U.K. Atomic Energy Authority, Risley, and Dr. R. S. Pease, Director of Culham Laboratory, to a symposium on "Energy Resources in this Century and Beyond" during the annual meeting of the British Association for the Advancement of Science, at Leicester, 4th-9th September, 1972.

Introduction

It is now thirty years since Enrico Fermi and his colleagues obtained a net yield of nuclear energy from a fission neutron chain reaction in an assembly of uranium and graphite. The principles they used have formed the basis of a series of 11 nuclear power stations built in Britain. These are the so-called Magnox stations, totalling about 5 GW(e) or 8 per cent of the total installed generating capacity, which provide some 10 per cent of the country's electricity. The first of the stations, Calder Hall (4 × 50 MW(e)), has been operating over 16 years; the most recent and largest, Wylfa (2 × 600 MW(e)), was brought into operation by the Central Electricity Generating Board a little over a year ago.[1]

The C.E.G.B. have reported that in 1971 their cheapest electricity—about 0.3p/kWhr—was generated by some of these nuclear stations[2]; the cost was very competitive with that for electricity from the most modern oil-fired stations and lower than that from any of the coal-fired stations.

In other parts of Europe and the world a several times greater capacity of nuclear power plants is already operating and a much greater capacity is being constructed, additional to nuclear power propulsion units in naval and prototype commercial ships. Nuclear energy is thus established as a practicable large-scale source of power. A much larger programme of nuclear power stations will however have to be built in Britain in the next few years if a potential burden of high electricity costs from escalating fossil fuel prices is to be avoided.

The main purpose of this paper is to consider the potential of nuclear energy for the more distant future, beyond the end of the century. It is important to recognise the scientific and technical developments needed to realise this potential. The most important feature of nuclear energy is that it offers the prospect for supplying all of the world's long term energy needs when the traditional fuels, oil and natural gas particularly, are becoming scarce and costly. To serve this purpose many more nuclear power stations must be built and some new reactor systems developed for introduction at times when significant improvements can be effected. The two main possibilities discussed here are the so-called breeder reactor, a near future prospect based on fission, which makes efficient use of uranium and could additionally use thorium; and the fusion reactor which, if it can be developed, will make available the nuclear energy of the light elements, notably deuterium and lithium. The importance of these two sources of energy is their potential for long-term large-scale use.

The abundance of nuclear fuels

World useful energy requirements over the next 50 years have been forecast by various authorities. Table 1 indicates that it is likely to be of the order of 0.5Q* per year in about the year 2000[3].

Uranium is an element occurring widely at low concentrations on land, Figure 1, and in sea-water. Limitations on its use are set by the cost of mining and concentrating the ore but even if uranium has to be extracted from the sea, the cost is not formidable. From ores containing about 0.1 per cent to 0.5 per cent of U_3O_8 by weight the cost is below $20 (U.S.A.)/kg. Much larger quantities are available at higher extraction costs—the limit being set by the enormous reserves in the sea at a cost of around $200 kg. Estimated reserves of U_3O_8 at the lower cost, excluding those in Russia and China,

*Q = 10^{18} BTU $\simeq 10^{21}$ joules

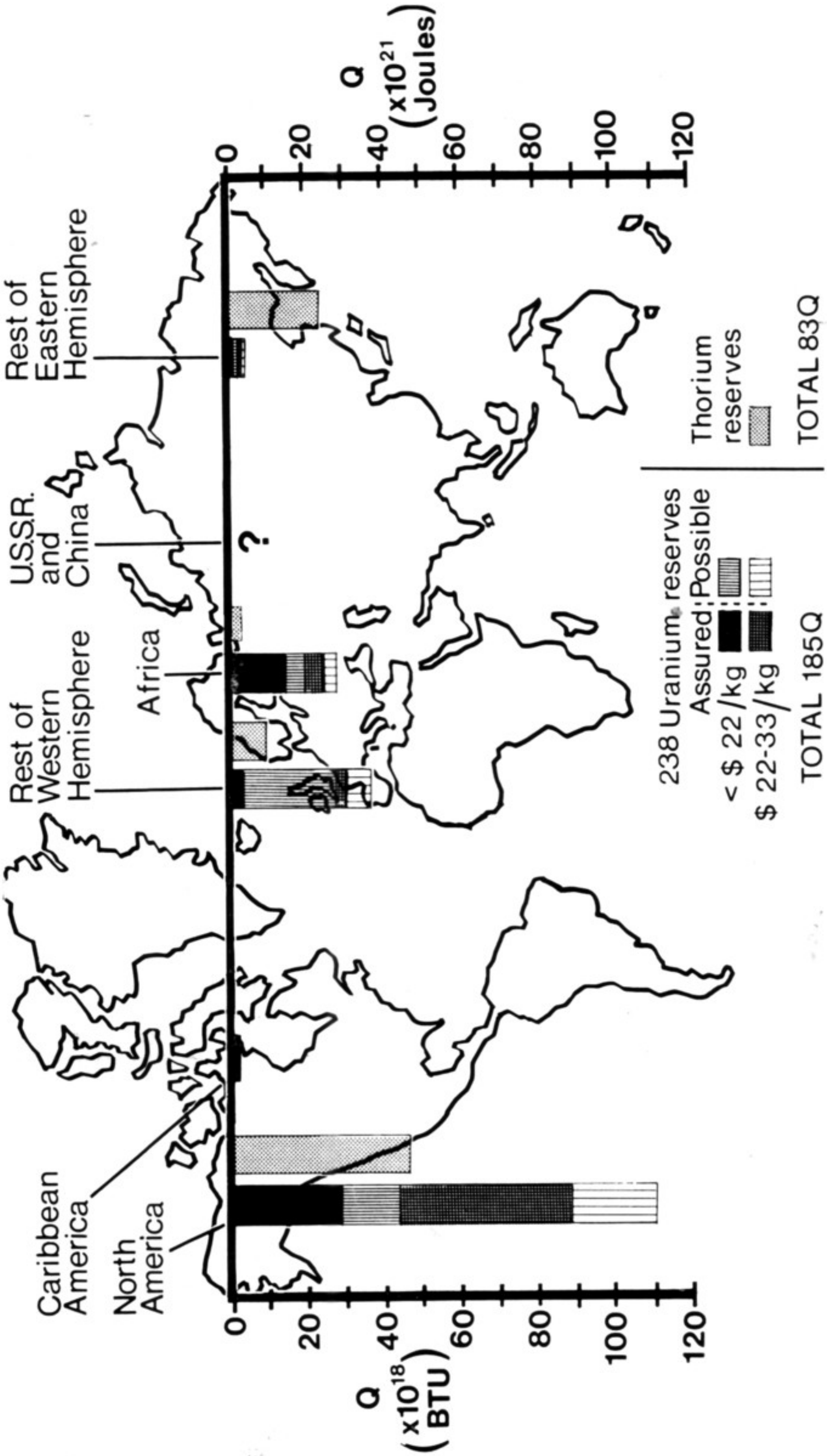


Fig. 1 *World fission fuel reserves at less than $33 per kg.*

Table 1
Estimated annual demand for useful energy by world regions*

	Consumption in 1968 Q†	Estimated Consumption in 2000 AD Q†	Estimated Consumption in 2030 AD Q†
Africa	.0016	.017	.058
America	.0415	.145	.338
Caribbean & S. America	.0037	.023	.113
Western Europe	.0185	.069	.197
USSR & East Europe	.0195	.099	.335
Middle East	.0011	.010	.039
Asia	.0074	.072	.275
Rest of East Hemisphere	.0037	.010	.029
Totals	0.10	0.45	1.4

* After allowing for the differing efficiency in final use of the various fuels (mean efficiency $\sim 45\%$)
† 1 Q = 10^{18} British Thermal Units

total about a million tons[4] (Table 2). Approaching six million tons should be available at costs lower than that for sea-water extraction. The world total of uranium comprises an astonishingly small mass by comparison with that of known fossil fuels; but the nuclear energy content is potentially very large as energy per unit mass is about 10^6 times that of chemical energy.

The present Magnox nuclear power stations depend on fission of the isotope U-235 (abundance 0.7 per cent of natural uranium) using only about 0.2 per cent of the total uranium fed to them[5]. At this level of utilisation each million tons of uranium represents about 0.15Q (Table 3) so world land resources contain approaching 1Q total energy. The effect of ore costs on generating costs is shown in the table. Thus on the basis of present utilisation in Magnox reactors, uranium might be termed rather scarce and expensive as a long term future energy source. Advanced thermal reactors[6] enable slightly better utilisation, achieved by enriching the uranium in the U-235 isotope and designing the fuel to yield more heat during its stay in the reactor. The breeder reactors considered in detail below are designed to use effectively a much higher proportion of the uranium fed to them, giving at least 50 times better utilisation, with two major effects. First, 10^6 tons of low cost uranium becomes an abundant source of energy, over 50Q, and total land based reserves reach 300Q. Second, much more abundant low grade uranium ores and sea water reserves can now be used without significant effect on the cost of energy which is of fundamental importance.

The envisaged fusion reactors, now the subject of world-wide research will use deuterium and lithium. Deuterium is highly abundant and very cheap, one gramme being present in every 25 litres of water. Lithium is less abundant than deuterium but is still very abundant (Table 4). A recent survey[7] has indicated that 6 x 10^6 tons (500Q) of known reserves exist in the U.S.A. alone at \$20/kg or less. A utilisation of 25% is expected[8] and total fuel costs are estimated to be about 0.001p/kWh[9]. Reserves of fusion fuel are therefore abundant, potentially providing an inexhaustible supply of energy.

Thus the present fission reactors, though currently operating cheaply and satis-

Table 2
Uranium resources in the free world

Investigator	Estimated reserves in tonnes of U_3O_8 at less than \$20 per kg	\$20-\$30 per kg	\$30-\$60 per kg
Hubbert	1,500,000	1,500,000	Not stated
Seldenrath	635,000	684,000	Not stated
United Nations	700,000	700,000	Not stated
Mandel	1,300,000	Not stated	1,950,000

Table 3
Natural uranium—Comparison of nuclear heat content and electricity costs for various utilisations and ore costs

	Uranium utilisation		
	0.2%	1%	75%
Total heat content† per 10^6 tonnes	0.14Q	0.7Q	52Q
Ore cost component of electricity costs*	p/kWh	p/kWh	p/kWh
(a) at $20 kg U_3O_8	0.08	0.017	2.2×10^{-4}
(b) at $100 kg U_3O_8	0.40	0.085	11.0×10^{-4}

* Assuming 180 MeV per fission and 30% conversion efficiency
† $1Q = 10^{18}$ BTU $\sim 10^{21}$ joules

factorily, are relatively inefficient in their use of uranium fuel. The fast breeder reactors will make more efficient use of uranium and keep fuelling costs low for the foreseeable future. Deuterium and lithium reserves provide a copious supplement of available energy if the technology of fusion can be developed. These prospects are now discussed.

Nuclear breeder reactors[10]

The possibility of breeding fissile fuel—that is producing more fissile fuel than exists in naturally occurring uranium—rests on two facts; first, the capture of a neutron in U-238 produces Pu-239 which, like U-235, is easily fissionable; second, when, as a result of neutron capture, Pu-239 undergoes fission, it produces more than two neutrons. One of these neutrons must be used to maintain the fission chain reaction, one must be captured in U-238 to produce replacement Pu-239 and the remainder are available either to make excess Pu-239, or to be lost by parasitic capture in structure and coolant. The number, η, of neutrons produced per fission is critical to the utilisation of the non-fissile but relatively abundant U-238 and, in particular, the amount by which η exceeds 2 determines whether or not breeding gain can be achieved. Because η is rather larger (>3) and parasitic

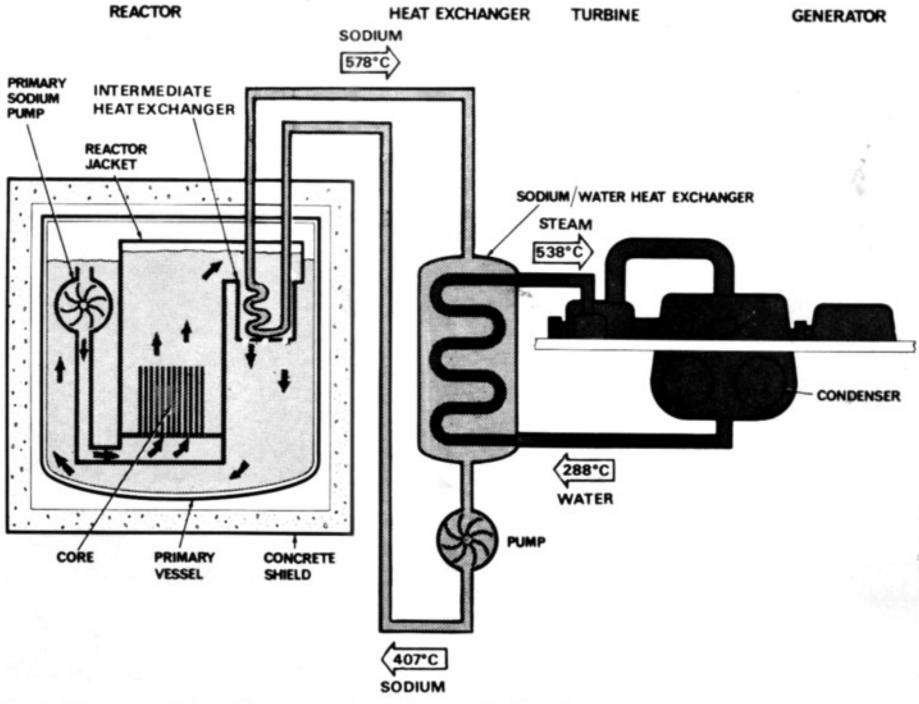
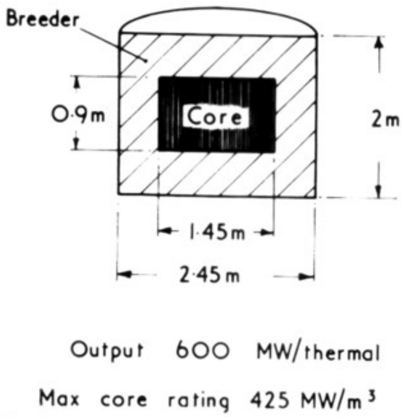


Fig. 2 *Diagram of electricity generating sodium-cooled fast breeder power reactor*



Inventory

		Tonne
Core	Pu	0·8
	U	3·2
Breeder	U	11·2

		Tonne
Feed depleted Uranium	per GW Year	1·0
Plutonium Output	per GW Year	0·2

Fig. 3 *Diagram of P.F.R. core and fuel logistics*

capture is smaller when the neutrons producing the fission are moving at their initial fast speed (corresponding to an energy of about 1 MeV) than when they are slowed down to thermal energies as in the magnox reactors, the breeder reactors currently under intensive development use fast neutrons to sustain the fission chain reaction.

The active material of a breeder reactor core is a 1:4 mixture of Pu and U as metal oxide (or carbide) for stability at high fuel temperatures. The core comprises a very efficient coolant (liquid sodium) and the essential minimum of cladding and construction material in a compact assembly to reduce slowing down and capture of the neutrons. This leads to a most challenging and potentially useful characteristic of fast reactors—a very high core rating i.e. heat output per unit volume of core. The core for a 1000 MW(e) reactor is typically a cylinder 3 metres in diameter by 1.5 metres high and the fuel elements operate at about 20-30 kW/cc. An outline of a sodium cooled fast breeder generating system is shown in Figure 2.

Development of sodium-cooled breeder reactors started in Britain in the early 1950s. To establish the physics characteristics of fast reactor cores and show that breeding of a surplus of fissile material would be a practical proposition, the ZEPHYR zero energy reactor was commissioned at Harwell in 1954. To solve the engineering problems associated with the design of high-power density, fast reactor cores, and to demonstrate electricity generation, the Dounreay Fast Reactor (D.F.R.) was built and has now operated since 1959.

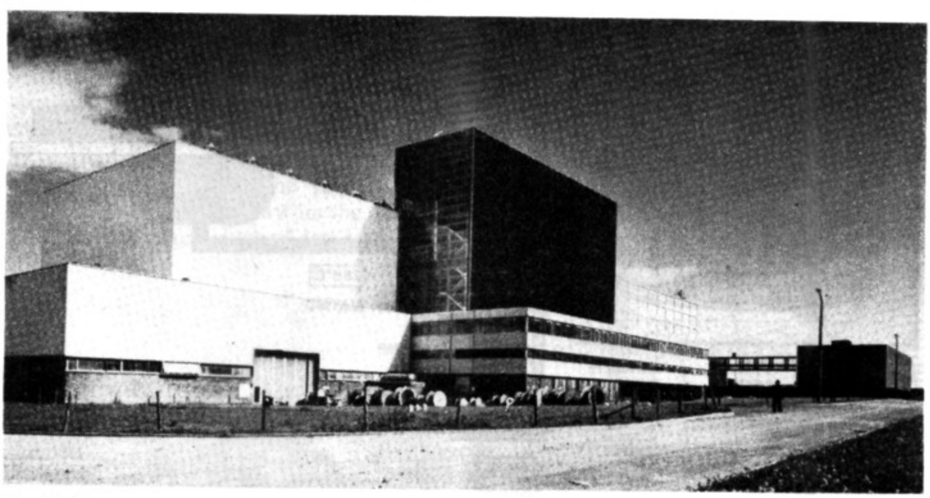


Fig. 4 *Prototype Fast Reactor—Dounreay*

Table 4
Energy content of world lithium reserves in Q†
(Data from Ref. 7)

Known and inferred reserves in the U.S.A.*	512 Q
Known and inferred reserves in the rest of the world**	170 Q
Present annual consumption in U.S.A. at 2/c/gm (in ceramics, lubricants and metallurgy)	0.206 Q
Sea water content (recovery cost unkown)	21×10^6Q

† 1 Q = 10^{18} British Thermal Units
* Based on maximising energy output rather than breeding gain
** At the present state of the market; prospecting is at a very low level

This reactor has enabled successful fuel-proving work to be carried out, and as a result authority was given in 1966 to construct a 250 MW(e) fast breeder prototype power station, also at Dounreay. The immediate purpose of the new reactor is to explore the engineering, fuel development and economics of commercial sized equipment, particularly fuel elements. Due to come 'on stream' in 1973, the Prototype Fast Reactor (P.F.R.) will be the culminating stage of twenty years research and development. The P.F.R. core dimensions and fuel logistics are shown in Fig. 3 and the present state of construction of the station is shown in Fig. 4.

Of the many technical developments needed for economic fast breeder reactors, none is more central to success than the development of the fuel pins which represent the most severely stressed elements of the system. Although the ore cost may be negligible, the fabrication costs of fuel elements is high. A high degree of cladding integrity and substantial burn up (5-10 per cent fuel utilisation) must therefore be achieved to ensure low electricity generation costs.

Following prolonged full-power demonstration runs during 1963-64, the multiple-pin oxide-fuel designs proposed for P.F.R. and later reactors were put in D.F.R. Such assemblies have now been irradiated successfully to 10 per cent fuel burn-up, which promises well for commercial operation. During irradiation, as indicated in Fig. 5, the fuel in the pins suffers substantial textural changes due to a mechanism believed to be associated with strong thermal gradients. So far

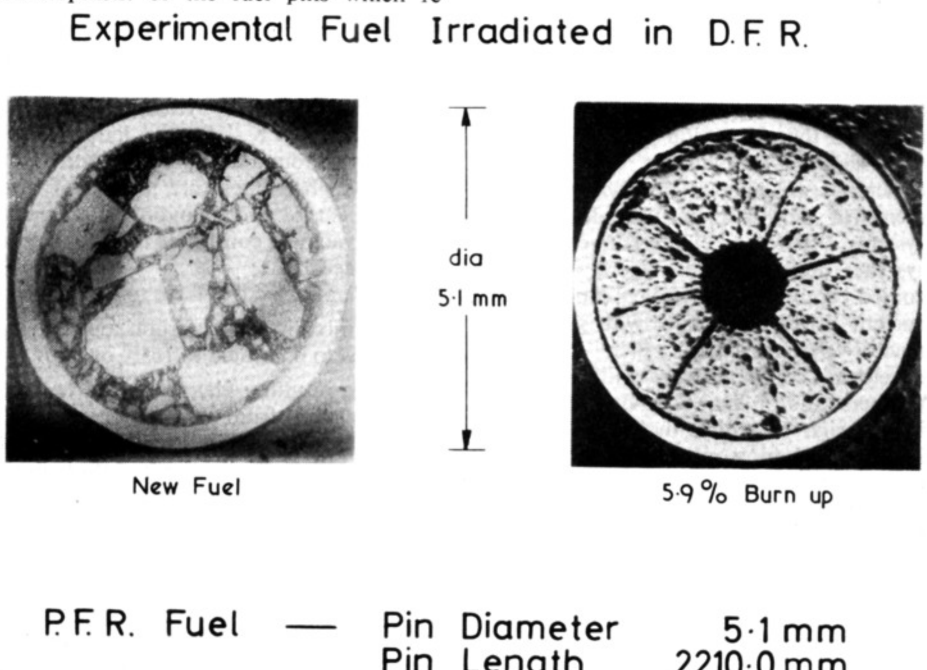


Fig. 5 *Experimental P.F.R. fuel pins—sections and dimensions*

Table 5
U.K. breeder reactor parameters

		Dounreay D.F.R.	Prototype P.F.R.	Commercial C.F.R.
Thermal output	MW	60	600	3000
Maximum neutron flux	10^{15} cm^{-2} sec	2.5	8.5	11.0
Fuel type	—	metal	oxide	oxide
No. of fuel pins	—	204	25350	89700
Fuel pin diameter	mm	17	5.1	5.1
Peak fuel pin rating	W/mm^2	1.5	2.3	3.0
Maximum burn-up	%	5	7.5	10

these changes have been accommodated without serious distortion or loss of integrity of the fuel cladding.[11] It remains to be demonstrated that the same high fuel burn-up and clad integrity can be maintained under production/commercial conditions in P.F.R. A comparison of basic parameters of United Kingdom fast reactors is shown in Table 5.[12]

When the P.F.R. is successful, the way will be open for generating units exceeding 1300 MW(e) to be built for commercial operation in the 1980s. These would produce electricity at a projected cost only 75 per cent of that of contemporary power stations using the alternative thermal fission or fossil fuels. Thus the development of fast breeder reactors using liquid metal cooling is at an advanced and exciting stage in Britain. Indeed, it shows good prospects not only of releasing the potential nuclear energy of U-238 but also of providing substantially cheaper electrical power than present Magnox and other thermal fission systems.

If, against the current odds, serious difficulties are encountered with development of liquid metal breeder reactor systems, there are alternative breeder systems under study. There is a gas-cooled breeder reactor which could extend current British experience with gas-cooled reactor systems and which might be developed collaboratively with European partners and/or the U.S.A. Also there is a design in which the fissile material is contained in a molten salt. Both of these systems are, however, at the conceptual stage of development compared to the oxide-fuelled sodium-cooled system.

Controlled nuclear fusion[13]

The possibility of extracting nuclear energy from some of the lightest elements rests on the fact—first demonstrated by Cockcroft and Walton in 1932—that when light nuclei collide with a sufficient energy, nuclear reactions can take place in which far more energy is released than is present as the incident kinetic energy of the colliding particles. The most favourable reaction for the fusion process is—

$$D + T = {}^4He + n + 17.6 \text{ MeV}$$

which has the largest cross-section (5 barns), one of the highest energy yields, and the lowest effective threshold energy ($\sim$ 10 keV). The tritium needed for this reaction is obtained by neutron interaction with lithium, viz:

$$n + {}^6Li = {}^4He + T + 4.8 \text{ MeV}:$$

$$n + {}^7Li = {}^4He + T + n - 2.5 \text{ MeV}$$

Supplementary (n, 2n) reactions in nuclei such as beryllium or molybdenum can also be used to assist tritium production.

To use fusion reactions as a practical energy source, it is necessary to create and control the high temperature state of matter—the so-called plasma state—so that a net gain of energy can be obtained from thermonuclear reactions in the plasma at $\approx 10^8$K. It has indeed been necessary to found a major new branch of physics—high temperature plasma physics—to gain the understanding apparently needed to achieve controlled thermonuclear fusion reactions.

Two main objectives have to be reached:

(a) a mixture of deuterium and tritium has to be heated to 10^8K or more;

(b) the resulting plasma has to be held isolated from ordinary materials, which otherwise would cool and contaminate it; this isolation must be maintained for at least a time τ, which depends on the particle density n, and is given by $n\tau > 10^{14}$cm^{-3}sec (Lawson criterion).

It is this second criterion, involving the confinement time and the density, which requires a very high degree of control of

Table 6

Plasma conditions required in a D(T, n)α thermonuclear reactor

General

$T \gtrsim 10^8$ K = 10^4 eV; $n\tau_c \gtrsim 10^{14}$ cm^{-3}s (Lawson criterion)

Reference design toroidal system: 5000 MWT(Tn)

Steady state with plasma heating by reaction products

Temperature ($T_i \sim T_e$)	— 2×10^4eV
Particle number density, n	— 3×10^{14}cm^{-3}
Confinement time, τ_c	— 0.6 sec
$n\tau_c$	— 1.8×10^{14}cm^{-3}s
Particle collision mean-free-path	— 2×10^6cm
Field strength, B	— 100 kG
β,—ratio plasma to magnetic pressure	— 0.075
Plasma minor radius	— 125 cm
τ_c/Bohm time	— 120
Major radius	— 550 cm

the plasma, and which has yet to be demonstrated.

Fusion research

The technique most studied so far uses magnetic fields to confine and control the plasma. High temperature plasma consists entirely of freely-moving charged particles and is a compressible and highly-conducting fluid which interacts with a magnetic field. In effect magnetic fields can exert pressure on a plasma and thus confine it. Typical operating conditions of an envisaged toroidal thermonuclear reactor are given in Table 6. However, they have not yet been achieved simultaneously in the laboratory; the apparatus needed to do so is large and our state of knowledge has not hitherto justified the investment. Instead a wide range of experiments has been undertaken aimed at establishing the principles of magnetic confinement, using many different plasma conditions and magnetic field strengths and shapes (Table 7).

To assess the results of these experiments, it is helpful to compare the present situation with that ten years ago when fusion research was last discussed at the British Association.[14]

First, a very substantial underlying framework of high temperature plasma physics has been established. The importance of this basic work is evident from Table 7, which shows how we have to extrapolate from modest experimental conditions to reactor conditions. One of the many important contributions has been the development of light-scattering techniques to probe the microstructure of plasmas. Light from lasers performs for plasmas the same function that X-ray scattering and Brillouin scattering plays in the analysis of solids. Accurate measurements of plasma density and temperature as a function of position and time can now be made, the magnetic field strengths can now be measured without disturbing the plasma with probes, and the fluctuation spectra and correlation lengths in the plasma can now be measured.[15] As a result, all the underlying concepts of linear plasma physics—unverified in 1962—have now been experimentally established. For example, the basic charge neutrality correlation length—a concept borrowed from the electro-chemists and applied theoretically to plasmas—had received concrete verification by 1967.

Second, magnetic confinement of plasmas was in 1962 seriously threatened by gross instabilities, analagous to those encountered in some fluid equilibria. It was found that these instabilities could

Table 7

Plasma conditions

	Experiments	Toroidal reactor
Number density, n, cm^{-3}	$10^8 - 10^{19}$	$\sim 10^{14}$
Temperature, T, eV	$10^{-1} - 10^4$	$\sim 10^4$
Confinement time, τ_c, s	$10^{-8} - 1$	~ 1
Pressure ratio, β	$10^{-9} - 1$	$\sim 10^{-1}$
"Lawson product" $n\tau_c$, s/cm^3	$10^8 - 10^{12}$	$\sim 10^{14}$

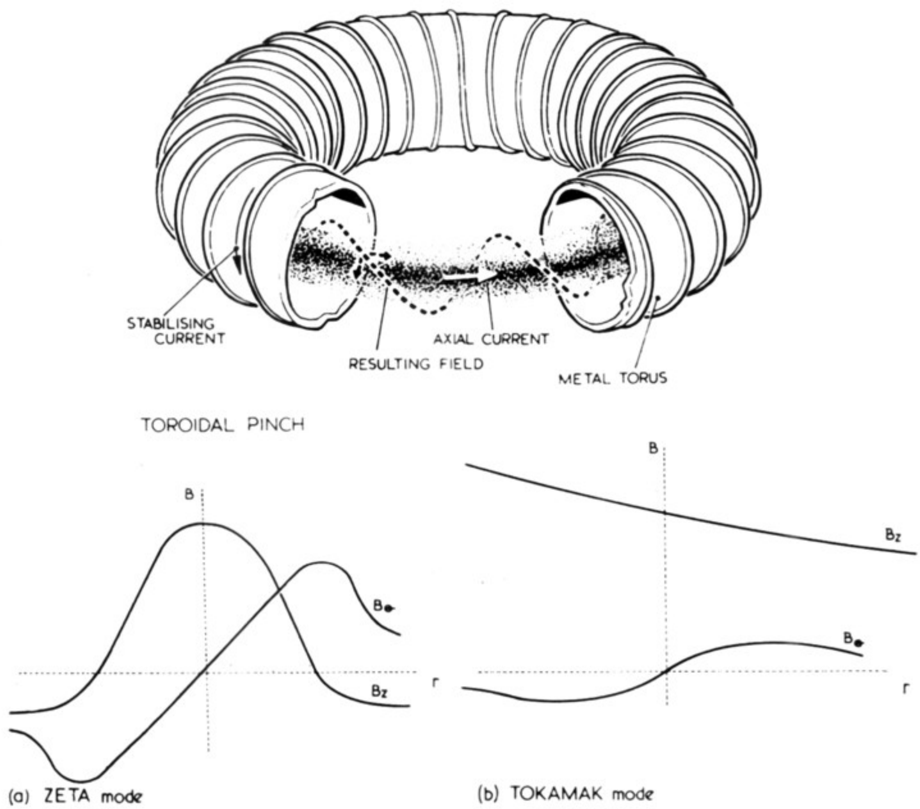


Fig. 6 *Toroidal pinch systems*

destroy equilibrium and confinement very rapidly, in a time determined largely by the velocity of sound and the dimensions of the apparatus. It has now been demonstrated in a wide variety of confinement systems that these gross instabilities can be suppressed in accord with the prediction of ideal magneto-hydrodynamic theory and this was first achieved in the so-called magnetic well systems. A more recent example is provided by the ZETA toroidal pinch discharge system, which featured in the 1962 account as being grossly unstable. In toroidal pinches the plasma is heated and confined by the magnetic field of a strong current passed through low pressure gas in a torus, as illustrated in Fig. 6. The ZETA system appeared then to be a most difficult system to stabilise because the large additional free energy associated with the electric currents in the plasma is potentially destabilising. However, in fact, experimental developments showed that the gross instabilities in the system could be suppressed and detailed agreement between theory and experiment has been obtained. More remarkably it has been found that providing the initial conditions are chosen correctly, these toroidal pinch systems are self-stabilising; that is, after an initial period of gross turbulence, a quiescent and well-contained plasma appears confined for up to 3 msec, an improvement of 100 in performance[16] Fig. 7.

Third, great progress has been made in understanding the various processes by which plasma diffuses across magnetic fields, once gross stability has been achieved. In particular, rapid diffusion processes such as the Bohm diffusion, can it seems be largely suppressed.

The most successful confinement system to-date, and the one showing most promise for extension to reactor-like conditions is the Russian TOKOMAK system. It is a toroidal pinch discharge stabilised by a very strong applied magnetic field (Fig. 6). Here the plasma parameters achieved have been particularly striking and have lasted for up to 1/10 of a second, as measured by laser light scattering techniques in a joint

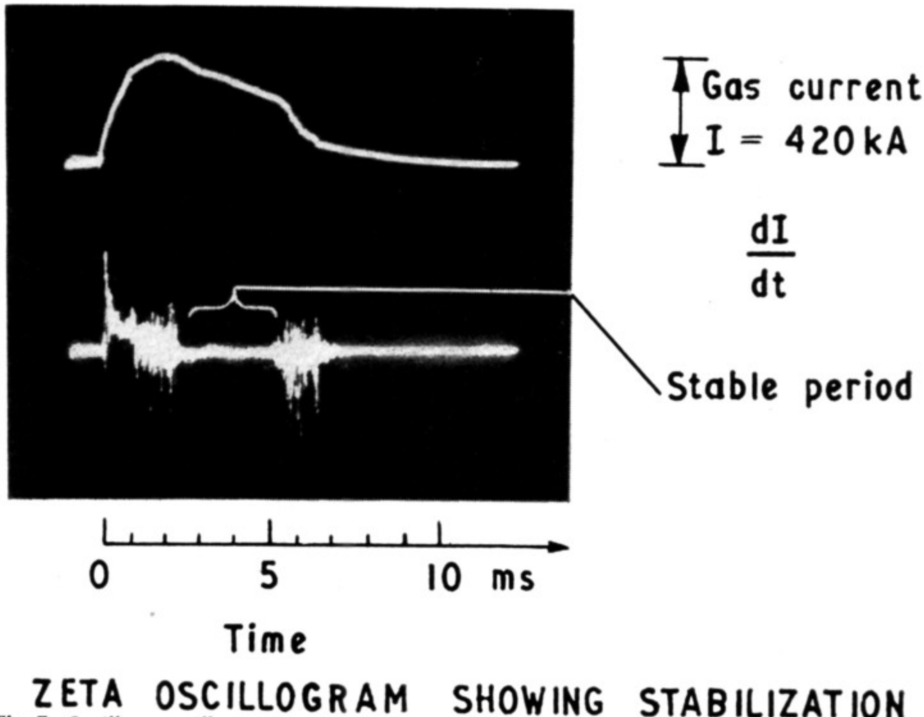


Fig. 7 *Oscillograms illustrating self-stabilisation in* ZETA *toroidal pinch*

British-U.S.S.R. study of the Russian T-3 TOKAMAK, Fig. 8.[17] The plasma temperature rises, as it should according to simplest theory, as the square of the discharge current, and electron temperatures of 30×10^6K have been reached. Ion temperatures—also in accord with theoretical prediction—have reached 6×10^6K and abundant thermonuclear reactions in deuterium have been identified. The containment times increase with the current and have reached values of 10-20 milliseconds. The product of n and τ in these experiments approaches 10^{12}cm^{-3}sec, compared to the 10^{14} defined by the Lawson criterion.

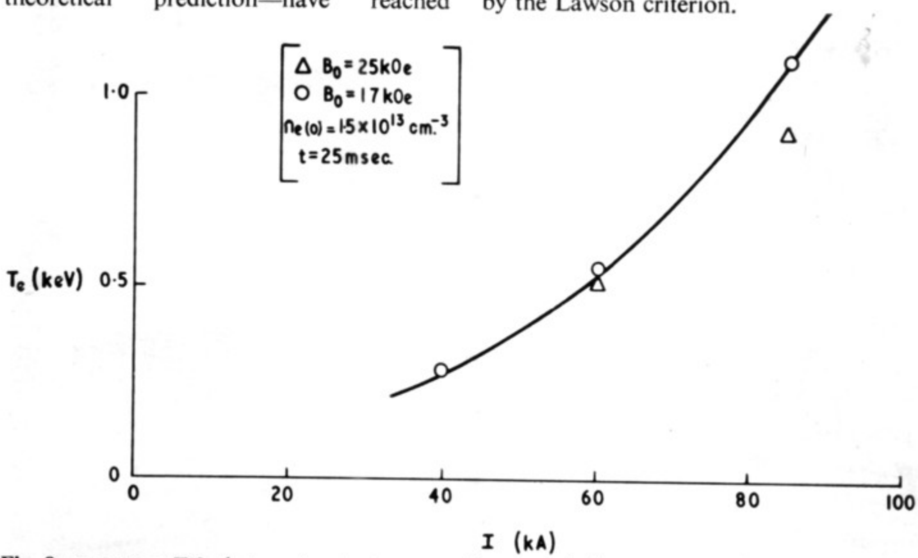


Fig. 8 TOKAMAK *T-3 electron temperature as a function of plasma current for constant electron density, and stabilising fields of 17 and 25 kOe*

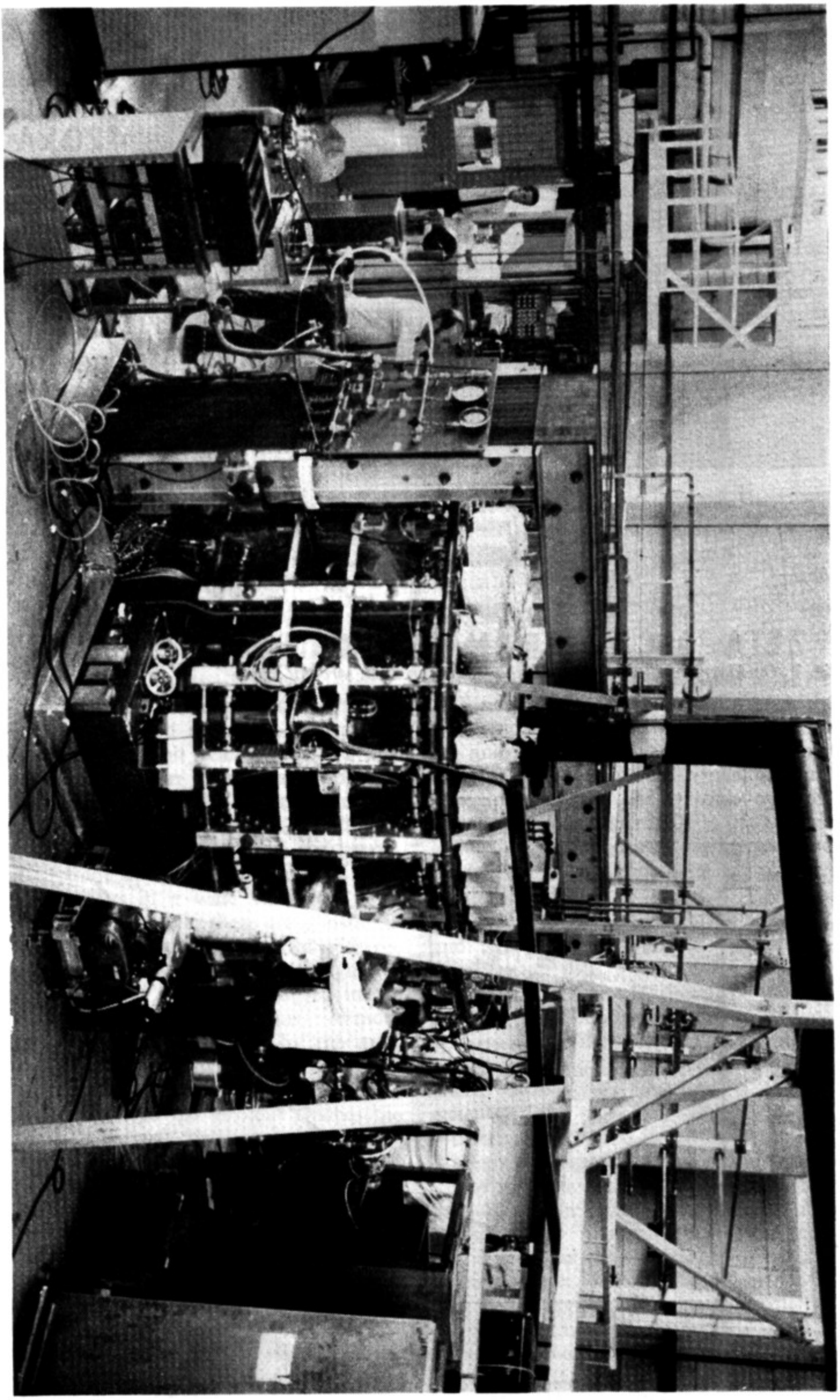


Fig. 9 CLEO *experiment—Culham Laboratory—September 1972*

In other systems of the toroidal type, such as stellarators and the so-called toroidal multipoles, equally significant advances have been made, including confinement times of several tenths of a second, although in relatively cold plasma. These observed confinement times are now typically within a factor of ten of the best predictions of theory, whereas in 1962 many orders of magnitude separated observation from theory. Fig. 9 shows the latest toroidal confinement apparatus, CLEO, brought into operation at Culham to compare the confinement properties of a stellarator with those of a tokamak.

Fusion technology

Accompanying these advances in plasma control, outline studies of fusion reactors have been carried out, the main technical problems have been brought into focus and more exact estimates have been made of the plasma parameters and of the technical advances needed to achieve economic power generation. The main conclusions of these initial studies are as follows. Many of the materials problems in fusion reactors—heat transfer, thermal stress, radiation damage from neutron fluxes, shielding—are qualitatively similar to those in fast breeder reactors. The thermal loadings are not so high, and the constraints set by the need to breed tritium are much less severe than those of breeding plutonium. The fuel of a thermonuclear reactor is very cheap, only small quantities are needed, and little fuel processing is required. But a fusion reactor using magnetic confinement has to have a powerful magnetic field, and the capital cost of providing this is the major novel item whose price will, at least to some extent, offset the advantage of cheaper fuel. Indeed, it seems that the large scale production costs of superconducting materials may have to be brought down by about a factor of ten as part of the overall reactor development—though this would still result in costs greater than present raw material costs.

Thus the prospects of developing fusion reactor systems based on magnetic confinement are now much more promising. However, the extrapolation from present experiments to reactor conditions is rather large and certainly too great to be sure of success. It is now necessary to build apparatus designed to bridge the gap, and to achieve simultaneously plasma temperature, density and confinement time close to those needed in a reactor. Construction of such large-scale apparatus is

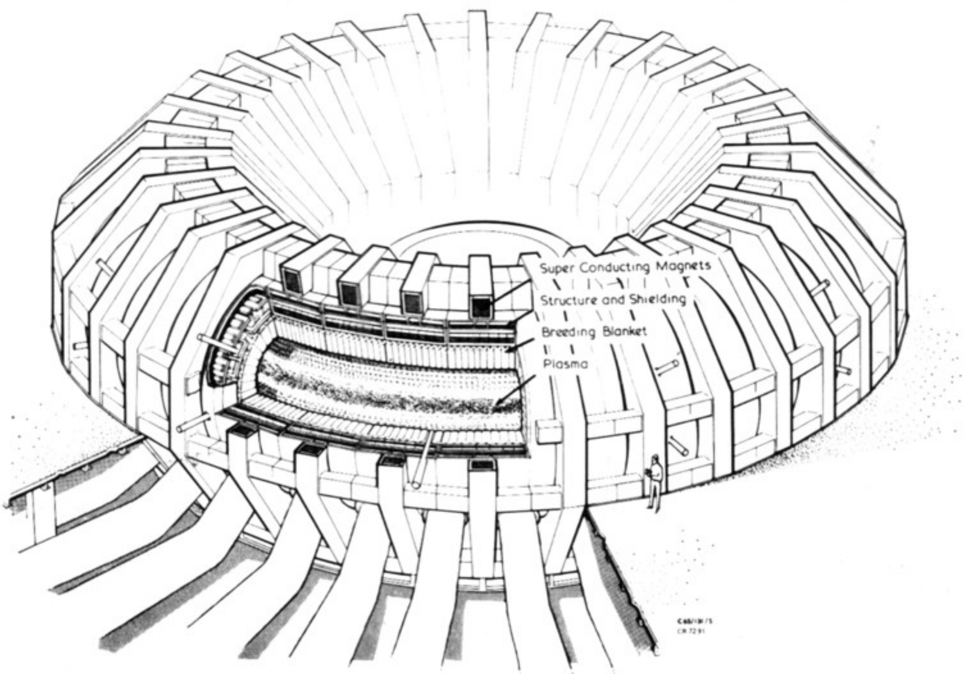


Fig. 10 *Lithium-cooled toroidal fusion reactor*

Table 8
Computer calculations of laser-induced implosion of DT to super-high densities
(from Ref. 18)

Initial pellet radius	0.4 mm
Laser energy	60kJ
Ablation pressure	$10^{6} - 10^{11}$ atmospheres
Maximum density	$5 \times 10^{26} cm^{-3}$
Maximum fusion energy yield (favourable assumptions)	1.8 MJ
Effective confinement time	$\sim 10^{-11}$ sec.

now under way in Russia, the United States and in Germany. It thus seems likely that many of the uncertainties of magnetic confinment in toroidal systems will be resolved, and if the outcome is favourable we can proceed to a prototype programme leading, in due course, to fusion reactors perhaps of the order of 2500 MW(e) output (Fig. 10).

Fusion in inertially confined dense plasmas

From time to time throughout the last twenty years, proposals have been advanced for achieving Lawson's criterion by explosive heating of a deuterium-tritium mixture at high densities. With solid density of 5×10^{22} nuclei per cc, the Lawson criterion requires that the containment time should exceed 0.2×10^{-8} seconds. Since the velocity of disassembly will be about the velocity of sound at 10^{8}K, i.e. about 10^{8}cm/sec, it is easily shown that pellets of about 1 cm dimension are required, and consequently about 10^{8} joules of heating energy. To supply this energy in substantially less than 10^{-8}sec is a very formidable task especially to meet an economic target.

However, the results of detailed calculations carried out at Livermore Radiation Laboratory, U.S.A., have recently been declassified, and these indicate the possibility of significant advances being made by compression of solid hydrogen,[18] using spherically symmetrical irradiation with high powered lasers. Similar, but less extensive calculations carried out by the U.K.A.E.A. indicate the same possibility. The principle depends essentially on the *avoidance* of a strong shock wave which can only give a compression of four times. A carefully-programmed pulse of energy is required to ensure an implosion compression close to the ideal adiabatic laws. The compressive force arises from the ablation of material at the surface of the sphere due to the strong laser heating there.

The most striking qualitative features of these calculations is that densities of up to 5×10^{26}nuclei/cc are predicted,—densities greater than are believed to occur at the centre of the sun. A net yield of thermonuclear energy might be obtained with 10^{4} joules of energy absorbed, rather than the 10^{8} joules needed for uncompressed material. However, no compression effects have yet been demonstrated in any experiment; moreover, very difficult developments in laser technology will be needed to achieve the compression and heating needed for a reactor. But we can expect a vigorous experimental attack on this topic over the next few years, not least because of its potential importance to plasma physics and to astrophysics. Also, nuclear reactions other than DT fusion could occur in such conditions leading to a number of interesting and highly speculative possibilities for direct conversion of nuclear energy to electricity.

Future developments of nuclear power

Controlled nuclear fusion offers the possibility of utilising a totally new, abundant and very cheap fuel which does not require elaborate fuel processing facilities, does not produce highly radioactive fission products and in which there is no prospect of a diverging nuclear chain reaction.

However, controlled fusion is still very much a research subject—there are many physics problems still to be resolved—and it has by no means reached the threshold of practical application as have fast breeder reactors. Because of the great importance of long term energy supplies, the development of breeder reactors should proceed unchecked by the possibility of their eventual replacement by fusion reactors.

The time scale of development and application of fast reactors is shown in Figure 11, which envisages large scale British commercial application growing in the 1980s. The corresponding programme for fusion reactors can only be

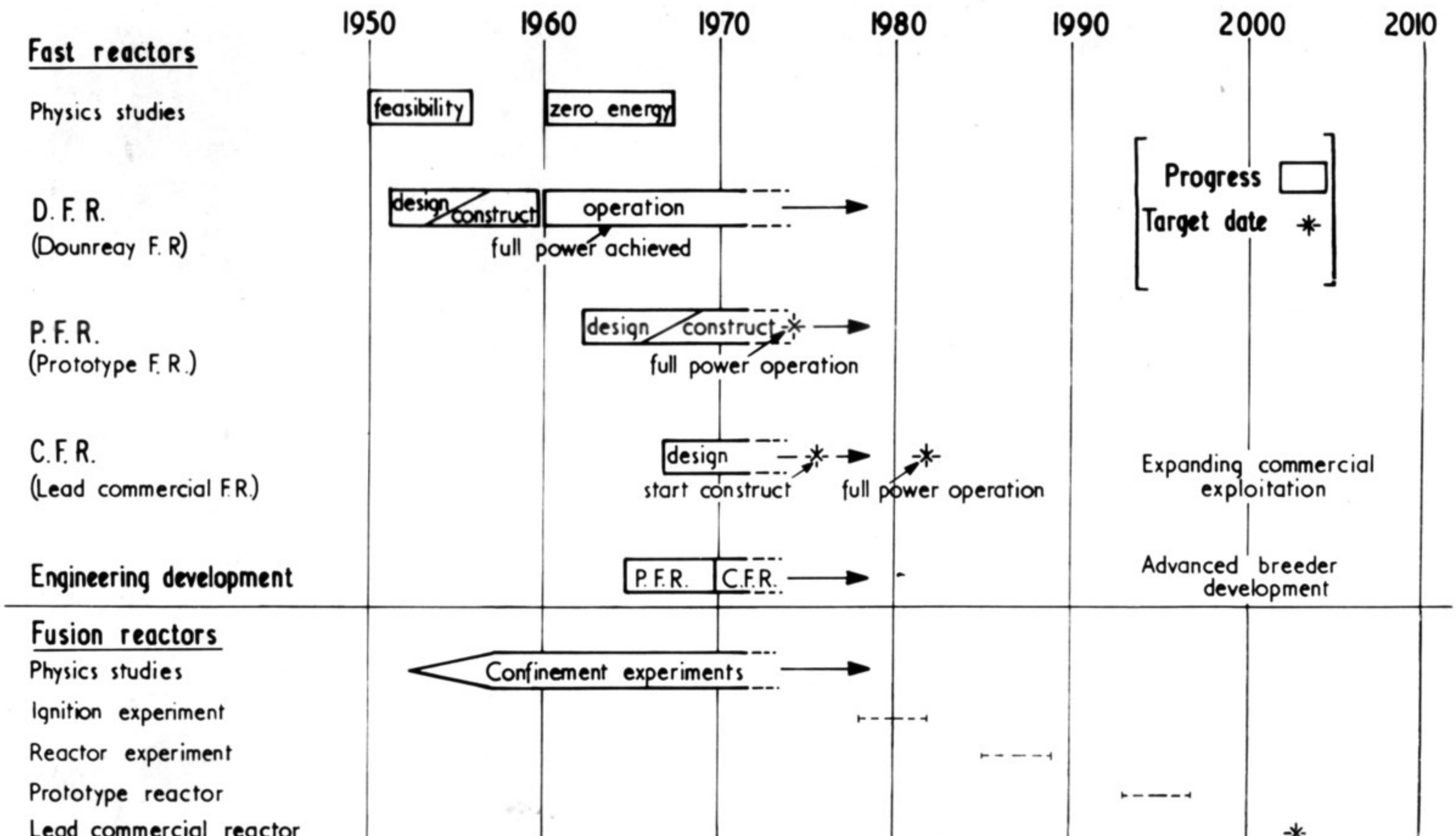


Fig. 11 *Development programmes—fast breeder and fusion reactors*

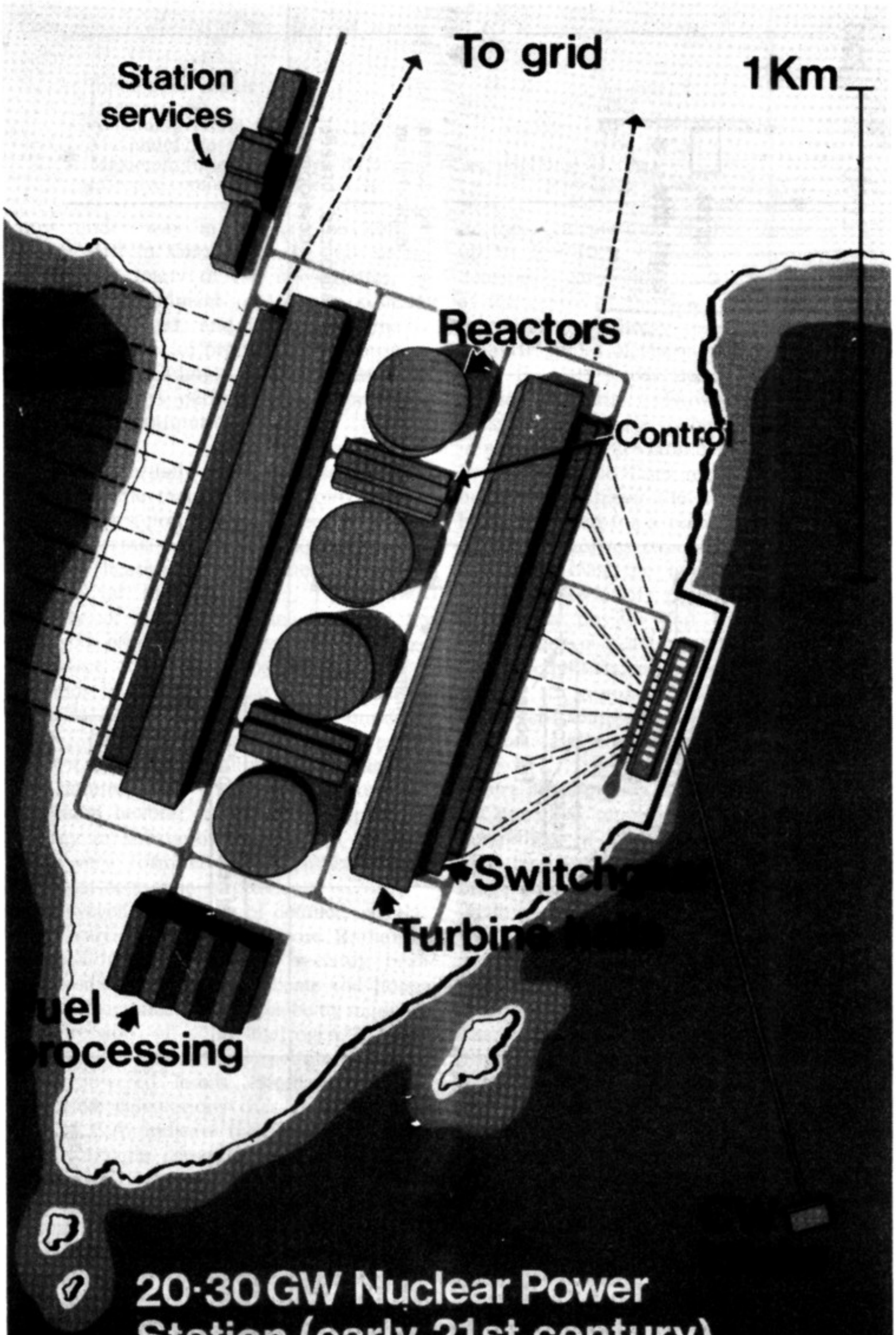


Fig. 12 *20/30 GW nuclear power station (early 21st century)*

estimated on the assumptions of favourable progress with plasma physics research and future resource investment, the same as has been devoted to fast breeder fission reactors. Figure 11 also shows a possible progression of development experiments for fusion reactors. With a world research spend of $100-150 × 10^6 per year on fusion, and growing international co-operation, it seems likely that one or other of the highly industrialised countries will be operating some form of fusion reactor prototype by the turn of the century. It will then be possible to make a direct evaluation of the relative merits of fission breeder reactors and of fusion reactors to determine which source of nuclear energy can best meet our long-term energy needs into the twenty-first century.

Size of generating stations and siting problems

The unit size of nuclear reactors has already increased more than tenfold from the 50 MW(e) Calder Hall units. This increase is expected to continue through the fast breeder series and thermonuclear reactor sizes of 2000 MW(e) are contemplated. By the year 2000 the U.K. generating system is likely to have a capacity of about 200 GW(e) or more. All of the nuclear reactors currently under development are essentially heat generators, whose output will be converted to electricity through turbo-alternators. The consequent thermo-dynamic inefficiency will call for waste-heat disposal comparable with that of present generating stations; and, as good sites are already scarce, large output supply blocks for 20 GW(e) or so will be sited on the coast for easy access to cooling water supplies (Fig. 12), each site having a few nuclear reactors and generating sets. The nuclear fuel processing plants associated with fission reactors could economically be on-site, so eliminating the need for transport. A detailed study has been carried out for us[19] which indicates the technical feasibility of such large nuclear sites which also have the potential advantage of using much less land per installed kilowatt than with current stations.

Concluding remarks

In this symposium, our main task has been to present to you the magnitude of the contribution which nuclear energy might make to the energy demands of this century and beyond. We have emphasised that nuclear energy is contributing significantly to electricity generation, and is doing so cheaply and reliably.

The estimated reserves of uranium and thorium and of the light elements deuterium and lithium indicate that there are very large resources of nuclear energy potentially available. The outstanding task is to ensure that they are tapped cheaply.

From now until the end of the century, nuclear energy can and, in our view, should make a much greater contribution to electricity generation in this country—in the first place by the installation of advanced thermal reactor systems which utilise U-235 more effectively—and then by the installation of fast breeder reactors.

With the Prototype Fast Reactor due to come into operation in 1973, we are on the threshold of full-scale tests of the liquid-metal-cooled fast breeder system. The importance of success here will be the access to the large energy reserves in U-238 and the long-term stabilisation of electricity supply costs—a matter of great importance to a manufacturing nation such as ourselves. But for this cost stabilisation to be fully effective, a very much larger proportion of generating stations must be nuclear, generating perhaps 80 per cent of electricity requirement and, as the proportion grows, they must be able to operate effectively at lower load factors, around 50 per cent.

By the turn of the century, fusion reactors, currently the subject of rapidly developing research, may well be available in prototype form, not least as a result of the growing international co-operation in the field. This would make available a new, very cheap and abundant nuclear fuel which has potential environmental advantages. Ultimately, however, if both fast breeders and fusion are technically successful, the choice between fission and fusion will turn on overall costs, and we cannot at this stage judge the outcome.

Nuclear energy is mainly envisaged as a generator of electricity. The U.K. installed capacity will grow—perhaps to exceed 200 GW(e) in this century. In Britain, environmental requirements and the need for copious supplies of cooling water suggest that generating parks should be established at selected coastal sites. At each site, there would be a few large reactors and associated plant up to 20 GW(e) output.

Acknowledgments

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References

1. RUTTER, R. I.—Some Aspects of the Performance of the Mark I Gas-Cooled Reactors of the C.E.G.B.—Peaceful Uses of Atomic Energy, Proceedings of the 4th United Nations International Conference, Geneva, 6-16th September, 1971, Paper No. A/Conf/49/P.468.
2. BROWN, F. H. S. — C.E.G.B. Press Release — April 1972.
3. BROOKES, L. G.—Private communication based on United Nations, E.E.C. and E.F.T.A. projection and growth of the world's urban and rural population 1920-2000, Table 53, United Nations, 1969.
4. (a) HUBBARD, M. K.—Energy Resources —Chapter 8 of Resources and Man, U.S. National Academy of Sciences Publication 1703, 1969.
   (b) SELDENRATH, T. R.—Prognosis of world energy supply between now and the year 2000—Chemisch Weekblad, pp. 20-26, October 1970 (in Dutch).
   (c) World Energy Requirements and Resources in the year 2000. A Report by the Department of Economic and Social Affairs of the United Nations. Ibid, Paper No. A/Conf/49/P.420.
   (d) MANDEL, H.—Resources of primary energy—Ibid, Paper No. A/Conf/49/P.371.
5. MOORE, R. V.—Fast breeder reactor power stations—Atom, Vol. 14, No. 3, pp. 59-74, March 1969.
6. BOOTH, E. S.—Whither nuclear power?—Proc. I.E.E., Vol. 118, No. 9, pp. 1215-1226, September 1971.
7. HOLDREN, J.P.—Adequacy of Li supplies as a fusion energy source—Appendix 37 of Hearing before Joint Committee on Atomic Energy of the Congress of the U.S. 10-11th November 1971 (UCID 15953).
8. LEE, J. D.—Tritium breeding and energy generation in liquid lithium blankets—Proc. B.N.E.S. Conf. Nuclear Fusion Reactors, Culham Laboratory, September 1969, Paper 5.3, pp. 471-482.
9. CARRUTHERS, R., DAVENPORT, P. A., MITCHELL, J. T. D.—The economic generation of power from thermonuclear fusion, Culham Laboratory Report No. CLM-R 85, October 1967.
10. CULLER, F. L., HARMS, W. O.—Energy from breeder reactors—Physics Today, Vol. 25, No. 5, May 1972, pp. 28-39.
11. LAWTON, H., *et al*—Irradiation Testing of Fuel for the British Prototype Fast Reactor—Ibid, Paper No. A/Conf/49/P.498.
12. CARTWRIGHT, H., CAMPBELL, R. H., WOLFF, P. H. W.—Review of the progress of sodium-cooled fast reactors in the U.K.—Ibid, Paper No. A/Conf/49/481.
13. Report of the I.A.E.A. Panel on International Co-operation in Controlled Fusion Research and its Application, Nuclear Fusion, Vol. 10, No. 4, 1970, pp. 413-421.
14. PEASE, R. S.—Experiments on the problem of controlled thermonuclear reactions, Nature, Vol. 196, No. 4861, 29th December, 1962, pp. 1247-1253.
15. EVANS, D. E., KATZENSTEIN, J.—Laser light scattering in laboratory plasmas—Rep. Prog. Phys. Vol. 32, No. 2, April 1969, pp. 207-271.
16. ROBINSON, D. C., KING, R. E.—Factors influencing the period of improved stability in ZETA—Proc. 3rd Int. Conf. Plasma Physics and Controlled Nuclear Fusion, Novobirsk, August 1968, Vcl. 1, I.A.E.A., 1969, pp. 263-276.
17. ANASHIN, A. M., *et al*—Experiments on laser and microwave plasma probing and measurements of the diamagnetic effect with the TOKAMAK T3A device—Soviet Physics, J.E.P.T., Vol. 33, No. 6, 1971, P.1127.
18. NUCKOLLS, J., WOOD, L., THIESSEN, A., ZIMMERMAN, G.—Laser compression of matter to super-high densities—Thermonuclear (C.T.R.) Applications, Nature, Vol. 239, No. 5368, 15th September, 1972, pp. 139-142.
19. MERZ & MCLELLAN—Report on the Integration of Fusion Reactors into Power Networks, U.K.A.E.A., Culham Laboratory, 1970.

B.N.E.S. conference

An international conference on "Nuclear Fuel Performance" will be organised by the British Nuclear Energy Society at The Institution of Civil Engineers, London, from 15th to 19th October, 1973.

The purpose of the conference is to bring together engineers and scientists with a direct interest in the performance of power reactor fuel. It should be of interest to those operating or developing fuel for B.W.R., P.W.R., S.G.H.W.R., CANDU, Magnox, A.G.R. and H.T.R. The aim will be to present a balanced programme of papers and sessions dealing with both the gas-cooled reactor fuel and water reactor fuel.

For further information apply to Mrs. J. Grahame, British Nuclear Energy Society, at The Institution of Civil Engineers, 1-7 Great George Street, Westminster, London, SW1P 3AA. Telephone: 01-930 7444.

The changing role of Harwell

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of process plant operations, and the development of methods for the reconcentration of fruit juices or the recovery of effluent waters for re-use.

The environment and its resources

Some of Harwell's most interesting work relates to the present day concern with the protection of our environment from pollution and with the accurate assessment of mineral and other natural resources. We have, for many years, used radioisotope tracer techniques to study the movements of silt and other sediments in estuarine and coastal waters, in particular to assess the relative merits of alternative spoil grounds for dredging operations. This work now includes help with preliminary investigations into other large scale industrial waste disposal schemes, for example of micaceous clay wastes in the English Channel and liquid chemical plant effluent in the Bristol Channel. The Harwell Hazardous Waste Service, based largely on our experience in the handling of radioactive and toxic materials associated with atomic energy, provides an analytical, consultancy and supervisory service that is proving invaluable to industry and local authorities alike.

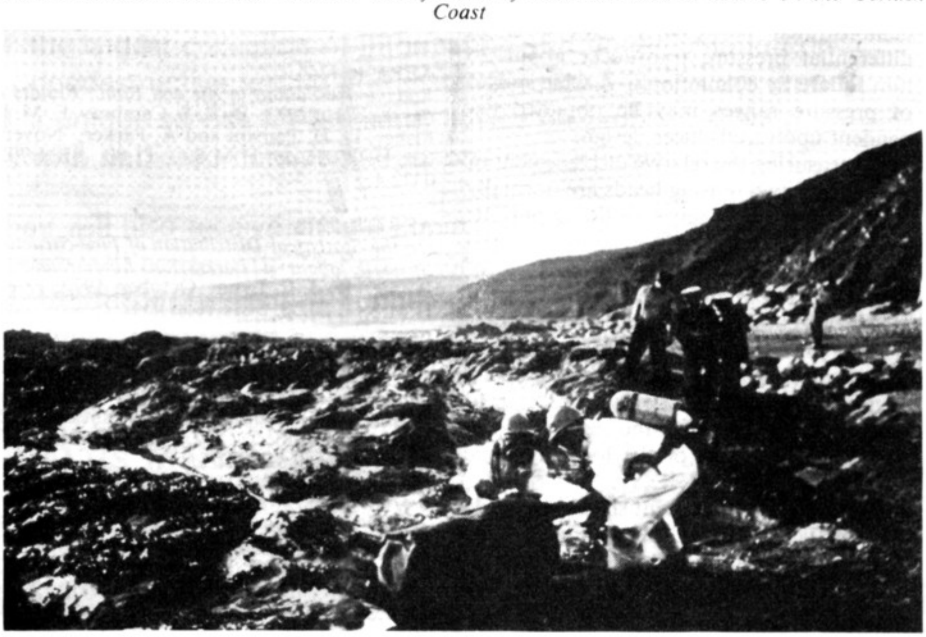
Atmospheric pollution is studied by another Harwell group which operates a nationwide monitoring service aimed at understanding the fundamental nature and causes of the problem.

Hydrological studies leading hopefully to better use of water resources include the accurate measurement of river flow by tracer and instrumental techniques, the investigation of underground water reserves by measurement of low level natural radioactivity, and the study of the mechanism of permeation of rain water through different geological strata. Instruments for geological prospecting and mining control, which help with the efficient and non-wasteful exploitation of mineral resources, include portable analysers and borehole logging probes for *in situ* assay of ore bodies particularly non-ferrous metals such as tin, copper, tungsten and zinc. The mining industry and the instrument manufacturers are both taking an active part alongside Harwell in these developments.

Conclusion

This article describes only a few of Harwell's very wide present-day interests, but it is hoped that it provides the reader with an insight into the way a Government establishment can, given the will and the opportunity, adapt itself to changing circumstances and continue to play a vital and inspiring role in technological advance.

Harwell's Hazardous Waste Service: identification of chemicals washed ashore on the Cornish Coast



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

Novel non-contact measurement

An electronic measuring system, developed in the U.K.A.E.A.'s Reactor Development Laboratories, Windscale, has solved many of the problems of making measurements remotely or at high temperature. The system is based on the accurate measurement of the variation in electrical charge movement between two sets of plates. The refined electronic circuit incorporates compensatory devices which permit changes of 10^{-6} picofarads to be measured at the ends of cables up to 50 metres in length. This technique has been applied to displacement (the basic parameter in most engineering measurement), pressure, differential pressure, fluid flow and transient detection, level determination, intruder detection and other 'quantities'.

The measuring system was developed initially for use in the fluid flow and vibration rigs which are operated by R.D.L., because of a total lack of non-contacting displacement measuring equipment suitable for remote (long lead) applications at temperatures up to 350°C.

Extension of the useful temperature range of the system to about 800°C is readily attained using mineral insulated cables. The high temperature use has been demonstrated particularly with a small differential pressure transducer about 30 mm square by 80 mm long. A wide spread of pressure ranges may be obtained dependent upon transducer design.

In measuring the relative displacement of two bodies, two sensing heads are normally used, giving a very sensitive linear output; for example, a pair of heads about 25 mm square can resolve changes of position of 0.0025 mm for an initial clearance of 25 mm.

The detection of transient flow changes is a very promising application, where the sensor, although in effect a drag-producing device, offers only a very low resistance to flow. In a typical case, the resistance will be only 25 per cent of the local dynamic head.

Enquiries for equipment should be made to the licensees, D. J. Birchall Ltd., Chiswick Avenue, Industrial Estate, Mildenhall, Suffolk. Telephone: Mildenhall (0638) 712288, or for further information contact Mr. J. A. Robson, U.K.A.E.A., Reactor Development Laboratory, Windscale Works, Sellafield, Seascale, Cumberland, CA20 1PF. Telephone: Seascale (094 02) 333, Ext. 6221 or 546.

2nd January, 1973

A.E.A. Reports available

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