April 18, 1958

Letter, John D. Cockcroft, UK Atomic Energy Authority, to Homi Bhabha

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Summary:

John D. Cockcroft of the UK Atomic Energy Authority answers questions from Homi Bhabha regarding nuclear research and includes the text of a lecture he gave regarding the development of nuclear power in the UK.

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UNITED KINGDOM ATOMIC ENERGY AUTHORITY

Atomic Energy Research Establishment,
Harwell,
Didcot, Berks,

18th April 1958.

Dear Homi,

Thank you for your letter of April 7th. I am sending you a couple of reprints on my James Forrest lecture.

On the question of the A.G.R., the first experimental model with an output of about 30 megawatts (electrical) should be in operation sometime in 1961. This of course would not have the low capital cost referred to in my papers, since this referred to a full scale power station.

Assuming this time-scale is met, then the first full-scale power station using the uranium oxide fuel and beryllium canning might come into operation round about 1965 - perhaps a little earlier.

You ask whether it would be possible to convert a power station of the present 1960 variety to the A.G.R. type by replacing the fuel elements by new ones.

I am somewhat doubtful whether this would be possible, but I could have the matter looked into by our Industrial Group.

On the question of sending two or three people to Wantage to work with our groups working on food preservation, I will ask Schonland to reply to you on this question. There will certainly be no difficulty in principle about this; we will need to check on what accommodation is available. Would you be willing for them to come under the International Agency ticket? We have offered them 6 places.

Yours sincerely,

Sd. John

J. D. Cockcroft

Dr Homi Bhabha,
Government of India,
Department of Atomic Energy,
Apollo Pier Road,
Bombay 1.

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The Further Development of the U.K. Nuclear Power Programme

Text of the James Forrest Lecture, 1958
given to the Institution of Civil Engineers
on 18th March, 1958

By **Sir John Cockcroft**
(Member of the United Kingdom Atomic Energy Authority
for Scientific Research)

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My first James Forrest Lecture on the Development of Nuclear Power was delivered in 1955, three months after the publication of the Government White Paper describing plans for the construction of nuclear power stations to develop 1,500-2,000 megawatts of electricity by 1965. The White Paper suggested that the programme was provisional and would be altered in many ways in the course of time and that new technical developments might perhaps lead to a more rapid improvement in the performance of stations than had been assumed. That this condition was wise is shown by the changes in output and in the programme during the last three years which I will describe in this lecture.

The first important change has been in the output of individual nuclear power stations. The White Paper made a conservative forecast that the output of a two reactor power station might increase from the 70 megawatts of Calder Hall to between 100 and 200 megawatts. This forecast has been overtaken by the design outputs of 275, 300 and 500 megawatts from the Berkeley, Bradwell, Hunterston and Hinkley Point power stations. Aided by this, the overall programme has been increased and 5,000-6,000 megawatts are now to be installed by 1966.

The increase in output over Calder Hall has been achieved by straightforward engineering development. First by an increase in the size of the reactor and a corresponding increase in the amount of uranium fuel, as shown by the slide. Second by an approximate doubling of the amount of heat extracted from each ton of uranium. This increase in rating has been achieved by increasing the fuel element surface temperature from 410°C to about 425°C; by a 50 per cent increase of the pressure of the carbon doxide heat transfer gas and by improvements to the heat transfer surface. The progressive increase in fuel element temperatures and ratings is shown in the next slide. The overall result of this has been progressively to decrease capital costs per kilowatt, as is shown by the next slide.

Whilst these designs have been proceeding there has been a substantial development of our technological knowledge although in a rapidly developing field such as this, design has inevitably anticipated technology.

One major contribution to our technological knowledge has come from the operational experience gained from Calder Hall during the last 22 months. This has been remarkably good. The Calder Hall reactors were designed for a thermal output of 180 megawatts and 35 net electrical megawatts. These power levels can be comfortably increased by about ten per cent. The flexibility of operation has been good. Power levels can be increased at the rate of up to 10 M.W. thermal per minute, though usual operational rates are set at half this. Power levels can therefore be increased from 30 M.W. to 180 M.W. in half an hour. The operational load factors have been high and the second Calder Reactor has achieved a full power load factor, higher than most.........................

Fuel element performance is the key to the performance of any reactor.

The Calder reactors were the first to demonstrate the phenomenon of radiation induced creep predicted by Dr. Cottrell at Harwell shortly before they were commissioned. The local stresses produced by the passage of fission fragments through uranium makes creep occur at 100 times lower stress than in the absence of neutron irradiation. In Calder Hall six fuel elements are stacked one above the other so the bottom elements are heavily loaded like struts and creep causes them to bow. Experience has confirmed the Cottrell effect and it has been necessary to fit stays to the fuel elements to overcome this.

Apart from this experience, the behaviour of fuel elements has been good. During 27 months of operation of the first charge of No. 1 reactor of Calder Hall only 3 fuel elements out of 10,000 developed slight faults in the sheath. This resulted in a slow inleakage of carbon dioxide leading to slow oxidation of the uranium metal and a corresponding outleakage of radioactive fission products. These are detected by the electronic devices which sniff each fuel element channel for leakage. The next slide shows the slow increase of activity over several days. There is no urgency to change a faulty fuel element and this can be done at one of the regular maintenance shutdowns. The next slide shows a radiograph of a leaking fuel element - it is usually rather difficult to find the fault. It appears that the stresses due to very slow expansion of the fuel can strain the magnox sufficiently to cause a few such faults to develop. This will be cured by increasing the ductility of the magnox.

Our experience with the second reactor of Calder hall has been broadly similar. However our experience has so far been limited to irradiation exposures which are only about a fifth of those which will have to be achieved in the Electricity Board's reactors.

The Electricity Board reactors will operate the fuel elements at higher temperatures. The fuel element life is expected to be dominated by the internal pressure exerted by fission gases. These collect in small bubbles in which pressures of several hundred atmospheres may build up. At temperatures of 450°C-600°C uranium is fairly plastic and the internal pressure causes a volume expansion which may be of the order of ten per cent at 3,000 M.W. days per ton exposure, the actual amount depending on metallurgical imperfections, such as inclusions, creep strength and other factors. The magnox can is therefore being designed to accommodate such expansions. An extensive programme of testing fuel elements for the civil reactors is envisaged in the Calder reactors. Conditions in the experimental channels of these reactors will be brought as nearly as possible to the conditions of the civil reactors.

The second uncertainty in the performance of Calder Hall was the magnitude of the CO_2 -graphite reaction, leading to carbon monoxide. Experiments on the magnitude of this effect had been carried out at Harwell in loops in the BEPO reactor. The next slide shows the rate of accumulation of carbon monoxide when in Calder Hall. This agrees well with Harwell experience and does not present any problems.

The Authority is devoting a good deal of effort to ensuring that the Calder Hall and the future Electricity Board reactors can at all times be operated in a safe manner. The Windscale accident has focussed attention on the storage of energy in graphite. As the graphite in reactors is bombarded by fastneutrons, carbon atoms are knocked out of their normal places in the graphite lattice and take up interstitial positions. If these atoms return to vacant lattice positions the stored potential energy is released. The rate at which energy is accumulated is illustrated by the next slide. This depends markedly on the temperature at which irradiation occurs. The higher the temperature the less the rate of accumulation of stored energy since some self annealing occures.

It is worth noting that if the permeability of the Windscale filters had been ten times less we would have had no public health anxiety after the accident due to emission of radio iodine and consequent contamination of milk - and this in spite of a major fire in which about three tons of uranium was oxidised. The lessons learnt from the Windscale accident will help to ensuere the safety of nuclear power development in future.

The future development of reactors

The 1955 White Paper suggested that the second stage of the U.K. nuclear power programme might use liquid cooled reactors and in my 1955 lecture I briefly discussed three possible reactors - the pressuriesed and boiling water reactors and the liquid sodium cooled graphite moderated reactor.

During the last three years we have carried out a detailed design study on the sodium graphite reactor and a research study on the pressurised water reactor.

The liquid sodium cooled graphite moderated reactor has the potential attraction of attaining high outlet coolant temperature - of the order of 500°C with correspondingly high thermodynamic efficiencies - of the order of 37 per cent. The system pressure is low because of the low vapur pressure of liquid sodium whilst heat ratings of at least 10 megawatts per ton seem achievable with a cluster of small diameter uranium rods or uranium oxide fuel elements. So with these parameters reactors giving at least 400 megawatts of electrical power would be possible.

The set off against these advantages, the neutron economy of the reactor is poor partly because of the absorption of neutrons by the sodium, and enriched uranium fuel of about twice the natural U.235 content would be required. So fuel would be expensive.

More important still are the compatibility and safety problems of the reacotor. Liquid sodium is not campatible with graphite so they would have to be kept apart by pressure tubes surroundings the fuel elements. It would be necessary to use zirconium or an alloy of zirconium for the pressure tubes, since steel absorbs too many neutrons. Liquid sodium can be extremely corrosive if the oxygen content rises above a few parts per million and at the present stage of development the inflowing liquid sodium in contact with the zirconium tube wall could not exceed 350°C. For the main coolant circuit a low alloy steel compatible with liquid sodium would have to be found. Stainless steel would be too expensive.

Finally we have the safety and maintenance problems associated with liquid sodium. The radioactivity of the sodium would amount to about 100 million curies and although it decays with a half life of 15 hours, any leak would present lengthy and troublesome maintenance problems.

The possible economic advantages of the sodium graphite reactor do not therefore seem to outweigh its serious development and maintenance problems.

The pressurised water and boiling water reactors are the mainstay of the U.S. and Russian nuclear power programme at present cannot be lightly dismissed. They are characterised by a samll reacotor pressure vessel - 10 feet diameter compared with the 50 ft. diameter of Berkely and the 70 ft. diameter sphere of Bradwell. The heat rating of the fuel is high - about but with development capital costs ought to be able to come down to the region of £ 90 per kilowatt.

The water moderated reactors have the disadvantage that enriched uranium fuel must be used. The Yankee Atomic Power Co. reactor will use uranium oxide fuel containing 2.6 per cent of U. 235. At U.S. prices of enriched fuel this would have a prime fuel cost of about £ 100000 per ton with substantial additions for fabrication. The U. K. price for natural uranium fuel element is less than £ 20,000 per ton. Even if the expected long burnups of 8,000 M. W. days per ton are achieved, fuel costs at U.S. prices would be over 0.2 pence per unit.

Enriched uranium fuel produced in any European country would be much more expensive than in the U.S. This is because of the enormous scale of the U.S. diffusion plants - each of them uses 2,000 M.W. of electricity. Secondly, their electricity is extremely cheap - about 4 mils - about a third the price of electricity to a European diffusion plant. Ths U.S. diffusion plant can be thought of as bottling cheap Kentucky coal. Fuel costs in this country for PWR reactors would be about 0.35 pence per unit.

The overall result is that even with maximum potential development, overall electricity costs in this country for PWR reactors would be unlikely to fall below 0.7 per unit. We are not therefore pursuing this reactor for large scale power. In the United States their prospects are more favourable because of the lower indigenous cost of enreched uranium.

We are therefore investigating two future lines of development. First the development of the gas cooled graphite moderated reactor to the maximum of its considerable potentialities. Second the possible advantages of a change to heavy water as a moderator.

We have called the first of these projects the advanced gas cooled reactor (A.G.R). The objective of the A.G. R. is to decrease capital costs per KW by a substantial amount - of the order of 3o per cent - by increasing the surface temperature of fuel elements to about 600°C. By this means and by using clusters of smaller diameter fuel elements, average ratings should be increased to the region of 8 M.W thermal per ton. To enable this increase of fuel elements temperature to be obtained we will change from uranium metal fuel to a sintered uranium oxide fuel element. Sintered UO_2 has a melting point of about 3,400~~0~~°C. This type of fuel is already being used in the Westinghouse PWR reactor and has been shown to have very good irradiation stability, and burnups of up to 8,000 M.W. days per ton have been achieved. The next slide, taken from a paper by W.B. Lewis shows sections of fuel elements which have beenirradiated to 5,000 M.W. days per ton in the NRX reactor. The second slide shows a fuel element in which the pellets of uranium oxide fitted only loosely into the can so that the fuel become hotter and developed a hole in the centre due to sublimation and recrystallisation. A third slide shows a section of UO_2 fuel irradiated by Harwell to 3,000 M.W. days per ton.

The UO_2 fuel elements would probably be sheathed in beryllium. We have already fabricated Beryllium cans and sealed them and have thermal cycled specimen fuel elements hundreds of times through the F changed point without damage. A first specimen, is now going into our DIDO reactor to determine their overall irradiation stability.

We are already carrying out experiments with a zero energy reactor, NERO, to study the nuclear properties of the A.G.R. reactor.

greater irradiation stability and higher efficiency ought to allow us to obtain about twice the amount of heat per ton. We believe therefore that overall fuel costs will be about the same as the first generation reactors - about 0.16 pence per unit.

Because of the high ratings however, capital costs of the order of £ 80 per K.W. ought to be achieved so that with the load factors of the order of 70 per cent predicted for the late 1960's overall costs should come down towards the 0.47 pence per unit prophesied by Sir Christopher Hinton for 1970 in his Axel-Johnson lecture. This at least is our target.

The promising alternative reactor to the A.G.R. is the heavy water moderated gas cooled reactor.

This reactor has the potential advantage of a smaller reactor size than the graphite moderated reactor leading to lower capital costs and it ought to be possible to achieve £ 80 per KW in large outputs (500 MW(El). Fuel ratings would be similar to those of the advanced gas cooled reactor whilst because of the favourable neutron economy of heavy water reactors, only a slight enrichment would be required and fuel costs would be lower than for the A.G.R.

The use of a liquid moderator avoids stored energy and oxidation problems and the fact that the moderator is kept cool, reduces reactivity temperature coefficient problems.

Substantial quantities of heavy water would be required and this would contribute between £ 10 and £ 15 per KW to the capital cost of £ 80 per KW. Heavy water is available at present in the U.S. at about £ 20,000 per ton. Technological work on heavy water production has been carried out at Harwell during the last few years and we believe that it would be possible to produce heavy water at comparable prices in U.K. and other European countries. The overall economics of the heavy water gas cooled reactor should therefore be as favourable as the A.G.R.

The ultimate development of the gas-cooled reactor would substitute all ceramic fuel elements for the designs using metal sheaths. This might allow outlet gas temperatures to be increased to about 700°C resulting in further increases of ratings.

The Authority is at present pursuing a research study on the high temperature gas-cooled reactor. They are attempting to develop impervious ceramic sheaths for a fuel element which is a ceramic - a mixture of graphite, uranium and thorium. A zero energy experiment is being built at Winfrith Heath. This will enable to nuclear properties of the reactor at high temperature to be studied.

If successful this reactor might have applications to propulsion.

At the far end of the spectrum of reactor development is the Fast Reactor which has the objective of increasing the utilisation of uranium a hundred fold over the thermal reactors.

When the Fast Reactor project was started the outlook for uranium supplies to support a large nuclear power programme was far from assured. Today we have reached the point where Uranium available to the West is over 30,000 tons a year and much more could be produced if necessary. This is more than is necessary to support any foreseeable nuclear power programme up to the late 1970's, so the original urgency for developing the fast reactor has largely disappeared. However, in order to get

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This question will be resolved by the coming into commission of the Dounreay 60 M.W (thermal) fast reactor.

In the course of its design we have come to appreciate more fully the difficult technological and safety problems of this reactor so we will proceed aautiously with its operation and development and will not expect it to play a major part in our programme before the 1970's.

In the long run fusion reactors may replace fission reactors; and certainly our final objective should be to use the energy available from fusion reactions in deuterium. This after all has been a very satisfactory energy source for the sun and stars for thousands of millions of years and if we can emulate thier performance on earth we shall not only have an inexhaustible supply of very cheap fuel but we should have the satisfaction of solving one of the most fascinating scientific problems of our time

Towards this, ZETA is only the first step in the way, though a most encouraging one. Encouraging because its initial performances show that it has a considerable development potential and we can begin to design for 100 million degrees when the energy output from fusion reactions would approach theenergy input. Four years ago this would have been unbelievable.

Sir Leonard Owen, who is a member of your Council and who is Managing Director of the Industrial Group of the Atomic Energy Authority, has often expressed surprise to me that the members of your Institution do not take a wider interest in the application of nuclear energy to civilian use. Your charter, which defines Civil Engineering as ' The art of directing the great sources of power in nature for the use and convenience of man; as the means of production and of traffic in states both for external and internal trade ' would indicate that the civil engineer should take the widest possible interest in these nuclear stations. Up to now, he has contented himself with the problems of taking the leavy loads of reactors and shields on re-inforced concrete foundations together with the details, such as cooling water, drainage, roads, etc. As any particular type of reactor passes out of the research stage into the project stage, an engineer must take charge of it who is responsible for all aspects. Up to the present, this engineer and his immediate assistants, with exceptions, have come from the mechanical field and the civil engineering part of the project is under their overall control. There would appear to be no basic reason for this provided the civil engineer prepares himself to take the wider responsibilities.

It has often occured to me that to take control of the design and building of these modern and complicated plants, involving a wide knowledge of science and technology, a type of engineer should be trained who has a thorough grasp of the basic principles common to all engineering and is not just narrowly trained in the techniques of any of the current specialities such as civil, mechanical, electrical, chemical engineering. One of the greatest problems in the rapid build-up of atomic energy has been the shortage of engineers who can take charge of the design and building of a <u>complete</u> project and who can, with their scientific colleagues, speed the development of really cheap power from nuclear energy.

I am sure this will apply to other fields of engineering in the future.