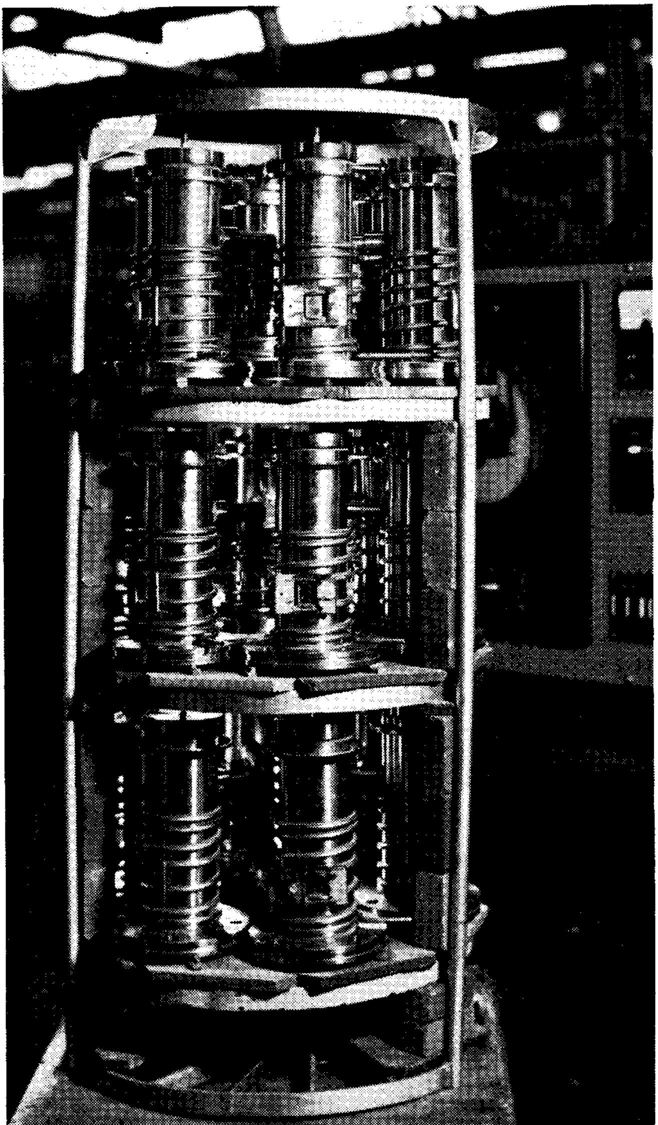
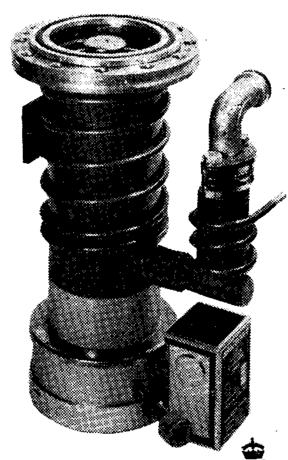
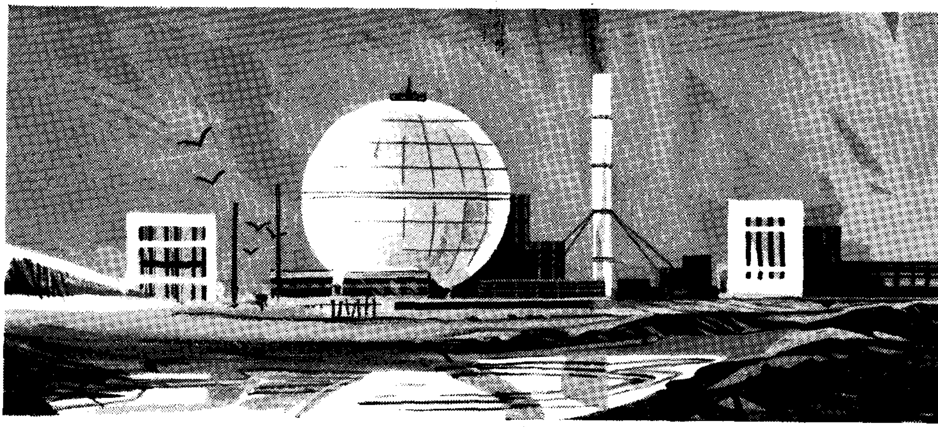
ATOM

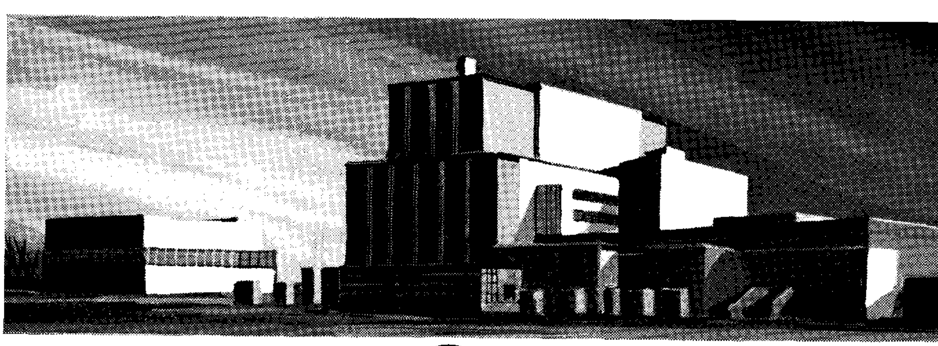
Number 154 / **August 1969**

MONTHLY INFORMATION BULLETIN OF
THE UNITED KINGDOM ATOMIC ENERGY AUTHORITY









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OF THE UNITED KINGDOM
ATOMIC ENERGY AUTHORITY

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Contents

ATOM
monthly bulleting of the UKAEA is distributed to the staff of the Authority, to similar organisations overseas, to industrial firms concerned with the exploitation of nuclear energy, to the Press and to others to whom a record of information of the work of the Authority may be useful

Enquiries concerning the contents and circulation of the bulletin should be addressed to

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

Reprocessing Spanish nuclear fuel

(A similar release was issued in Madrid)

The United Kingdom Atomic Energy Authority and the Spanish Junta de Energia Nuclear have to-day signed an agreement for reprocessing a minimum of 28 tons of nuclear fuel from the Jose Cabrera nuclear power station near Madrid (usually known as the Zorita station). The fuel will be reprocessed at the Authority's reprocessing plant at Windscale, Cumberland, during the period 1971-75.

Background notes

1. The Zorita nuclear power station is a 160 megawatt (electrical) pressurised water reactor. It is the first nuclear power station in Spain.

2. The extracted uranium will be purchased by the Authority and, since it is of U.S. origin, its use will be subject to control for peaceful purposes in accordance with the bilaterial agreements between the U.K. and U.S. Governments.

3. The extracted plutonium is very likely to be returned to Spain for fuelling later civil power reactors. Its use will be controlled for peaceful purposes in accordance with the bilaterial agreements between the U.S. and Spanish Governments, the U.K. and Spanish Governments, and the U.S. and U.K. Governments.

4. U.K.A.E.A.'s plant at Windscale in Cumberland has a reprocessing capacity of over 2,000 tonnes of spent nuclear fuel per annum and is capable of treating natural uranium metal fuels and also enriched uranium oxide fuels. It is currently processing the arisings from the reactors in Britain's nuclear power programme and contracts have been obtained for the reprocessing of fuel from the Tokai Mura reactor in Japan, the Latina reactor and the Garigliano reactor in Italy, the N.P.D. reactor in Canada, and the NOK Beznau reactor in Switzerland.

4th July, 1969.

Lord Penney, O.M.

LORD PENNEY, Rector of the Imperial College of Science and Technology and former Chairman of the U.K.A.E.A., was appointed to the Order of Merit by Her Majesty the Queen on 14th July, 1969.

Royal visit to Winfrith

Her Majesty The Queen and H.R.H. The Prince Philip, Duke of Edinburgh, visited the Atomic Energy Establishment, Winfrith on 11th July, 1969.
Left to right: H.R.H. The Duke of Edinburgh, H.M. The Queen, Mr. Anthony Wedgwood Benn, Minister of Technology, Sir Martin Charteris and Sir John Hill, Chairman U.K.A.E.A.

The DRAGON Project 1959-1969

The Tenth Anniversary of the inauguration of the DRAGON *Project fell on 1st April,* 1969. *At the anniversary meeting attended by guests from many parts of the world, at A.E.E. Winfrith on 25th June, the Minister of State, Ministry of Technology, Mr. J. W. P. Mallalieu, said:*

I am very pleased and honoured to be here today and on behalf of Her Majesty's Government to welcome to this country this distinguished international gathering, to celebrate the tenth birthday of our now world-renowned DRAGON—hot of breath but peaceful of intention.

We have heard an admirable survey of the current status and future prospects of the project from Dr. Shepherd. I am sure we all look forward to hearing from Dr. Eklund, first Chairman of the DRAGON Board of Management, whose reminiscences of the early days we are eager to hear. Perhaps he will not mind if I say here how pleased we are that he has been able to accept a further appointment as Director-General of the International Atomic Energy Agency in Vienna, and that he may be assured of our common support in his important work there.

We are delighted also to have Herr Hellwig with us, as vice-President of the Commission of the European Communities, for our association with EURATOM in this project is one we value.

But now I should also like to refer at this time to a man, now sadly no longer with us, without whose enthusiasm for international co-operation in science and technology, the idea of DRAGON might well never have existed at all. Certainly without his quiet, determined drive towards an objective in which he believed, it would hardly have been so well and truly launched. I refer, of course, to the late Sir John Cockcroft.

The first European project in the formation of which he had a powerful hand was CERN. To quote Lord Penney, Sir John " quietly pushed the scheme forward both in Britain and on the Continent " from 1949 to 1953.

His next venture was the formation of the European Atomic Energy Society, which because it owed so much to his initiative was invariably known in its early days not by its official title but as " The Cockcroft Club ". At a time when official links between national organisations in this field were fewer than they are today, he undertook quite informal discussions with the scientists who were his personal friends all over Europe and formed a small society of which he became the first president. This body published no proceedings but existed none the less to promote among Europeans the exchange of ideas in nuclear research and engineering for peaceful purposes. I am pleased to note that despite the very necessary and desirable growth of more formal associations among the nations, the Cockcroft Club is still active and flourishing.

It was at one of its meetings that the DRAGON idea was born. Sir John recalled at the inauguration ceremony of the DRAGON reactor in 1964, and here I quote his own words: " I remember particularly the conference of the European Atomic Energy Society on the summit of Monte Faito in 1956 at which the project was discussed. I think that this conference had a considerable effect in arousing international interest in the project."

From that time on he was this country's most consistent and determined advocate of an international high-temperature reactor project and we should remember his contribution with gratitude today.

Concept's origin

As you know the high-temperature reactor concept originated in Britain as a result of work done at Harwell in the mid-50s. Its emergence at a time when there was a strong desire in this country to find a firm basis for fruitful international collaboration in the nuclear field put us in a favourable position to submit to O.E.E.C. what we regarded as (and has since proved to be) a highly practical project. The proposal was accompanied by our offer to provide the nucleus of the staff—that is, those who had conceived the H.T.R. idea originally—and a suitable site at the Atomic Energy Establishment, Winfrith.

H.M. The Queen with Mr. D. W. Fry, Director of the Atomic Energy Establishment, Winfrith, in the General Services Building at Winfrith during the Royal Visit to the Establishment on 11th July, 1969.

At this point I should like to take the opportunity of referring to the debt that we—in this country at least—feel we owe to Mr. Compton Rennie, the first executive head of the project. Despite the acknowledged success of CERN in the field of fundamental science, we still felt that the setting up of an international project of a technological character would be taken as an acid test by our European partners of the feasibility of co-operation with us.

In Mr. Rennie we were fortunate to find a man not only of a professional standing that could command the respect of the highly distinguished team of scientists and engineers from all over Western Europe whom he was called upon to lead, but whose natural tact and friendliness and other diplomatic qualities made him a most effective exponent of international collaboration.

I was delighted to see the other day that the United States of America had chosen him for one of their " Atoms for Peace " awards, citing him as " a chief architect of the 12-nation Western European project to build the world's first helium-cooled, ceramic-fuel reactor, a pioneering breakthrough on the long road to breeder reactors that will produce more fuel than they consume ".

Management

But I am sure Mr. Rennie—and Dr. Shepherd, the present Chief Executive—would be the first to admit much of the success of the project has been due to its enlightened system of management. The Board has always been so constituted that technical matters were immediately within its grasp and its clear terms of reference and financing have never required it to refer back to the political area except when extensions of the project were at issue. Given clear objectives and this clear relationship with the Board of Management from the outset, the project has never lacked the authority to carry out its task in the manner which seemed best to those directly involved.

But again it would be wrong to ascribe the whole success of the project either to individuals or to its business-like way of conducting its affairs. Important though both of these have been and still are, the ultimate guarantee of success has been the favourable characteristics of the reactor system itself and for that the signatory countries of the DRAGON agreement must thank their own scientists, engineers and administrators who came together ten years ago to produce the results which we are celebrating today.

Rewards

I think it would be generally agreed that this successful international enterprise has brought two major rewards to those countries who have taken part in it.

First, it has provided a successful demonstration of international collaboration.

Secondly, it has demonstrated the technical success and commercial potential of the high-temperature reactor.

For a comparatively modest investment, every signatory country has received a high return in both these respects. Additionally contracts emanating from the project have been a stimulus to nuclear industry in all the countries concerned and—of perhaps even greater importance in the long term—they have played an important part in establishing international links between industrial concerns in the nuclear business.

Initially the DRAGON project did not need to concern itself with questions of commercial exploitation but, as a consequence of their success, they are learning to live in a new ambience of this sort.

The commercial future of the H.T.R. can now begin to be seen in the fact that Germany and Switzerland are already on the brink of exploitation, and that in the United Kingdom it is being developed as the next stage of advance in our well-established family of gas-cooled reactors.

The fact that European co-operation is a subject in which Her Majesty's Government has a firm and continuing interest will not, I think, have escaped the notice of any of those present here today. I think also that our record of co-operation in the DRAGON project provides an admirable example of the substantial contribution which Britain can make to technology in Europe.

Mr. Secretary-General, this ENEA DRAGON of ours is, as we see, a flourishing creature. We have nurtured him and he has repaid our care, and for our part we shall continue to do the best we can in the future.

Prolongation

Dr. F. Hellwig, vice-president of the Commission of the European Communities, said it was generally known that the Council of Ministers had agreed to the prolongation of the DRAGON agreement until 31st March, 1970. The Commission had now been considering a proposal for a further three years' extension thereafter. The member Governments had taken a positive position on this proposal so that the Council of Ministers should be able to come to a decision at their meeting the following week. He hoped their decision would be favourable.

The Director-General of the I.A.E.A., Dr. Sigvard Eklund said that the DRAGON Project had vindicated the faith of those who still believe that strength lies in unity and who in this belief established OECD and its nuclear power arm ENEA. On the scientific side he described it as *the* most successful regional project and one which could serve as a model for future projects of this type. It was a British concept and so it was fitting that British scientists had so much to do with its execution. He paid tribute to Lord Penney who was for many years a member (and one time Chairman) of the Board of Management and who " directed the project with an iron hand, tempered with a gentleness of manner and a consideration of the individual in a manner which typified his most endearing qualities ".

He also paid tribute to Dr. Compton Rennie, who was Chief Executive for nine years and who was recently awarded the C.M.G. and shared in the U.S. Atoms for Peace prize in recognition of his outstanding work on the DRAGON Project. The citation for the latter testified to the value of the experience gained in the DRAGON project to the American Peach Bottom and the German pebble bed reactors.

The ten years of DRAGON

The following is a report presented by the Chief Executive Dr. L. R. Shepherd, on the occasion of the 10th anniversary.

On 1st April, 1969, the 10th Anniversary of the O.E.C.D. High Temperature Reactor Project, a decade of fruitful collaboration between Western European nations in the field of nuclear technology was completed. It is the purpose of this meeting to commemorate this tenth anniversary and to review the results of the joint undertaking and the current status of the H.T.G.C.R.

At a time when there is a tendency to decry the value of international technical projects it is particularly important to learn from the experience of DRAGON about the effectiveness and problems of a joint enterprise rather than to base judgement on ill-informed commentary. Of course, the most important factor contributing to the success of any project, whether national or international, is its technical and scientific basis. If this is sound then the project, properly organised and managed, will succeed, otherwise it must fail irrespective of the ability of the engineers and scientists engaged and the skill of the management.

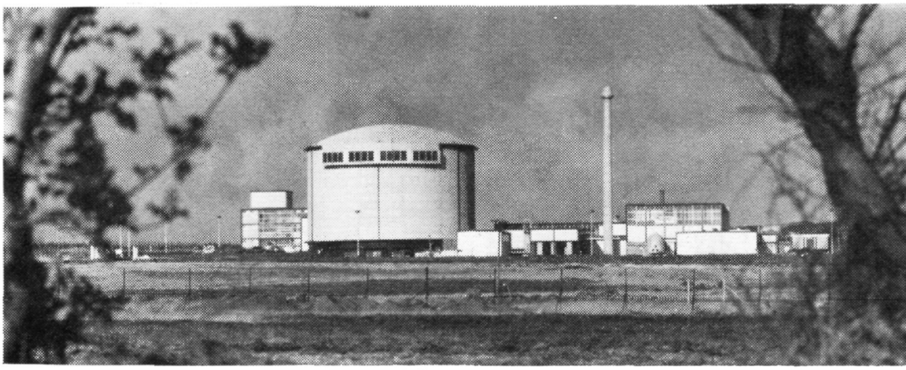
The DRAGON Project is succeeding in meeting its objectives because the concept of the helium cooled high temperature reactor is fundamentally sound. Indeed, it may well be shown by subsequent developments, to be the most viable system to have emerged so far in the application of nuclear energy. It is clear that had there been an O.E.C.D. Project based upon an aqueous homogeneous reactor as was once tentatively proposed, it certainly would have been a failure, because the system, apart from any question of its feasibility, would have lacked any real technical advantages.

Final judgement on the success or otherwise of the Project, of course, can only be made when there are power plants based upon the high temperature gas-cooled reactor technology actually built and operating. The present position, however, looks promising with large sections of the nuclear power industry and several utilities preparing to commit themselves in the construction and eventual operation of this system. It is not too soon, in the circumstances, to anticipate that the objectives of the DRAGON Project will be achieved and the only question to be resolved is whether the manner of their achievement, namely in the framework of an international collaborative enterprise, has been the most economic and technically effective possible. In making an assessment of this, some comparison is possible with the two other major projects concerned with the application of the high temperature gas-cooled reactor, namely those of General Atomic (now Gulf General Atomic) in the U.S.A., and the A.V.R. Project in Western Germany, bearing in mind that fairly close co-operation between the three groups has undoubtedly saved each considerable money and effort. It may be said at once that DRAGON has kept to its timetable at least as well as its rivals and that the cost to any individual Signatory Country has certainly been substantially lower than that incurred by either of the two countries with separate H.T.R. Projects because of the sharing of the budget. To this extent the joint programme has been amply justified.

H.T.R. concepts

The earlier reactors, based on graphite as a moderator, all have their fuel in the form of uranium metal or oxide arranged in a lattice of channels running through a large assembly of graphite blocks. This principle has been followed in the Magnox type, where the fuel elements consist of rods of uranium clad in magnesium alloy, and more recently the A.G.R. in which the uranium metal has been replaced by oxide and stainless steel has superseded Magnox as the fuel element cladding material. All of these power reactors have used carbon dioxide as coolant.

There are certain fairly obvious limitations to power reactors designed on such



A general view of the DRAGON *reactor.*

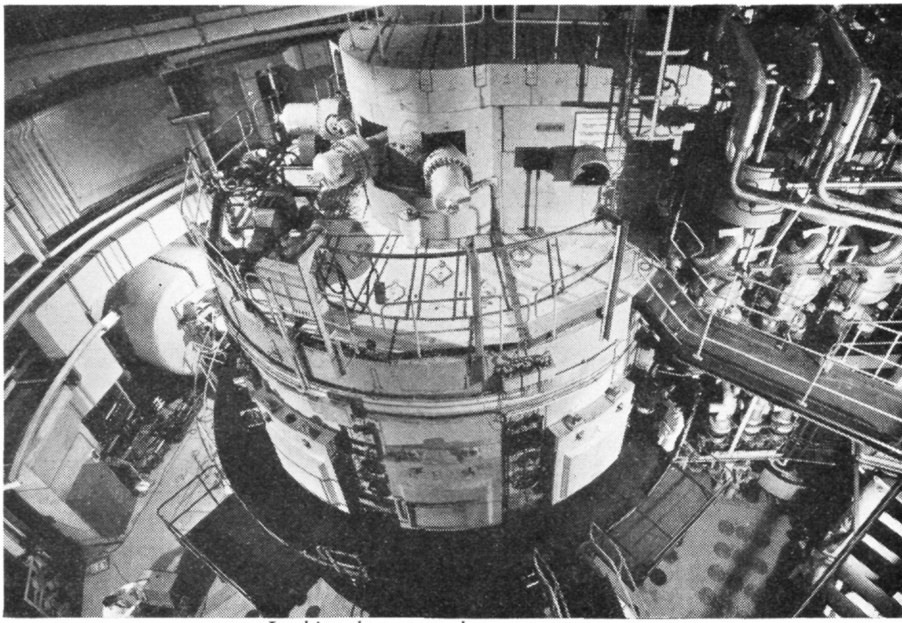
lines. The complete heterogeneity of the assembly restricts the thermal power density that is achievable since nearly all the heat is produced in the fuel rods which constitute only a very small fraction of the core. Consequently only low thermal power densities are achievable and relatively high temperature differences exist between the hottest regions of the fuel and the coolant. In addition the heat producing region of the core has a relatively low thermal capacity which can give rise to rapid temperature changes in the event of power excursions. Recent work has also indicated a further factor restricting the power density which relates to the dimensional changes arising in the fixed graphite structure as a result of fast neutron irradiation. Bearing in mind that this graphite is intended to remain in the reactor during the whole of its life, any constraint on the maximum permissible fast neutron dose necessarily restricts the power density that can be accepted.

The use of carbon dioxide, or for that matter any coolant that is not chemically inert, must also set an upper limit on the reactor outlet temperature.

The high temperature gas-cooled reactor departs in important respects from the established gas-cooled systems in such a way as to eliminate the shortcomings of the latter. In the first place the need to achieve a fairly high degree of homogeneity in the core has been recognised and the fissile and fertile components of the fuel are incorporated to a large extent in the moderating material. This results in a much higher proportion of the reactor core assembly being used for heat production, increases the heat transfer surface area and thereby reduces the temperature differentials. Consequently, although the maximum gas temperature in the H.T.R. is much higher than in any other system, the peak fuel temperatures are not. Furthermore, in the classical version of the high temperature gas-cooled reactor, that part of the moderator which is not intimately mixed with the fissile and fertile material is used as fuel element structure so that the whole of the core moderating material is removed at the end of the fuel cycle and none is left permanently standing in the reactor. Excessive fast neutron doses are thereby avoided and this, together with the better distribution of heat production, permits the achievement of higher thermal power densities which in turn lead to compact reactor assemblies and smaller and less expensive pressure vessels.

The second important feature of the high temperature gas-cooled reactor, in the version intended for power production, is the adoption of a noble gas coolant (helium) which immediately leads to the possibility of attaining very much higher outlet temperatures than would have been feasible with any other conceivable heat transfer medium.

The third feature, which is also essential to the achievement of high coolant temperatures, is the elimination of metallic cladding of the fuel. This is probably the most novel and critical factor in H.T.R. design, in that it has necessitated the employment of graphite sheaths and graphitic and ceramic materials to contain the nuclear fuel and its highly radioactive fission products. The success of the high temperature gas-cooled reactor has depended primarily on the feasibility of this particular feature. The fact that it has proved to be completely practicable has resulted in a reactor whose core is almost indestructible



Looking down onto the DRAGON *reactor.*

and not susceptible to the sort of melt-down accident that is encountered in other reactor types.

The combined use of helium and the graphite ceramic construction has opened new possibilities for the achievement of high gas temperatures, the ultimate limitation being eventually set by the primary circuit structure and components rather than by the materials of the core. The achievable temperatures make it possible to operate simple and highly efficient steam cycle power conversion with extremely compact steam generators and ultimately, perhaps more significantly, to use the coolant itself as a working fluid in gas turbine power conversion systems.

Concepts of high temperature gas-cooled reactors that have been evolved up to the present time may be divided broadly into two classes according to the construction of the core, these are—

(i) Prismatic cores and

(ii) Sphere beds.

The prismatic core was adopted by the DRAGON Project and also by General Atomic. It admits of a number of variants according to the manner in which the fuel is distributed, but broadly speaking there are two principal categories, namely (a) that in which all the moderator is contained in the fuel rods, partly as containment, (sheaths or tubes), partly in the fuel body, i.e. mixed with the fissile and fertile material, and partly in the form of spines or unfuelled central zones; (b) in which the bulk of the graphite is in the form of blocks through which coolant channels run and which contain fuel rods or pins—these structures more or less similar to the rods in the first category.

The DRAGON Reactor Experiment and Peach Bottom Reactors were based on the first category of prismatic construction, but subsequent designs for power reactors are of the second category.

The sphere bed type, otherwise known as the pebble bed, has formed the basis of the A.V.R. Reactor at Jülich in West Germany. It was also involved in studies carried out in the U.S.A. and elsewhere.

A variant of the sphere bed reactor is one in which very small spheres, of the order of 1 millimetre diameter would be involved. This form has been suggested for cases where very high thermal power densities are required (originally as a basis for nuclear rockets, but more recently for gas-cooled fast reactors).

Up to the present time the technology of the high temperature gas-cooled reactor has been applied specifically to thermal neutron systems, and not to fast reactors. Although the early ideas embraced the possibility of using beryllia or graphite as a moderator, subsequent developments have centred entirely around the latter. Work on beryllia has been held in abeyance and while the possibility of its ultimate use in certain circumstances is still recognised, it is doubtful that it is of any significance at the present stage of development of the high temperature reactor.

Special problems of the H.T.G.C.R.

The high temperature gas-cooled reactor, naturally, has many features in common with the earlier types of gas-cooled system, and where the problems are similar the solution already adopted in the established systems will be applicable, for example, the use of concrete pressure vessels in the large civil power plant. However, there are many problems peculiar to the high temperature reactor and it is these that have been identified and investigated by the DRAGON Project and the other groups concerned with the development of this system. The problems arise especially in connection with:—

(i) the graphite/ceramic core construction with its absence of metallic containment and structural components;
(ii) the use of helium and its technical and economic consequences;
(iii) the high coolant temperatures;
(iv) particular engineering features, for example, that arising from the requirement of complete core removal.

The use of graphite as a structural material, and as a containment for the fuel and its highly radioactive fission products, is perhaps the most revolutionary feature of the H.T.R. It was obviously necessary to establish that graphite structures could be handled, that they could withstand the conditions of exposure in the reactor core, that is to say the effects of fast neutron irradiation, and any chemical attack at the very high temperatures of operation by reactive components in the environment.

At the elevated temperatures involved, graphitic materials had certain obvious advantages compared with any metals or metallic alloys especially with regard to their refractory characteristics and thermal and mechanical properties. However, it was recognised that, in the absence of metallic barriers, the diffusion of fission products and their migration into the primary circuit would constitute a serious problem. First thoughts, in this connection, were concerned with the diffusion of noble gas fission products and on this basis the concept of the purged fuel element (adopted in the DRAGON Reactor Experiment and the Peach Bottom Reactors) was evolved as a method of containment. However, it was realised subsequently that certain other solid or volatile fission products, for example, strontium isotopes, presented the main problem.

The problems relating to the use of helium in the high temperature reactor are primarily associated with the need for conserving it and for maintaining it in an adequate state of purity, but it was also appreciated that certain problems would be encountered with materials in a very pure helium environment that were not normally involved in other more conventional gases.

With regard to conservation, the crucial factor is the comparative scarcity of helium, and the relatively high cost of its extraction and transportation. Clearly, helium could not be disposed of as readily as common gases such as nitrogen or carbon dioxide which may be thrown away without serious economic penalty. Consequently, high standards of leak tightness would be required in the circuits of high temperature reactors which would influence both the standard of manufacture of reactor components and also lead to special design features. Any penetration into the reactor circuits would demand special attention to the method of sealing employed and there would be a strong incentive to eliminate penetration by rotating or moving shafts.

Since the primary reason for using helium as a coolant lies in its complete chemical inertness, the achievement and maintenance of a high level of purity is obviously a major concern. At the high temperatures of operation contemplated, the presence of significant concentrations of impurities, particularly of the oxidising varieties such as carbon dioxide and water vapour, could lead to excessive corrosion of the core graphite and deposition of this carbon around the primary circuit. This would necessitate thorough investigations of the manner and extent of core corrosion and carbon deposition to determine permissible levels of concentration of such oxidising impurities, and a complementary development of appropriate methods for continuous purification of the helium. It was recognised that the initial source of such impurities in the reactor was likely to be the large quantity of graphite making up the core and reflector of the system, but in the long run the possibility of leakage of water vapour from the high pressure steam generators into the lower pressure primary circuit helium might be the main source of impurity. The problem of purifying helium to extract embarrassing oxidising species is coupled with the requirement to remove any gas-borne fission products, particularly isotopes of the noble gases, krypton and xenon which escape from the very hot fuel.

The achievement of a very high degree of purity in the helium raised its own special problems which were also recognised at the outset. These include difficulties which are also encountered in vacuuo, namely, that of the sticking of surfaces that are in intimate contact and the problems of bearings, etc., that result from this phenomenon. Furthermore, in very low concentrations of oxidising impurities certain metal and alloys at high temperatures can display undesirable characteristics that arise from the absence of adequate oxide diffusion barriers protecting their exposed surfaces. While it would be easy to exaggerate the importance of these phenomena, they have nevertheless, necessitated careful attention in the choice of primary circuit materials.

The high helium temperatures achieved in this reactor system, of course, in themselves present problems with regard to thermal insulation and the choice of materials for primary circuit components and structure. Helium outlet temperatures may range from 750°C upwards according to whether the system is to use steam power conversion or gas turbines. As the temperatures are increased the problems will become increasingly severe, and eventually it is to be expected that some limitation may be set despite the inert nature of the coolant. We are not presently at this stage of limitation even with conventional primary circuit metals.

It has already been emphasised that the conservation of helium introduced new problems in engineering design. One of these has resulted in extensive work on the application of gas bearings in the circulating equipment. However, it is perhaps the matter of fuel handling that is of major concern to the designers of a high temperature power reactor because of the need to remove all the core structure with the fuel. It is this aspect of the high temperature reactor that has given rise to the alternative lines of development of prismatic or sphere bed systems, and it is important to emphasise that while the nature of the problem is differing between the two lines of development, neither is free from handling problems.

Developments leading up to the Dragon Project

The basic idea of a gas-cooled reactor in which fuel in a ceramic form is more or less homogeneously incorporated with a graphite or beryllia moderator, goes back to the early days of atomic energy. Proposals both for power and particular propulsion applications, where high temperatures and power densities would have been involved, were advanced more than 20 years ago, but no serious work on such systems was undertaken until the latter half of the 1950s.

The prismatic concept, upon which the DRAGON Reactor Experiment and the Peach Bottom Reactor were eventually to be based, was evolved at A.E.R.E., Harwell during 1956. In February of that year a High Temperature Gas-Cooled Reactor Project Group was set up in the Reactor Division of A.E.R.E. to consider the feasibility of a helium cooled reactor of the thermal neutron class based on graphite or beryllia moderation and with emphasis on thorium fuel cycles. The possibility of having to use an alternative coolant to helium was kept in mind and initially the idea that the mixture of nuclear fuel and moderating material in the fuel elements might have to be clad in metal was also envisaged. In fact, some of the earliest proposals entertained the idea of using zirconium or stainless steel clad fuel elements. The evolution of ideas, however, was extremely rapid and within the first two months the possibility of metal sheathing was abandoned and the challenge of relying entirely on graphite fuel containment accepted.

It was recognised that so many novel features were involved in the high temperature gas-cooled reactor that an essential preliminary to its industrial application would be the construction and operation of a reactor experiment. By early April, 1956, a design concept for such a reactor of 30 MW thermal power output (later reduced to 10 MW) had emerged, incorporating the main core and pressure vessel layout features that were subsequently adopted in the DRAGON Reactor Experiment.

During the ensuing three years which preceded the start of the DRAGON Project, work proceeded on the reactor experiment concept, design features were pursued in a certain amount of detail and some early development work on components was undertaken. Reactor physics investigations embraced no only the problems of the proposed reactor experiment, but also were concerned with the study of thorium fuel cycles for power reactors. Some preliminary assessments of the economics of the system, as applied to electrical power generation, were included. Appropriate methods of reactor physics calculations were evolved and associated computer codes prepared. Possible methods for purifying helium were investigated and some initial studies of graphite corrosion at elevated temperatures were undertaken in order to arrive at specifications of acceptable impurity concentrations.

Of particular importance was the work carried out on the incorporation of uranium and thorium with graphite to form fuel bodies. Cold compacted mixtures of the carbon and metal powder were developed for this purpose and an irradiation programme was instituted to test their behaviour under reactor operating conditions, especially to determine the extent of fission product emission from them at high temperatures. To prevent migration of the radioactive fission products into the primary circuit a design of purged fuel element was evolved which required the use of an impermeable graphite sheath around the fuel body and a bleed flow of helium passing down through this fuel rod to sweep the emitted radioactive gases into a fission product trapping system which was also to combine the function of helium purification system. This was the principle of fission product containment which was eventually adopted in the DRAGON Reactor Experiment. However, while accepting this method of containing the radioactivity, the idea was advanced, in 1957, of coating individual grains of uranium carbide with pyrolytic carbon, by which means it was expected that the fission product activities could be confined at their source. The feasibility of this idea was not to be established for a further three years when the DRAGON Project was already in existence and suitable methods of coating small spherical fuel particles had been developed in the U.S.A. Two important major experiments were initiated by the early Project Group and subsequently taken over in the DRAGON Project programme, namely, ZENITH, a hot zero energy reactor and a large experimental loop that was to be installed in the PLUTO reactor at Harwell.

While, during this pre-DRAGON period, the investigation of the high temperature gas-cooled reactor was centred about the Project Group at A.E.R.E., the rapidly expanding scope of the work embraced activities in other Harwell Divisions, and eventually a Design Office was set up in the Industrial Group of the U.K.A.E.A., with the intention of carrying out the detailed design and construction of a reactor experiment. This latter enterprise, however, was short-lived because of the pre-occupation of the Industrial Group with the Advanced Gas-Cooled Reactor, the fast reactor and other systems which were being actively pursued by the Authority. Towards the end of 1957 the idea gained ground that the high temperature gas-cooled reactor might be an important subject for a collaborative programme within the then O.E.E.C. framework. A paper summarising the state of the work in the U.K.A.E.A. was prepared and presented at a European Atomic Energy Society Symposium in Rome—27th to 29th November, 1957. This paper was brought up to date and subsequently presented at the Second Geneva Conference on the peaceful uses of atomic energy in September, 1958. The subsequent sequence of events following the proposal, which was put to the top level O.E.E.C. Committee on co-operation in the reactor field in March, 1958, have been outlined in the First Annual Report of the DRAGON Project and need not be repeated here. The proposal, which was for a joint Project at A.E.E. Winfrith, over a period of 5 years, embraced the construction of the reactor experiment, now uprated to 20 MW thermal power, and an associated research and development programme in high temperature gas-cooled reactor technology. Although a provisional estimate of £10M as the cost of such a Project had been put forward, a more detailed estimate by the Project Group and the Design Office of the Industrial

Group indicated a figure of £13.6M. The U.K.A.E.A. undertook to bear the difference in cost in addition to its own contribution to the original £10M, taking into account the fact that it would inherit the reactor experiment and the other assets of the Project at the termination of the Agreement.

In the final year, prior to the start of the DRAGON Project, the work was concerned to some extent with the preparation of proposals for consideration by the technical experts of the prospective Signatory Countries, and a preliminary technical assessment was made by a group of experts in May, 1958. The status of the work that had been done was reviewed and proposals were set out for the future programme including the design and construction of the reactor experiment. A time-table based on an assumed start of the detailed design work in mid-1959, and construction of the reactor experiment commencing on the 1st April, 1959, envisaged the completion of this work by the end of 1962 and the commissioning period and approach to criticality from mid-1962 to the middle of 1963.

Work of the Dragon Project

Although the Project started nominally on 1st April, 1959, there were considerable delays primarily associated with the building up of staff and facilities on the Winfrith site. Detailed design and manufacture of reactor experiment components except in the case of one or two key items kept reasonably well to schedule, though start of construction in early Spring of 1960 was some six months later than had been envisaged in 1958. Eventually the loading of fuel in the reactor experiment took place in August, 1964, and the reactor achieved criticality on the 23rd of that month. It was not possible, however, to embark on operation at power until the middle of 1965, some two years later than had been assumed in 1958.

In judging this performance, it is important to stress that none of the delay could be attributed directly to problems arising from multi-national participation. The important fact emerges that the purely national H.T.R. projects, namely, the A.V.R. and Peach Bottom Reactors were subject to similar delays and the DRAGON Reactor maintained a clear lead over its 'rivals' in reaching the operational stage.

With the creation of the DRAGON Project it was possible to greatly expand the scale of the research and development programme. To a large extent this benefited from the international nature of the enterprise, since useful facilities became available to the Project often on extremely favourable terms and the skills of staff in the various establishments of the Signatory Countries were usefully applied in support of the work. One area in which this was particularly true was in the programme of irradiation testing of the core components, i.e. the fuel elements and graphite. Following the first two Geneva Conferences several countries in Western Europe had planned the construction of relatively sophisticated research reactors and these began to operate at just the right time to be of use to the Project in its fuel development work. As a result, by the end of 1962 a very powerful test programme was in being.

Although the intention was to conduct a broad research and development programme covering problems of high temperature gas-cooled reactors in a general way, from the start of the Project, the objectives became more specifically directed to the immediate requirements of the reactor experiment. This was particularly true in the area of fuel element development where an early decision was made that the Project should set up facilities to manufacture the fuel bodies and establish a line to assemble the fuel elements for the reactor experiment from machined graphite and metal components made by external contractors to DRAGON specifications, and the fuel bodies made by the Project itself. All the initial development was directed towards the support of this production programme. Initially, before the successful introduction of fission product retaining fuel, the emphasis was on the development, in collaboration with graphite producers, of a material having a sufficiently low permeability to meet the requirements of the purged fuel element. With the introduction of the coated particle concept, however, this work became irrelevant and was discontinued. Thereafter no further graphite development was undertaken by the Project, all subsequent work in this area being concerned with the evaluation of commercial products that seemed appropriate to the high temperature reactor requirements.

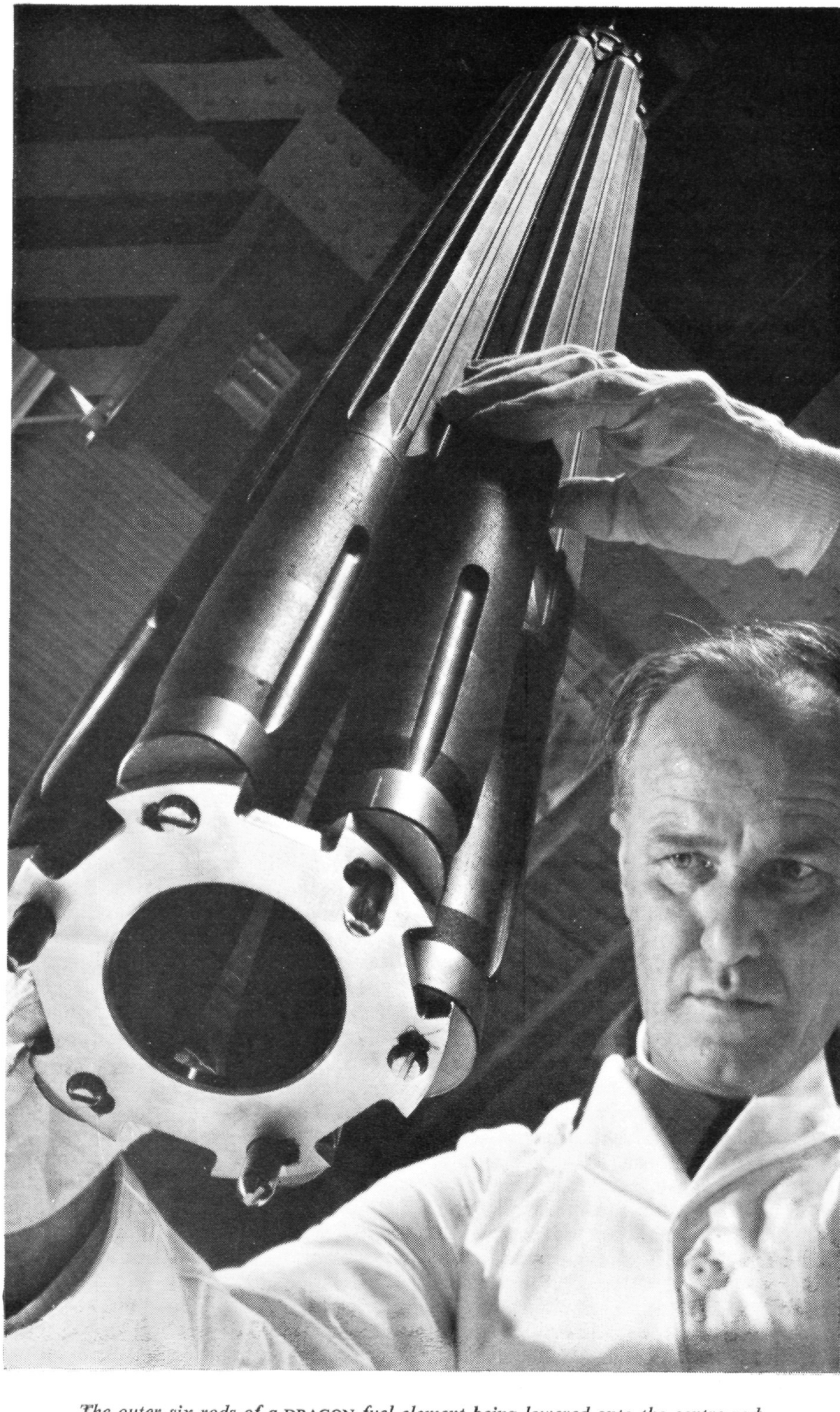
The original thoughts on fission product retaining fuel and early experiments at Harwell, prior to the DRAGON Project, related to the coating of small irregular carbide fuel particles (in the range 50/100 microns linear dimensions) by the pyrolysis of propane or benzine at relatively low temperatures (less than 1,000°C). It was envisaged that this coating could be deposited in fluidised beds or in a tumbler furnace through which the hydro-carbon was passed and in the Harwell experiments the latter process was chosen. The attempts were not particularly successful. Subsequently experiments in the U.S.A., at the Battelle Institute, Columbus, Ohio, materially improved the process by starting with spherical carbide particles and coating them in a fluidised bed at substantially higher temperatures. Communication of information to the Project on the success of this process was the result of a fruitful collaborative agreement between the Project and the U.S.A.E.C., which was started in 1960, and which provided for the exchange of information on the work done by the Project in connection with the reactor experiment and that done by General Atomic in their Project to construct a high temperature gas-cooled power reactor at Peach Bottom, Pennsylvania. The DRAGON Project, during 1961, with the aid of its contractors, very quickly adopted the techniques for producing coated particles, and, indeed, considerably improved upon these. Much of the ensuing irradiation test programme was concerned with the evaluation of this type of fuel with particular emphasis on developing a satisfactory material for the initial charge of the reactor experiment.

One of the more important steps taken by the Project in the coated particle development was the introduction of composite coatings which involved a layer of silicon carbide sandwiched between pyrocarbon layers. The great advantage in this type of coating lies in the fact that silicon carbide forms an effective barrier against the diffusion of certain alkali, earth, and rare earth metallic fission products which diffuse rather readily through pyrocarbon.

In its work to establish the characteristics and fabrication techniques for the reactor experiment fuel, the Project had to follow two lines. Ultimately the interest was in the development of fuel for power reactors and such fuel would consist mainly of fertile material (U-238 or Th-232) containing a smaller proportion of fissile material, e.g. U-235. In typical power reactor fuel cycles, one would expect to find ten or more fertile atoms per fissile atom in the fuel body. It would not have been possible to have filled the DRAGON Reactor Experiment core with material of this type because of its small size and consequent high neutron leakage. As a result only 25% at most of the DRAGON Reactor Experiment core could be taken up by fuel which was relevant to power reactors. The remaining 75%, of necessity, had to incorporate highly enriched material (93% U-235) to keep the total neutron absorption within reasonable limits. As a result the core of the reactor experiment is made up of so-called driver fuel (the highly enriched type), which has to be replaced at intervals of less than 200 days in order to maintain adequate reactivity, and experimental fuel, which is that containing fertile material and which is the subject of investigation into appropriate materials for power reactors. The latter may remain in the core for an indefinite period, because the fissile material is continuously replenished.

Initially, the Project being concerned with thorium cycle fuels, the emphasis was on experimental fuel in which the fertile material was thorium. When later in 1967 the emphasis moved to low enriched uranium cycles considerable rethinking was necessary in the specification of coated particles and fuel bodies with the result that, to some extent the experimental evaluations of the materials had to be started anew.

It is not the purpose of this review to go into the details either of the research and development programme or of the problems of construction of the reactor experiment since these have been fully covered in the Annual Reports of the Project and other publications. It is sufficient to say that over the first three or four years from the start of the Project satisfactory solutions to those problems outlined in a previous section were obtained in respect of the requirements of the reactor experiment. Particular reference may be made to the development of leak tight joints, valves and welds and to the application of mass-spectrometry leak detection on a factory scale to ensure the leak tightness of the components fabricated for the reactor



The outer six rods of a DRAGON *fuel element being lowered onto the centre rod.*

experiment, and finally the use of the same techniques during the assembly stages of the reactor. As a result the plant conformed to the apparently severe specification which laid down that less than 0.1% per day of the contained helium could be allowed to escape from the primary circuit. Relating to the requirement for high standards of leak tightness, the Project had decided to use completely contained electrically driven circulators in the primary coolant circuit of the reactor in order to avoid problems with shaft seals. Despite the relatively large size of these units it was further decided to adopt dynamic gas bearings in preference to the more conventional oil lubricated bearings in these circulators. The successful development of such units by DRAGON Project contractors was one of the important results of our work. Satisfactory solutions were found also to the difficulties arising in connection with the operation of both dry and lubricated bearings and gears in highly pure helium environments in so far as such problems were encountered in the reactor experiment and, where the duty of such bearings is relatively light, these empirical solutions should find wider applications in future plant.

The prismatic concept of the high temperature reactor involves the handling of large complicated graphite structures. This is particularly the case in the DRAGON Reactor Experiment where the original fuel elements are complicated clusters of seven rods making up a structure some 2½ metres in height. The handling of such elements, and, in particular, the problems of charging and discharging them from the reactor by remote means within the helium environment constituted a major item in the engineering development. The eventual equipment, designed and constructed for the reactor, has up to the present time been completely successful.

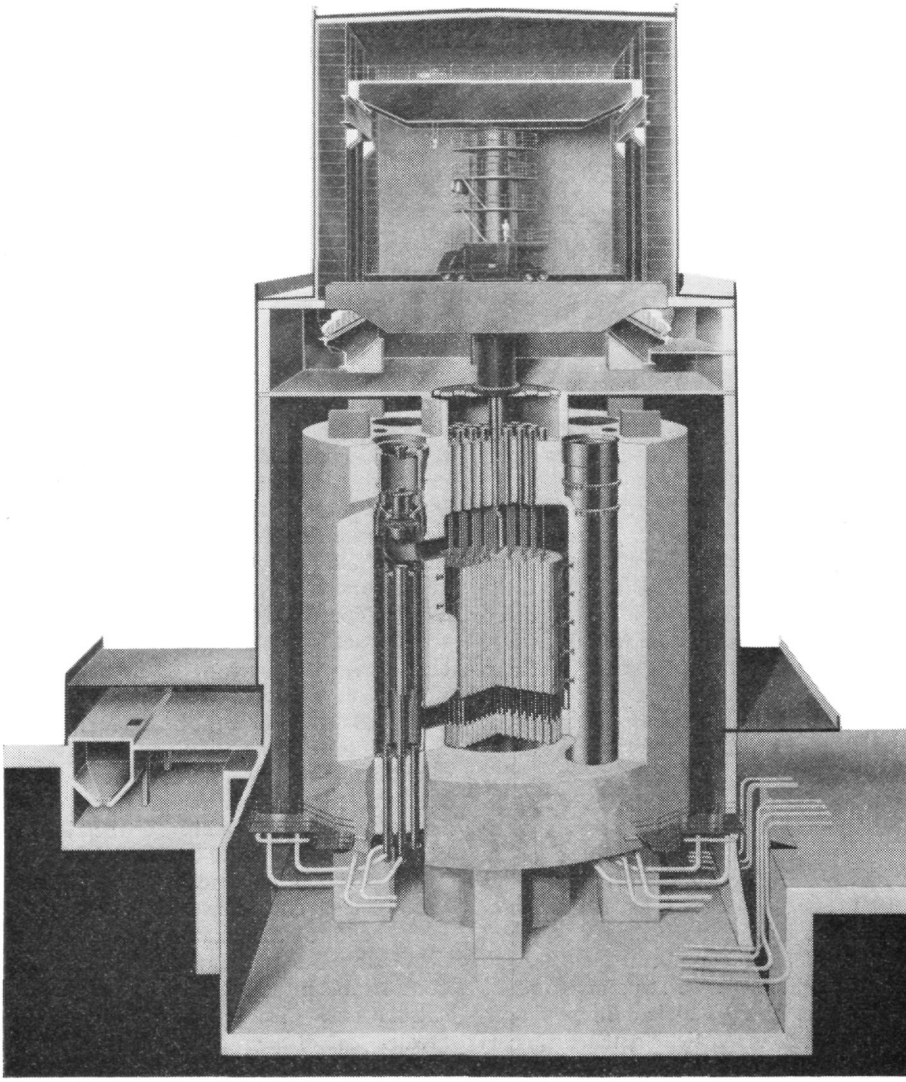
Considerable work was done by the Project relating to the specification of the permissible amount of impurity in the helium. This involved graphite corrosion studies done in a variety of loops including one operating in a research reactor. The complementary work carried out on the purification of helium and the removal of gaseous fission products was also an important aspect of the programme which involved the construction of a pilot plant comparable in size to the units ultimately constructed for the reactor experiment. The work included useful development in the instrumental field in connection with gas analysis and the resulting techniques allow for the measurement of the significant impurities down to concentration levels of about one part in 10^8.

Much of the engineering development was peculiar to the reactor experiment, for example, the use of the steel pressure vessel, and the fact that the DRAGON circuit did not include high pressure steam generators which would be the case in steam cycle power reactors. However, many of the investigations have resulted in solutions which are no less relevant to the problems that will be encountered in large power reactors, and the work of the Project in these areas can be considered to have been very important in the general development of the reactor system.

Heat transfer was never considered to be a critical problem in this reactor because of the refractory characteristics of the fuel elements. However, it is naturally important to establish the fuel body temperatures since these govern the rates of fission product emission, so the Project conducted investigations on convective heat transfer, thermal conductivities of the materials involved and of the helium gaps which were present in fuel elements.

The design of the reactor experiment and the eventual core constitution, the problems of control, temperature, poisoning and depletion effects naturally necessitated a considerable programme of reactor physics calculations. These items made up the greater part of the physics work, but some effort was devoted to the study of fuel cycles for power reactors, and as time went on this was increased. The use of thorium as a fertile material almost exclusively dominated fuel cycle studies until mid-1966, after which the emphasis moved towards low enriched uranium cycles.

While it may be said that most of the special problems of the high temperature reactor had been anticipated even before the start of the Project, the nature of the problems changed materially with the evolution of the reactor concept. This was particularly true of the core and fuel elements where, as we have already emphasised, the problems initially centred around the achievement of low permeability and high density graphites appropriate to the purged fuel element idea. The actual



A model of an H.T.R. (with downward coolant flow) designed by The Nuclear Power Group.

fuel bodies, compacted from heavy metal carbide and graphite powders, did not appear to present a special problem. While it was true that with increase of temperature fission product diffusion rates would also rapidly increase, it was nevertheless assumed that the impermeable graphite tubes and the purged system would prove effective in preventing excessive contamination of the primary circuit. The high dilution of the carbide fuel in these early compacts eliminated the problem of accommodating the less mobile fission products arising from high burn-up. In the third year of the Project the picture changed radically, partly because of the adoption of coated particles and partly because of new facts accumulating from experience in the irradiation of graphitic materials.

It was realised at a fairly early stage, both from the work of the DRAGON Project and that of other groups active in the gas-cooled reactor field, that dimensional changes of graphite and other graphitic materials such as pyrocarbon under fast neutron irradiation could present serious problems. Circumstances would be set up which might lead to fracture of carbon tubes and other structures or of the particle coatings. In fact, at the time that the DRAGON Reactor Experiment was ready to begin operation this was a matter of some concern and very early failure of fuel bodies was contemplated. Fortunately, a second phenomenon, creep induced by fast neutron irradiation, proved to be a vital factor in alleviating the stresses resulting from dimensional changes. Subsequent experience has so far failed to reveal any single graphite tube or structural failure in the DRAGON Reactor Experiment, but it has nevertheless been essential to mount and continue to conduct a major programme of carbon irradiation studies in order to provide data and materials specifications for reactor designers and to determine ultimate limits of failures.

Coated particles introduced their own special problems. Heavy metal loading now became a matter of some concern, since the fissile and fertile materials were concentrated into a relatively small volume instead of being spread throughout the fuel bodies. In most economic fuel cycles, whether based on thorium or enriched uranium, the achievement of a fairly high heavy metal loading is important. In the circumstances coated particles have to be accommodated as closely together as possible; and the kernels must constitute a high fraction of the total volume of the particles. Dilution of the heavy metal carbide or oxide in the kernels with additional carbon is not permissible. This results, naturally, in problems of accommodation of fission products and prevention of swelling under irradiation.

Of course, the effectiveness of the coated particles depends on the coatings being undamaged and uncontaminated with fissile material during manufacture, and remaining intact under reactor operating conditions despite the influence of high burn-up and the fast neutron irradiation of the pyrocarbon coatings. It is not surprising that the many problems of characterising particles, developing adequate production techniques, and determining the limits of operating conditions have occupied a considerable amount of the Project's attention during the ensuing years.

At the end of 1961 the Project was firmly engaged in the first phase of its task, i.e. the design and construction of the reactor experiment and the supporting research and development programme, and it was possible to start thinking about the next phase which would involve the use of the reactor experiment and other facilities and the experience of the Project in the further development and commercial exploitation of the high temperature reactor. At this stage the Board of Management of the Project set up a Working Party to consider the possibility of extending the DRAGON Agreement for a period of three years to the 31st March, 1967. As a result the recommendation was made that the Project should be so extended with a new overall budget of £25M, and that the further programme would provide not only for the operation of the reactor experiment, and continuing research and development programme, but also for an assessment study into the application of the high temperature reactor to commercial electrical power production. The study was to include the production of a reference design of power reactor and an evaluation of its economics.

The recommendations were accepted and the Signatories entered into a new Agreement covering a period of eight years instead of the original five. The DRAGON Project then embarked upon the second phase of its work which was to be increasingly concerned with the exploitation of the high temperature gas-cooled reactor. In the initial stages, however, the Project's engineers were still largely preoccupied with the reactor experiment and the Project's contribution to the power reactor assessment studies set greatest emphasis on core design, physics and fuel element problems. The engineering design aspects were supported in an extra mural contract with two continental reactor constructors both of whom had some experience in the design and construction of gas-cooled systems. The collaborative study started towards the end of 1962 and led, one year later, to the Project's first reference design of a thorium cycle high temperature gas-cooled power reactor. Subsequently, as more engineering effort became available, the Project produced later and more detailed designs with accompanying economic assessments, the results of which were particularly encouraging.

The power reactor studies continued to be concerned almost entirely with thorium fuel cycles up to the middle of 1966 on the grounds that these would ultimately prove the most economic and give the best utilisation of thorium and uranium resources that was possible in thermal reactors. The disadvantage of thorium cycles lies in the requirement of highly enriched U-235 as the fissile feed material and, in view of the doubt attached to the commercial availability of this, it was considered politic to switch the emphasis of the studies to low enriched uranium fuel cycles. There was an initial deviation into a study involving a heterogeneous core layout with most of the graphite forming a fixed structure, as in earlier gas-cooled reactor systems, but serious doubts were expressed concerning the ability of a permanent graphite structure to withstand fast neutron irradiation over the full lifetime of a reactor in the very highly rated cores that were being contemplated. The Project's interest, therefore, reverted to the more homogeneous designs which had characterised the thorium studies and in which all the graphite was incorporated in the removable fuel elements. The Project's work in the assessment field continued on a broad basis up to the Summer of 1968, and in that time all the main features of the present concept of HTR power reactors were set out by the DRAGON engineers, and generating cost assessments made on the basis of the proposed designs. As a result of these fairly detailed studies by the Project, nuclear design and construction groups in industry were attracted by the possibilities of the system, and have taken over the further task of carrying the work to the stage of commercial exploitation. It is worth noting that their subsequent assessments have entirely confirmed those of the Project.

The purpose of the assessment studies has been two-fold, namely, to demonstrate the economic advantages and technical feasibility of high temperature gas-cooled reactor power stations and secondly to help to define the future requirements of the Project's development programme. The latter has been especially true in relation to the work on core materials and fuel elements. In the course of the assessment studies, designs of power reactor fuel elements were quickly evolved and the problems associated with these were exposed. The Project's task was then primarily concerned with the development and proving of the appropriate fuels including the establishment of fabrication techniques and the evaluation of the behaviour of both the fuel materials and the fuel element structure.

The main function of the reactor experiment in this connection has been to act as a fuel irradiation facility and as a means of determining the mutual interaction of the core, the helium environment and the rest of the primary circuit and its components. The maximum availability of the reactor experiment for this purpose has, naturally, been a matter of considerable concern, as it will continue to be in the third phase of the work of the Project which, to a great extent, will be conducted in support of the commercial exploitation of the high temperature reactor.

The first low power operation of the reactor experiment took place in the form of a brief run of about one week from the end of June, 1965 at about two megawatts. Sustained high power operation, however, did not start until early September beginning with an exploratory period of about 50 days at 10 megawatts before going up to full power. Over the ensuing 12 months a total of 225 days of operation was achieved including one virtually uninterrupted run of 100 days at full power. During 1967 and 1968 there were many serious interruptions in the operation programme arising from the damage to the primary heat exchangers due to water side corrosion. The causes of the failures are now fairly well understood being attributable primarily to incorrect water treatment in the secondary coolant circuits, with water flow instability and maldistribution of the helium flow on the gas side as contributing factors. The errors in the water treatment have been rectified and the instabilities reduced as far as possible and as a result the reactor has operated at power for 66% of the available time during the past six months, bringing the total operating time (above 10% of full power) to 650 days, or the equivalent of 500 days at 20 MW. It is worth noting that some of the earliest thorium cycle experimental fuel specimens have been in the reactor for almost the whole of this time and have thereby been subjected to at least 50% of the exposure under operating conditions that they would have encountered in a power reactor working on an economic fuel cycle.

A further extension of the DRAGON Project Agreement from 1st April, 1967 to 31st March, 1970 was negotiated and agreed in stages within a further budget increase to £31M. This enabled the

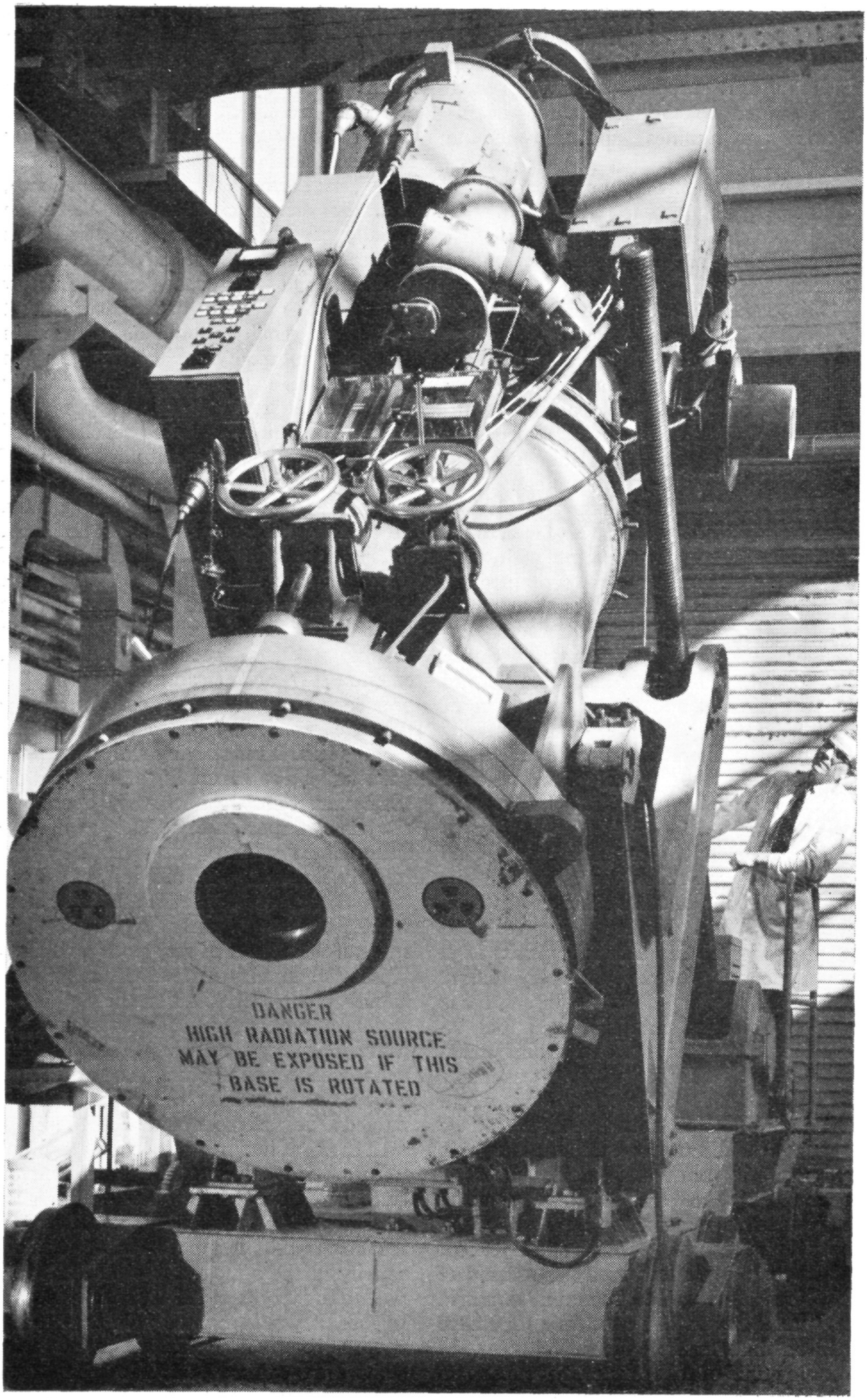
Project to carry the power reactor assessment on the low enriched uranium cycle reactors to the stage where the technical feasibility and economic advantages were demonstrated to the satisfaction of industries and utilities, and allowed the development and testing of the appropriate fuel elements to be taken to an advanced stage.

Present status of the High Temperature Reactor

During the past three years two other helium cooled high temperature reactors, the A.V.R. Pebble Bed Reactor at Jülich, and the Peach Bottom Reactor have come into operation and the experience with these and the DRAGON Reactor Experiment has clearly demonstrated the technical feasibility of this type of system. The operation of Peach Bottom and A.V.R. is particularly interesting in so far as both are power producing systems with high pressure steam generators contained in their primary circuits. In these two power reactors, as in the DRAGON Reactor Experiment, the problems associated with the leak tightness of the pressure vessels and primary circuits and the conservation of their helium content have been adequately solved. It is interesting to note that while shaft seals have been avoided in DRAGON, they were accepted successfully in the other two systems.

The problem of maintaining a high standard of purity of the helium in the primary circuits of these reactors has been resolved to the extent that it is possible in DRAGON to maintain a total impurity level of about one volume part per million. There will be no difficulty in matching this in power reactors provided that inleakage of water vapour from steam generators is kept within reasonable limits. In this connection it is worth noting that no significant steam leakage has so far been observed in the high temperature power reactors presently operating. In the DRAGON Reactor Experiment, the secondary heat exchangers have been completely leak tight except when corrosion has caused penetration of individual tube walls. The tube failures in DRAGON heat exchangers, while they have had an unfortunate effect in reducing the running time of that reactor, have made an important contribution to the technology of the high temperature reactor. The low level of plate-out activity has made them readily accessible and it has been shown to be possible to develop very rapid means of detecting leaks and plugging offending tubes. Current designs of high temperature power reactors involve readily accessible steam generators and it is fair to say, therefore, in the light of experience, that the steam circuits can be made initially completely leak tight, that leaks as they occur can be readily detected and rectified, and that such leaks anyhow should not be frequent occurrences so that no serious penalty should be incurred in shutdown to rectify such leaks. In the circumstances it may be said categorically that there is no reason to suppose that high temperature gas-cooled reactors need operate with significant sustained levels of carbon dioxide and water vapour in the primary circuit and that consequently, problems of core corrosion need not exist.

The accessibility and maintenance of primary core components, of course, depends upon the level of primary circuit radioactivity and the extent to which fission products, such as iodine 131, caesium 137 and strontium 89 and 90, are deposited from the coolant. The ultimate controlling factor in this is the fuel material itself starting with the coated particles, and so the quality of these and the temperature under which they operate is of some importance. The experience accumulated with DRAGON has been extremely favourable in this respect. Even in the first charge of the reactor experiment which contained early types of fuel, some of which was of very poor quality by present standards, the level of the primary circuit activity deposited on the circulators and heat exchangers was not such as to cause significant embarrassment in their maintenance and repair. It has proved possible to abandon the principle of the purged fuel element and despite this, with the continuous improvement resulting from the fuel development, primary circuit activities have been steadily reduced until at the present time, they are so low that corresponding concentrations of radioactivity in the atmosphere would not give rise to a very serious ingestion hazard. In fact, it would probably be true to say that the very low level of gas-borne radioactivity in the primary circuit of the DRAGON Reactor Experiment may be compared favourably with the activity in the primary



A handling flask for irradiated DRAGON *fuel.*

coolant of any other type of power reactor. It is, of course, necessary to demonstrate that correspondingly low concentrations of fission products will obtain in the primary circuits of power reactors, and that the low level of emission of these from fuel elements will be maintained over the full life cycle of the fuel. If, as one confidently expects, such low levels of radioactivity are achieved, not only will the problems of accessibility and of maintenance be relatively simple, but also the safety of the system in respect to an accidental release of primary circuit gas would be very high.

Since the release of fission products into the primary circuit of the reactor will be dependent upon temperature-sensitive diffusion, adsorption and evaporation processes, the operating temperatures of the fuel will be of considerable importance; the higher the peak fuel temperatures the greater the degree of release. Acceptable maximum temperatures will have to be defined, but it is already possible to specify conservative figures which would not be difficult to achieve in appropriate fuel element designs and below which release should not be significant. In this connection, it is important to note that the elements of high temperature gas-cooled reactors do not fail catastrophically at elevated temperatures. For short excursions to high temperature, there is merely a temporary increase in the emission of fission products which reduces to the original level when the fuel is cooled back to the starting temperature. If such excessive temperatures are maintained for several days, permanent damage can result from the interaction of the particle kernels and coatings. Experiments carried out in the DRAGON Project have shown that brief excursions to temperatures in excess of 2,000°C (700° or 800° above normal operating temperatures) can be tolerated.

This behaviour introduces an enormous safety factor into the system, particularly in so far as most designs of high temperature reactor are temperature stable, that is to say, increases in the core temperature result in a reduction of reactivity, so that the possibility of excursions to high temperature are very limited. In fact, safety considerations in the operation of a high temperature reactor are concerned mainly with the possibility of accidental ingresses of water vapour, or air, into the core, displacing the inert helium and rapidly attacking the high temperature graphite surfaces. Such an accident could only result from a pressure vessel or penetration failure, and even in the event of such an accident, with the triplex coated particle fuel, the extent of fission product release could be kept well within safe limits. A crucial factor affecting the successful application of any reactor system, of course, is the behaviour of the core structure and fuel elements. The position has been reached where a mass of highly encouraging experience on these components of the high temperature reactor has been accumulated, but an established situation has not yet been achieved on any set of core constituents relating to a particular reactor design. This situation is a natural result of the frequent changes in design concepts and fuel cycles. Initially, preoccupation with thorium cycles and the particular problems of the DRAGON Reactor Experiment (or the A.V.R. and Peach Bottom Reactors) determined the detailed aspects of the work. Now, with the later emphasis on low enriched uranium cycles and the subsequent evolution of core design, the fuel specifications and the problems associated with them have changed materially, to the extent that some, though not all, of the experience accumulated earlier has become irrelevant.

In the original core design of the prismatic high temperature reactor (DRAGON and Peach Bottom) the core was highly homogeneous, with the fuel rods including the whole of the core graphite. It would have been difficult to have adapted this type of design to the large core of a civil power station reactor because the fuel rods would have been too long and fragile to handle. Present power reactor core concepts involve columns of graphite blocks stacked one on top of another with channels running through these which contain fuel rods similar to, but significantly smaller, than DRAGON Reactor rods. The rods are charged and discharged with the blocks. This last type of design is significantly more heterogeneous than the DRAGON or Peach Bottom cores. In addition, the bulk of the graphite is now separated from the fuel rods and is at a significantly lower temperature. The power reactor core construction has many advantages over the original DRAGON Reactor Experiment concept, but it has also certain disadvantages. On the merit side, the graphite blocks are much more robust than the relatively complicated DRAGON Reactor Experiment fuel clusters. The graphite of the blocks, furthermore, is operating in a much more favourable temperature range from the standpoint of its behaviour under fast neutron irradiation, and this temperature tends to be fairly uniform throughout the block, so that stresses and any tendency to distortion should be greatly reduced. Furthermore, if current experience is any indication and the trend in the improvement of fuel maintained, it is possible that a high proportion of the graphite blocks of the reactor core may be re-used.

The major disadvantage in power reactor core design, relative to the earlier prismatic concept, lies in the greater concentration of the fissile and fertile material in the fuel bodies which occupy a relatively lower proportion of the total core volume. This has resulted in somewhat greater thermal power density in the fuel bodies, with a corresponding tendency to higher heat fluxes and fuel temperatures. More particularly, however, problems have arisen in achieving the high densities of uranium, or uranium and thorium, necessitated by the greater heterogeneity. In fact, this is currently one of the major preoccupations in the area of fuel development which has already necessitated the development of coated particles with larger kernel diameters (around 800 microns) and lower porosity (20% or less) than had been utilised in the earlier work. In the same connection, it has become important to achieve higher densities of packing of the coated particles in the fuel bodies than had appeared to be necessary a few years ago. The result is that the experience directly relative to present power reactor concepts has been limited in extent and duration; this applying particularly to the accumulation of irradiation data. However, it is most important to emphasise that the products presently under test are based upon the accumulation of many years of experience with a gradually increasing sound scientific foundation underlying it. The stage has already been reached, in fact, where one can predict with some confidence that both the coated particles and the graphite structures containing them will be well able to withstand the conditions of their exposure in high temperature power reactors, and to a large extent the future work in this area will be concerned with demonstrating this fact, with improving the products, and with obtaining an accurate picture of their behaviour so that the reactor designers will have at their disposal all the basic data concerning the performance of the cores which they design.

In the light of the foregoing it can be said that the feasibility of high temperature power reactors, with respect to the more critical features, has been firmly established and that the future is concerned largely with demonstrating these to the satisfaction of utilities who are interested in applying the system and also to obtaining detailed information and data required by the designers of such power reactors. The incentive to exploit the high temperature reactor for electrical power production has been clearly demonstrated not only by the assessment studies of the DRAGON Project and other research and development groups, but more significantly by the power reactor constructors, who will be directly concerned in their commercial application. In all cases the outcome of economic evaluations of the system has shown that it compares favourably in generating costs with any of its potential competitors. There is small reason, therefore, for delaying the adoption of such systems in Europe, particularly bearing in mind that the first serious commercial station of this type is already under construction in the United States of America.

Future prospects

One of the most important features of the high temperature reactor is the fact that while in its present state of development it can already show savings in generating costs over competitive systems, at the same time it presents far greater possibilities for improvements than any of its competitors. The reason for this is fairly clear, namely, that at the present time, and in the initial proposals for power reactors, one is working very far from the conditions that may ultimately be expected to limit the performance. The presently proposed operating temperatures and core thermal power densities of first generation power reactors, namely 800°C helium output temperature and 5 to 6 thermal MW/m^3, are less than those that have obtained in the operation of the DRAGON Reactor Experiment. With the evolution of core design and improvements in fuel one may envisage substantial improvements in both of these. In fact, there is every reason to suppose that helium outlet temperatures well in excess of 1,000°C could be achieved.

It is doubtful if improvements in these respects would lead to substantial advances using steam power conversion cycles. However, the eventual future of the high temperature reactor lies in its use in direct cycle with helium turbines. Here the most immediate prospect lies in the reduction of capital cost resulting from the much more compact power plant that would be obtained in this manner compared with the steam power system. Ultimately, however, the application of the direct cycle, with increasing helium temperatures, should result in substantial increases in power conversion efficiency, thereby giving rise to further reduction in generating costs.

The direct cycle application of the high temperature reactor is entirely feasible, but it requires a considerable amount of further development work before it can be exploited in the way that is presently possible with the more conventional steam power cycle application. There is a considerable incentive to embark upon such development without delay.

The fast reactor, which is ultimately an essential step in the exploitation of nuclear fission, presents an interesting challenge to the high temperature reactor technologist. While this is a very long term possibility it may be said that the adaption of the technique of high temperature gas-cooling to the fast reactor could be of enormous importance, and could remove some of the limitations that are encountered with sodium cooling. In particular the possible advantages of the direct cycle apply equally to fast reactors as to graphite moderated thermal reactors. It must be emphasised, of course, that the materials problems in the fast reactor application are likely to be far more severe than those that have been encountered with the present thermal systems, though this applies, no less, to the case of sodium cooling than to gas cooling.

Lessons of the Dragon Project

The terms under which the DRAGON Project was set up were outlined in the First Annual Report and it is not necessary to repeat these here. However, certain salient features are worth noting, namely,

(i) that the Project is governed by a Board of Management supported by a General Purposes Committee on both of which each of the Signatories is appropriately represented.

(ii) The Project has no legal personality, all necessary legal actions including the formal placing of contracts, being carried out by the U.K.A.E.A. on behalf of the Project,

(iii) the Project is, nevertheless, completely independent of the U.K.A.E.A. or any other individual Signatory in the planning and execution of its programme, responsibility being solely to the Board of Management and its General Purposes Committee.

This set up proved to be extremely effective. In the first place the organisation was divorced from national politics and reference back to the political area only became necessary when extensions of the Project were being considered. The Board of Management and General Purposes Committee have been composed of members who were well able to pass judgement on the technical performance of the Project and its members have at all times been primarily concerned with the success of the Project as a whole rather than in advantages to the particular Signatory that they represented. The objectives of the Project were at every stage clearly defined and not only were they considered from the start to be entirely feasible, but also to hold considerable promise in the development of nuclear power. It is doubtful if any previous nuclear project has been carried out by a more close-knit organisation in which the Project management was given so much authority to carry out its task with such simple machinery for obtaining swift authorisation for the planning and execution of its details.

No particular difficulty resulted from the fact that tender action was required to be made in all the Signatory Countries and that the resulting contracts were spread rather widely between firms in these various countries. Delays in placing contracts, and in their execution by firms concerned, were certainly no greater than might have been expected had only one country been involved. In fact, both with regard to cost and delivery dates, the Project almost certainly derived benefit from the international competition.

An important outcome of the fact that the Project was required to go to so many different firms in the Signatory Countries may well manifest itself in the immediate future in so far as links are being formed, and have been formed, between many of these organisations, in the future exploitation of the high temperature reactor in Europe. This may well prove to be one of the more important outcomes of the DRAGON Project.

No particular difficulty was encountered in the integration of the international team at Winfrith; on the contrary, with few exceptions, its members, no matter what their nationality, adapted themselves equally well both to the needs of the Project and also socially into their local communities. Within this international team a considerable *esprit de corps* quickly sprang up and has been maintained ever since.

The greatest difficulties that were encountered arose in the period immediately preceding and following the extension of the Agreement from 1967 to 1970. This was due, largely, to the long period of uncertainty regarding the future of the Project that existed when, for more than a year from the nominal start of this extension, its continuation remained in doubt. One of the results of this situation was considerable loss of overseas staff which has only lately been rectified.

Perhaps the most important justification for the collaboration, however, has been the international sharing of costs. Almost all of areas of modern technology are expensive in their development and the individual countries of Western Europe are too small to match separately the advances that may be made by neo-continental communities such as the U.S.A. and the U.S.S.R. But, these countries, depending on industry for their well being, cannot afford to fall behind in any major area of technology and it is essential, therefore, that they should act jointly in maintaining a reasonable position compared to the larger powers. If the DRAGON Project has been successful in showing that this can be done then it has more than justified the money that the Signatories have invested in it.

Work study school

THE Work Study School at Production Group Headquarters, U.K.A.E.A. Risley will be holding the following courses in the coming months:

Appreciation Course for Senior Management

No. 258 16 & 17 September
No. 271 28 & 29 October
No. 282 2 & 3 December.

Appreciation Course for Middle Management

No. 259 22–26 September
No. 278 24–28 November

Appreciation Course for Supervisors

No. 264 6–10 October
No. 283 8–12 December.

Appreciation Course for Shop Stewards

No. 273 10–14 November

Management and Incentives

No. 257 15–19 September
No. 261 29 Sept.–3 October
No. 268 20–24 October
No. 272 3–7 November
No. 275 17–21 November
No. 280 1–5 December

Basic Training Course for Work Study Practitioners

No. 255 8–26 September
No. 260 22 Sept.–10 October
No. 262 29 Sept.–17 October
No. 269 20 Oct.–7 November
No. 274 10–28 November
No. 279 24 Nov.–12 December
No. 281 1–19 December

Courses restricted to Work Study Practitioners Synthetic Data Course

No. 254 8–12 September
No. 285 15–19 December

Personnel from organisations other than the U.K.A.E.A. may attend some of these courses. Details are obtainable from The Manager, The Work Study School, U.K.A.E.A., Risley, Warrington, Lancs. Telephone: Warrington 31244 Extn. 3368.

Mechanical Standards

A leaflet describing the Harwell Mechanical Standards Laboratory has been published by the U.K.A.E.A. and is available from the Public Relations Office, Building 77, A.E.R.E., Harwell, Didcot, Berks.

Prime Minister's visit to Dounreay

THE PRIME MINISTER, Mr. Harold Wilson, visited the Dounreay Experimental Reactor Establishment during his tour of the Scottish Highlands on Friday, 11th July, 1969.

During his visit, Mr. Wilson, who was welcomed to the Establishment by Sir Charles Cunningham, Deputy Chairman of the U.K.A.E.A. and Mr. P. W. Mummery, Director, D.E.R.E., made a tour of the Dounreay Fast Reactor and saw progress on the Prototype Fast Reactor, now under construction on the site. He also met Staff and Trade Union representatives at the Establishment.

At a subsequent press conference in Inverness, the Prime Minister spoke of world interest in the achievements of D.E.R.E. and said that Dounreay could well set the pattern for nuclear development over the next decade.

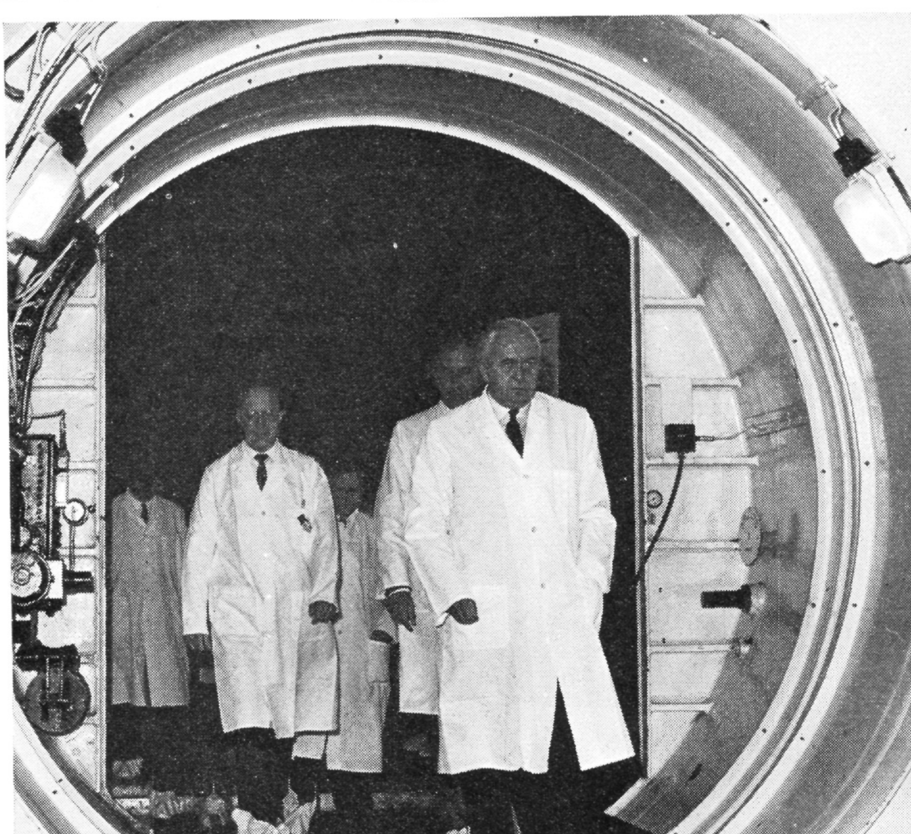
Connah's Quay application

The Central Electricity Generating Board are applying to the Minister of Power for consent to the construction of a nuclear power station adjacent to the existing station at Connah's Quay in Flintshire and are also seeking the views of the local planning authority, the Flintshire County Council.

2500 MW

The new station, to be known as Connah's Quay B, would have up to four gas-cooled reactors and associated equipment with an ultimate electrical output of about 2,500 MW.

The station, if approved, would be the third nuclear station in North Wales following the stations of earlier design at Trawsfynydd in Merioneth and Wylfa in Anglesey.



Mr. Wilson, accompanied by Mr. P. W. Mummery, Director, D.E.R.E and (left) Mr. F. J. Barclay, Manager, D.F.R. Group, leave through the airlock of the D.F.R. sphere.

Oldbury ceremony

The 600 MW(e) Oldbury nuclear power station was formally opened by Mr. Anthony Wedgwood Benn, Minister of Technology, on 10th June, 1969. Commenting on the architecture of the station, the Minister said :

"This impressive power station here at Oldbury has a colossal impact upon its surroundings and here is craftsmanship and skill.

" The profile is simple and dignified, the building unpretentious but full of grandeur. Inside it, in the reactor core, the pressure vessel, the turbines and the cooling system is some of the most intricate engineering work to be found anywhere in the world Every piece of equipment is precision designed and built to meet vigorous operating requirements.

" Enough can be seen to allow us to imagine it as a centre of pilgrimage for future engineers and technologists—along with Bradwell and Sizewell and Hinkley and Berkeley and Wylfa and Dungeness B.

" These people—many thousands of them—in the scientific and engineering design and construction teams that built and will operate this station have not only given us power in quantities that would have amazed our forebears, they have also built a thing of beauty."

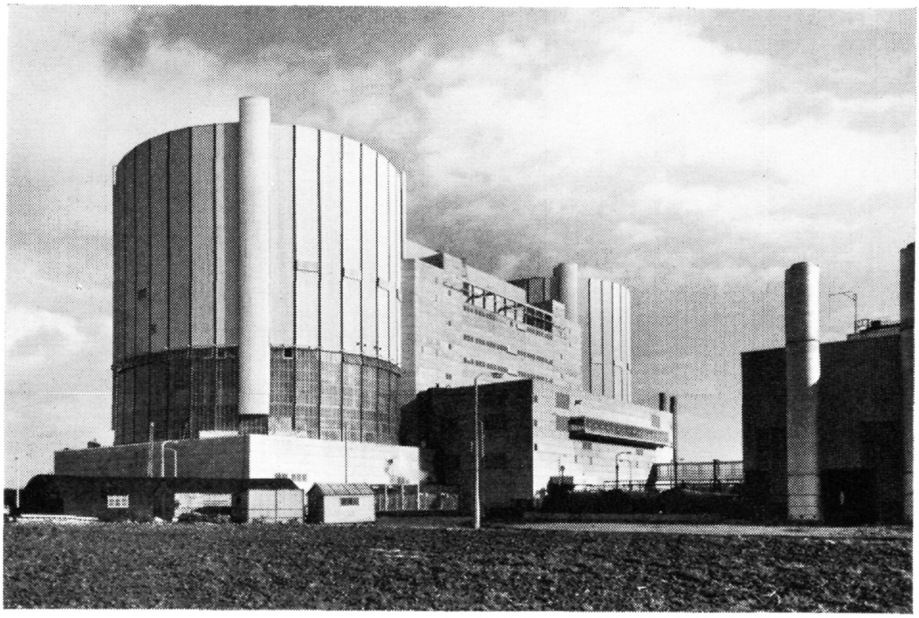
Six reactors sold to Brazil

An order from Brazil worth over £1½ million for six nuclear research and training reactors has been won by Fairey Engineering Limited of Stockport, Cheshire. The order is for five HELEN-type sub-critical reactors for training and basic research, and a HERALD 5MW reactor for more advanced work. Both types of reactor are sold abroad by Fairey Engineering under licence from the U.K.A.E.A. with whom Fairey has an agreement giving it access to A.E.A. research and training reactors. The HERALD reactor will be installed at Brazil's new centre of Government at Brasilia and the HELEN reactors will be installed at universities.

This latest contract follows a £600,000 contract from Chile for one HERALD and one HELEN signed six months ago. A HELEN reactor supplied by Fairey to Romania in 1967 and a more advanced research reactor supplied to Switzerland in 1966 are both operational.

AEA show in Australia

The U.K.A.E.A. will have a stand at the Expo Electric 1969 exhibition in Melbourne 3rd-11th October, and also at the International Trade Fair in Sydney, 16th-25th October.



Oldbury nuclear power station.

IN PARLIAMENT

Nuclear-powered airships

16th June, 1969

Mr. Raymond Fletcher asked the Minister of Technology if he will initiate a feasibility study of constructing nuclear-powered airships either in this country or in association with one or more of our European neighbours; and whether, in particular, he will consider a joint Anglo-German study of the construction of such airships with a view to a possible joint construction programme.

Mr. J. P. W. Mallalieu: With some nostalgic regret, no. The commercial prospects do not justify public expenditure.

Nuclear station for Greece

18th June, 1969

Mr. William Hamilton asked the President of the Board of Trade whether he will make a further statement about the proposed sale to Greece of a nuclear reactor in association with a purchase of Greek tobacco.

Mr. Crosland: Negotiations for the sale of this reactor are continuing.

The British manufacturers have tested thoroughly the samples of Greek tobacco supplied to them and can find no significant differences compared with the Greek tobacco which they had evaluated in the past. In their judgment this tobacco is still not suitable for blending purposes because of a continuingly distinctive aroma and flavour unacceptable to the British smoker.

However, the manufacturers have pointed out that they are always ready to test any tobacco to assess its suitability for the United Kingdom market and they will continue to keep in touch with Greek producers.

25th June, 1969

Mr. William Hamilton asked the President of the Board of Trade whether the prospective sale of a nuclear reactor to Greece is unconditionally attached to the sale of Greek tobacco to this country.

Mrs. Gwyneth Dunwoody: The Protocol signed in April provided for the simultaneous negotiation of separate though parallel contracts. This reactor appears ideally suited to Greek requirements. It is there-

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

Superconducting test facility

At the request of the Ministry of Technology the U.K.A.E.A. is to set up a Test Facility for Superconducting Materials at Culham Laboratory.

Under its Superconductivity Project, the Ministry has supported and co-ordinated work on superconductors in government laboratories, universities and industry since 1964 with the aim of ensuring an indigenous supply of superconducting materials in the U.K.

The new Culham test facility will consist basically of a pair of superconducting Helmholtz coils, immersed in a liquid helium cryostat. It is designed to produce magnetic fields of up to 80 kilogauss and a current supply (for test specimens) of up to 15,000 amps. Superconducting test specimens can be placed in the region of uniform magnetic field between the coils and their electrical characteristics measured over a wide range of current carrying conditions and with different orientations in the field. At the maximum, field specimens 5 cm wide can be tested and specimens 7.5 cm wide can be tested at lower fields.

The test facility will take one year to complete. It will enable manufacturers and users of superconducting materials to test commercial superconductors carrying very high currents in high magnetic fields to guarantee the technical quality of commercially produced materials and to test new forms of superconductors.

The techology of making, testing and operating superconducting coils has been developed at Culham for the nuclear fusion research programme and work on other applications of superconductivity has already been undertaken in collaboration with the Ministry of Technology.

The Laboratory already has a small test facility capable of accommodating samples up to 2 cm in width mounted transverse to the 80 kilogauss magnetic field.

This new test facility will be complementary to the high field facility at Mintech's Royal Radar Establishment, Malvern, which has been in operation since 1966 and is capable of testing smaller samples in fields of up to 150 kilogauss.

27th June, 1969.

A.E.A. Reports available

THE titles below are a selection from the July, 1969, " 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 857
The Estimation of Collision Probabilities in Complicated Geometries. By M. J. Roth. April, 1969. 7 pp. H.M.S.O. 1s. 3d.

AEEW-M 892
A Resonance Equivalence Procedure Convenient for Numerical Use. By J. R. Askew. May, 1969. 10 pp. H.M.S.O. 2s. 3d.

AEEW-R 543
Zip Mk. 2. *A Fortran Code for Calculating the Eigenvalues (Poles and Zeros) and Frequency Responses of Large Sets of Linear Equations Representing Complex Dynamic Systems.* By H. M. Sumner. March, 1969. 59 pp. H.M.S.O. 8s. 6d.

AEEW-R 586
*An Experimental Study of the Integral Properties of U*235 *and Pu*239 *in an Intermediate Energy Spectrum, and Comparison with Theoretical Prediction.* By W. N. Fox, D. C. King, I. J. Macbean, H. H. W. Pitcher, J. E. Sanders and V. G. Small. March, 1968 reprinted April, 1969. 58 pp. H.M.S.O. 11s.

AERE-AM 109
Analytical Method. The Determination of Praseodymium in Zircon by Absorptiometric and Radioactivation Methods. By G. S. Spicer. June, 1969. 9 pp. H.M.S.O. 2s. 6d.

AERE-M 2193
Beryllium. A Reappraisal of its Use in Nuclear Radiation Detectors. By J. H. Howes and J. W. Leake. April, 1969. 13 pp. H.M.S.O. 2s. 6d.

AERE-R 5921
A Differential Thermocouple and its Errors in a Reactor Environment. By A. Smith. April 1969. 12 pp. H.M.S.O. 2s. 6d.

AERE-R 5965
The Effect of High Pressure on the Electrical Conductivity of Praseodymium and some Praseodymium Alloys. By E. King and I. R. Harris. May, 1969. 20 pp. H.M.S.O. 3s.

AERE-R 6090
The Radiation Polymerisation of Impregnated Fibrous Materials. Recent Developments in the United Kingdom. By P. R. Hills, R. L. Barrett and R. J. Pateman. May, 1969. 40 pp. H.M.S.O. 6s.

AERE-R 6091
A Gas Target System for Continuous Production and Rapid Isolation of the Short-lived Radioisotope ^{35}Ar. By G. L. Wick. May, 1969. 11 pp. H.M.S.O. 3s.

AHSB(RP)R 89
Personal Beta Contamination Monitoring. By D. F. White. November, 1968. 24 pp. H.M.S.O. 3s.

AHSB(S)R 167
Recommendations on the Safe Handling of Zirconium Metal and Zirconium Alloys. By G. H. Bulmer. 1969. 53 pp. H.M.S.O. 8s.

AWRE 0-5/69
The Penetration of Glass Fibre Media by Aerosols as a Function of Particle Size and Gas Velocity. Part 1. *Non-Radioactive Aerosols.* By J. Dyment. May, 1969. 33 pp. H.M.S.O. 5s. 6d.

AWRE 0-20/69
The Thermodynamic Properties of Argon Plasma in Local Thermo-Dynamic Equilibrium, over the Range 1-30 *Atmospheres Pressure and* 5,000-60,000°*K Temperature.* By R. G. Turner and W. E. Worsfold. May, 1969. 235 pp. H.M.S.O. 30s.

CLM-R 99
Collisionless Interactions in Interstreaming Plasma Jets. By P. F. Little, B. E. Avis and R. B. Turner. April, 1969. 18 pp. H.M.S.O. 3s. 3d.

TRG Report 1836(S)
A Simple Model for Estimating the Bow of Fuel Elements after Complete Stress Relaxation. By R. G. Anderson. 1969. 20 pp. H.M.S.O. 3s.

IN PARLIAMENT

continued from page 239

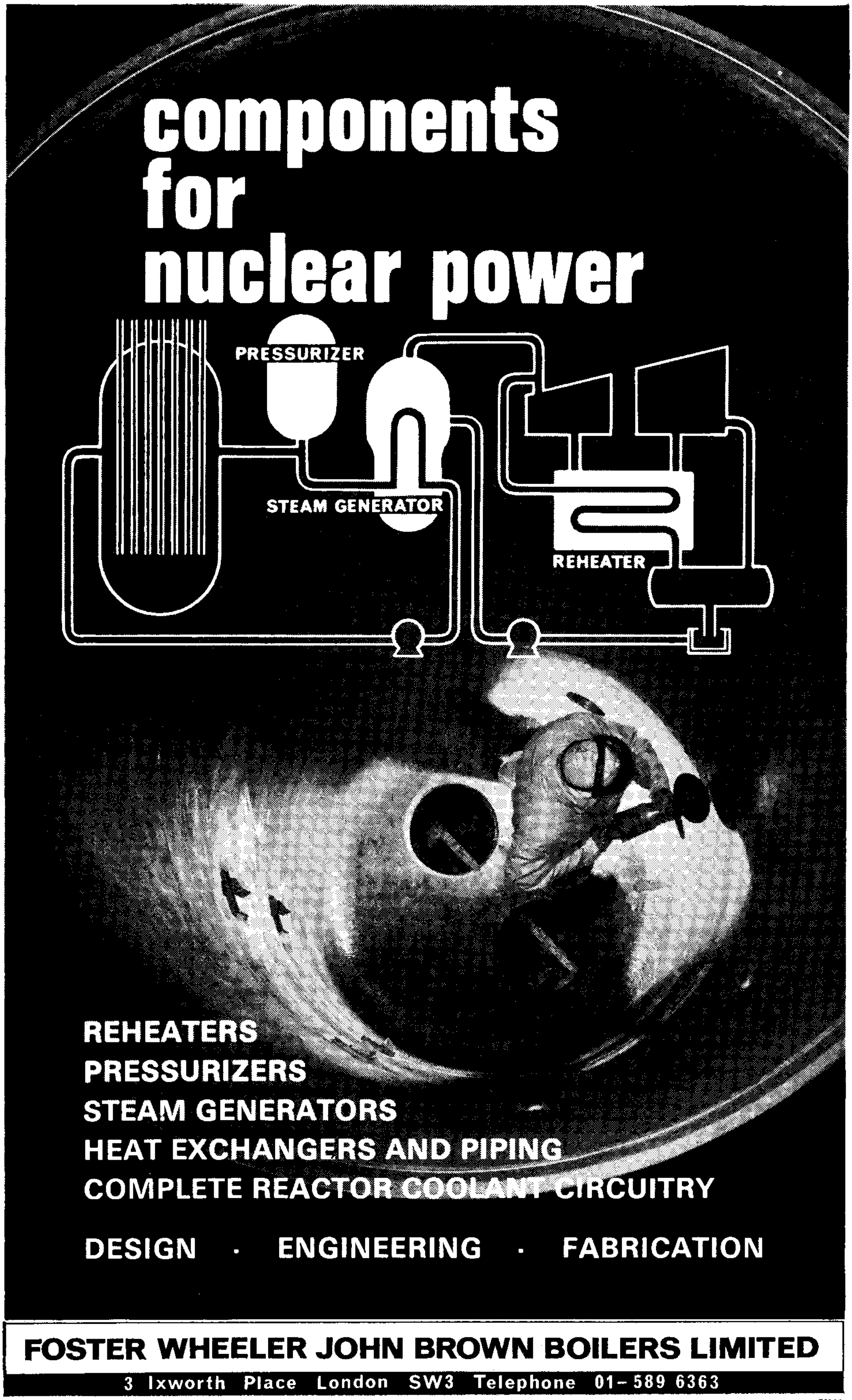
fore to be hoped that a way can be found to complete the sale of the nuclear power station.

Nuclear power stations

24th June, 1969

MR. EADIE asked the Minister of Power how much additional coal, gas or oil will be used to make up the planned energy requirements as a consequence of the delay in nuclear power station construction.

Mr. Freeson: A broad estimate by the C.E.G.B., published in the N.B.P.I.'s Report Cmnd. 3575, was that the cost in 1968-69 of delays in the commissioning of power stations of all types was some £60 million. As mentioned in earlier replies, the C.E.G.B. inform me that changes in the pattern of fuel usage and the financial consequences of these delays cannot readily be broken down to individual stations or types of station.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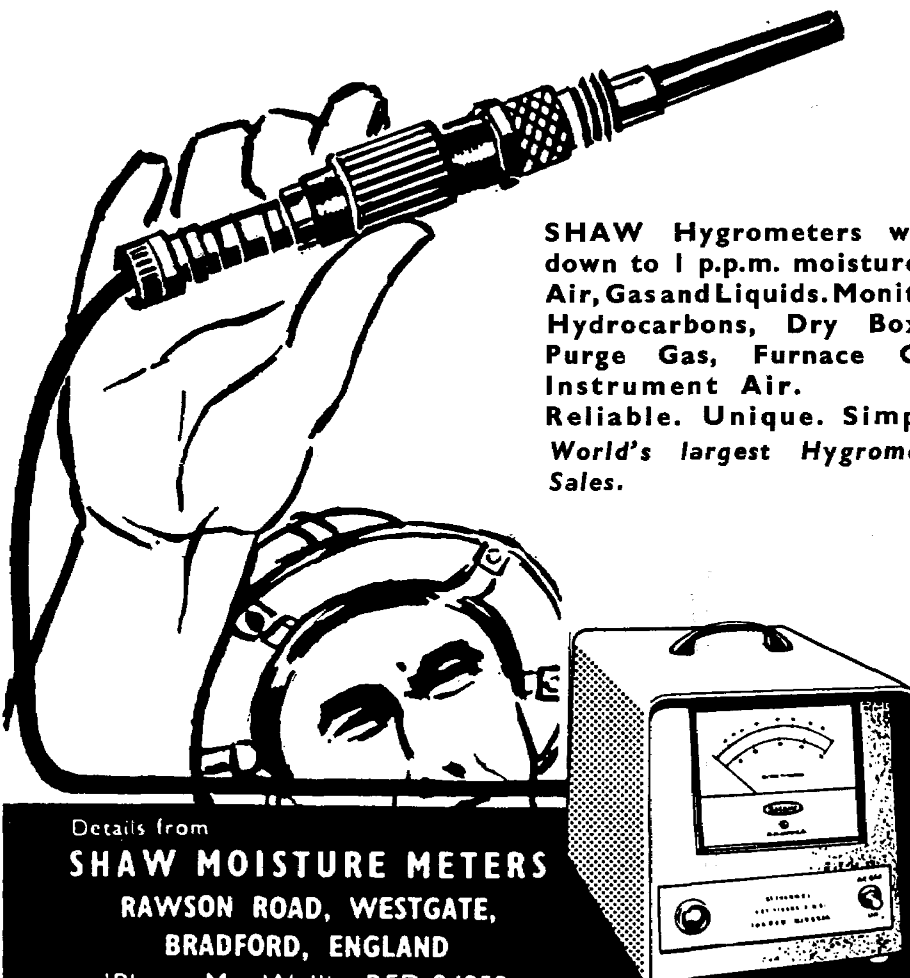

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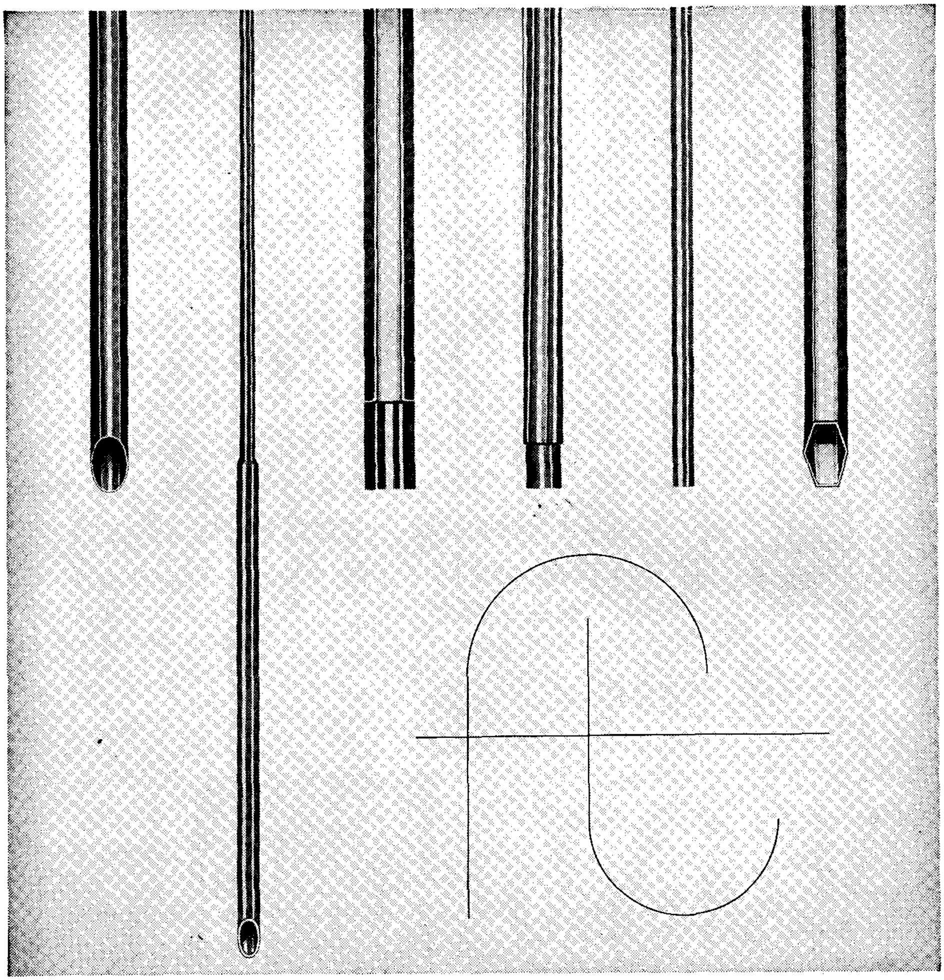

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