RUTHERFORD MEMORIAL LECTURE, 1963

The industrial development of nuclear power

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Twenty-five years ago Lord Rutherford prepared his Address as President of the 1938 Session of the Indian Association for the Advancement of Science at a time when nuclear physics was moving rapidly forward. New disintegrations produced by α-particles and by charged particles accelerated in high-voltage vacuum tubes and cyclotrons were being discovered with great frequency, and neutrons, especially slow neutrons, were being used to produce radioactive isotopes of many of the stable elements. By 1937 nearly a hundred of such isotopes had been discovered and Fermi and others had shown that the heaviest elements, uranium and thorium, after absorbing slow neutrons underwent a succession of β-disintegrations so producing elements of higher atomic number; these, Fermi called the 'transuranic elements'. Rutherford's Address on the 'Transmutation of Matter' briefly reviewed the great discoveries of the previous forty years in which he had played probably the leading role. In the first decade the transmutations of the radioactive elements were discovered, revealing 'a new and startling subatomic world where atoms break up spontaneously with an enormous release of energy quite uninfluenced by the most powerful agencies at our disposal'; in the second decade his nuclear theory of atomic structure was born and had become generally accepted; 'it was evident' he said 'that to bring about the transmutation of an atom it was necessary in some way to alter the charge of the mass of the nucleus or both together'; and in the third decade Rutherford achieved this transformation by firing α-particles into nitrogen gas and observing that occasionally hydrogen nuclei endowed with very high velocity were produced—the α-particle had entered into the nitrogen nucleus to form a compound unstable nucleus which instantly broke up with the emission of a fast proton, leaving behind an isotope of oxygen, having a mass of 17. About a dozen of the light elements could be transformed in a similar way, and in a few cases the energy of the proton and the recoil nucleus exceeded the energy of the incident α-particle.

At the end of this third decade Rutherford spoke, in his Anniversary Address as President of the Royal Society on 30 November 1927, of attempts to produce intense magnetic fields and high voltages for general scientific purposes. Dr Coolidge, the director of the General Electric research laboratory had constructed a variant of the Coolidge X-ray tube, fitted with a thin metallic window through which fast electrons could stream out into the air, as Lenard had shown thirty years earlier at a much lower voltage. I read Coolidge's paper as a research student and as I had had a little experience with high voltages when employed in the research
department of the Metropolitan-Vickers Electrical Company, I wrote to Rutherford to ask if I might be admitted to the Cavendish Laboratory to try to accelerate electrons to very high voltages with the object of looking for transmutations by energetic electrons. The M.-V. Co. through the good offices of the then director for research, Mr A. P. M. Fleming, offered me a Tesla transformer which could generate up to 600 000 V, and with this in the Cavendish Laboratory I learned how to construct vacuum tubes which could withstand about 450 000 V in air, and 600 000 V when placed under oil. Intense beams of 1 mA of electrons electrostatically focused through a slit orifice in the discharge tube were obtained and were deflected in a magnetic field to obtain a roughly monochromatic beam for scattering experiments. A short time after I began, E. T. S. Walton came to the Laboratory and tried to accelerate electrons by indirect methods, using a rapidly rising magnetic field—a method which later became known as the betatron—and in both these attempts we received great encouragement from 'The Prof.', for he was very hopeful of obtaining copious streams of high-speed electrons and atoms, by one way or another, 'which have an individual energy far transcending that of the $\alpha$- and $\beta$-particles from radioactive bodies'. At that time, although only $\alpha$-particles had produced disintegrations, there was no known reason why high-energy electrons should not also enter nuclei and the Prof. was a firm believer in 'try anything once, and see'. He did recognize that there would be formidable difficulties in obtaining particles having energies of many millions of electron volts but he always hoped that some reactions might be discovered with particles of more modest energy if the supply of them was great enough.

At the end of 1928, however, one of those great theoretical steps was taken which altered the whole course of experiment in this subject. Gamow propounded a theory based on the new concepts of the wave mechanics which explained the relation between the range of an $\alpha$-particle and the 'half-life' of the atom emitting it, the well-known Geiger–Nuttall relation; briefly stated, the higher the energy of the $\alpha$-particle the greater its chance of escaping through the energy barrier surrounding the radioactive nucleus although it has insufficient energy to surmount the barrier: the greater the chance of escape the shorter the half-life of that species of radioactive nuclei. Conversely, argued Gamow, the greater the energy of an incident $\alpha$-particle, the greater the probability of the particle entering the nucleus and probably causing a disintegration. His theory explained the disintegration by $\alpha$-particles of the light elements, atomic weights up to 32, examined by Rutherford and Chadwick. I well recall returning from Gamow's colloquium at the Cavendish Physical Society, to the room in which Cockcroft, Walton, and I worked, and Walton and I stood round Cockcroft as he put figures into Gamow's new formula—$1/\alpha$ of protons seemed a sensible figure—accelerated to, let us say, 300 000 V, and let them bombard a target of lithium; making generous allowances for loss of protons as the beam emerged from a Lenard window the number penetrating the energy barrier seemed sufficient to give an observable number of disintegrations. Thus began the concentration on the acceleration of positive ions to the moderately high voltages which I had achieved for electron acceleration, in the hope that disintegrations would be found at such voltages, and that many millions of volts would not
now be necessary. It is not often that theory had guided experiment as clearly as this. I think we younger ones were content to accept Gamow's revolutionary theory but when Rutherford opened the new High Voltage Laboratory at the M.-V. Co. in February 1930 he said 'What we require is a potential of the order of ten million volts and an exhausted tube capable of withstanding this voltage'; he was apparently 'playing safe' in case the Cockcroft and Walton experiments with only 500 kV failed to confirm Gamow's views! By 1932 the disintegration of lithium into two $\alpha$-particles after bombardment by 500 kV protons satisfied even Rutherford! Two years later with beams of deuterium ions accelerated to only 200 kV he and Oliphant produced D-D reactions which yielded a copious source of neutrons and also produced the third hydrogen isotope $^3$H. Gamow was fully vindicated. It is doubtful whether the Cavendish would have 'turned out the real facts of Nature' as Rutherford so often said, if Gamow had not led the way—at least not in 1932. The fact that I, and Walton, failed with electrons is entirely unimportant; the debt I owe to Rutherford is for the inspiring support he gave me in tackling a problem almost too difficult for the meagre facilities of the Cavendish in those days so that the years were happy years, and that inspiration and enthusiasm for scientific research has lasted a lifetime.

Of course the attempts by van de Graff and others in the fourth decade, 1927–37, to produce higher and higher voltages, and by Ernest Lawrence and others to give particles high energies by the indirect method of the cyclotron did not go unrewarded, for with higher energies of the incident particles the yield from any nuclear reaction increased as forecast by theory, and elements of higher atomic number could be disintegrated; Lawrence with 6 MV deuterons bombarded bismuth which became a radioactive bismuth identical with radium $E$, the daughter product emitting an $\alpha$-particle, like radium $F$, and so he had the distinction of producing elements identical with the true radioactive elements found forty years earlier.

In this fourth decade, in 1932, the neutron was discovered, the neutron speculated upon by Rutherford in his Bakerian Lecture of 1920. Blackett* has described how it arose from unexpected discoveries in different countries and how Chadwick in 1932 'reading the work of Joliot on this subject and with the background of Rutherford's speculation about the possible properties of the neutron, saw at once that here it was'. I remember commenting to Rutherford in 1933 that it was surprising that Joliot had not realized that the neutron could have been responsible for the astonishing experimental results he had obtained. Rutherford replied that Joliot had told him he had never read the 1920 Bakerian lecture and had never thought in terms of a neutral particle. Its discovery led in a few years to the large crop of new radioactive isotopes and the transuranic elements over which Rutherford cast his eye in the Address he prepared for you in India. Prophetically he spoke of radioactive isotopes doubtless 'still being produced in the furnace of our sun; ... on this view uranium and thorium are to be regarded as practically the sole survivors in our earth of a large group of radioactive elements, owing to the fact that their time of transformation is long compared with the age of our planet'. I shall refer

to this prophecy later: his prophecies were so frequently proved to be right because they were based on experimental facts which had been checked and rechecked—if he failed to prophecy the release of nuclear energy on a large scale it was for the good reason that up to the date of his death (19 October 1937) there was no reason to suspect the occurrence of a nuclear ‘chain reaction’ which alone could produce a massive yield of energy. If charged particles were used the energy released at disintegration may be a thousand times the energy of the bombarding proton or deuteron, but the chance of producing such disintegration was only one in a million. ‘Even allowing for the fact that the overall efficiency rises with increase of the bombarding energy there is a little hope of gaining useful energy from the atoms by such a process’—he wrote in The newer alchemy in 1937—and this is still true today, and he continued ‘At first sight the extraordinary efficiency of slow neutrons in causing transformations with large evolution of energy seems promising but we must bear in mind that neutrons themselves can only be supplied as the result of very inefficient processes of transformation. The outlook for gaining useful energy from the atom by artificial processes of transformation does not look promising.’ He contrasted the simple apparatus he had used in his 1919 disintegration experiment with the vast experimental apparatus in use in 1937, but, he said, ‘fortunately there is still plenty of scope for the individual worker in experiments of a simpler kind’. Sixteen months after his death fission was discovered with nearly no apparatus at all.

Fermi’s transuranic elements were being investigated in many laboratories and in January 1939 Hahn and Strassmann declared them to be not transuranic, but isotopes of barium. The realization that fission of the nucleus had occurred followed immediately and the great energy carried by each fragment was revealed in ionization and in cloud chambers. As the fragments would contain more neutrons than would stable isotopes of the same atomic weight they would be highly β-radioactive and some neutrons might even be emitted at fission, a speculation which at once led to the concept of a neutron chain reaction in a mass of uranium. The neutrons were found and calculations were made of the critical mass of uranium which would be explosive. I remember dining with Cockcroft at the Institution of Electrical Engineers Council on 13 April 1939 when our conversation covered uranium bombs and slow reactions which might be used for power stations. It was not until September 1939 that the number of neutrons emitted at fissions was ascertained (about 2-3) and later Bohr’s prophecy that the observed fission had been that of the scarce isotope uranium-235 (0.7 % abundance) was confirmed: this explained why disastrous fission had not occurred earlier in the world’s history. As for the abundant isotope uranium-238 this was found to be the parent of the true transuranic elements: it exhibited a very high resonance capture for neutrons of intermediate velocity and two β-transformations followed—in 23 min half-life to neptunium-239, and in 2-3 days half-life to plutonium-239 which was found to be fissile like uranium-235. It was at once realized that if a chain reaction of uranium-235 could be effected with slow neutrons, all spare neutrons could be used to make plutonium from the uranium-238 and this could be separated by chemical methods to form a concentrated fissile mass for a weapon.
Immediately after the Curie–Joliot discovery in 1934 of the production of artificial radioactivity of many elements bombarded by α-particles, Fermi and his school in Rome discovered that elements bombarded by neutrons became radioactive and that slow neutrons were more effective than fast neutrons in inducing radioactivity. He patented the use of a blanket of a light element surrounding a source of fast neutrons to moderate their velocity before absorption. Fermi, in 1939, in Columbia university realised that a chain reaction in ordinary uranium might be possible if pieces of uranium were separated from one another in water so that fast neutrons released at fission would be reduced to thermal velocity in the ‘moderator’ before encountering more uranium; in this way resonance capture in the abundant uranium-238 might be largely avoided. Water (light water) was found to have too high an absorption coefficient and by 1940 it appeared that pure graphite might be a satisfactory moderator. After two years of theoretical and experimental work necessitating the procurement of large amounts of very pure materials to avoid undue loss of neutrons, Fermi and the large group then at Chicago constructed a pile roughly 20 ft. cube of graphite with six tons of uranium and its oxide in the form of short 1 in. diameter cylinders embedded in the graphite on an 8 in. lattice spacing and when absorbers were withdrawn a self-sustaining chain reaction occurred (2 December 1942). No-one would have rejoiced over this achievement more than Rutherford for it was a scientific achievement of quite outstanding importance. Immediately construction of the large plutonium-producing piles was started at Hanford, Washington, to be cooled by the Columbia river because there was no time during the war to solve the problem associated with operating the piles at a sufficiently high temperature to make use of this heat energy.

Since 1945 many countries have constructed chain reacting piles, or reactors as they are now more generally called, and the world has truly embarked on an era of generation of nuclear power such as no-one could have forecast in 1937, the date of Rutherford’s death. Nearly 500 reactors are either in operation or under construction of which more than 300 are research reactors operating at between 100 W and 50 MW output. The large power-producing reactors now under construction will be producing 10 000 MW of electricity when completed, at a cost in the later reactors to go into operation, only a little higher than the cost of power from coal or oil. This vast development has been largely an engineering triumph based on numerous research programmes of the kind which would have appealed

† Rutherford wrote to Fermi in 1934 ‘I congratulate you on your successful escape from the sphere of theoretical physics! You seem to have struck a good line to start with’.

‡ This patent was filed in Italy, at the suggestion of the director of the laboratory, on 26 October 1934, four days after the discovery and covers of course the basic concept of the use of a moderator to enhance neutron capture by uranium-235 and therefore is used in almost all reactors. The patent was offered in Great Britain to the M.-V. Co. who in turn on my recommendation offered to build continuously evacuated high-voltage apparatus to produce radioactive isotopes, using Fermi’s patent and paying royalty on all sales, but when Fermi emigrated to America the offer was not accepted. Actually the patent probably was never valid in Great Britain since it suggests that any element of atomic weight less than 14 may be used to slow down the neutron velocity, whereas if boron is used neutrons will be captured. The American patent is worded differently and the U.S. Government paid a royalty of $300000 for the use of the patent up to its expiry date.
to Rutherford for he was a strong supporter of applied research and would have regarded the translation of his own very academic contribution in nuclear science to successful industrial development as of the highest national importance.

There have been four main paths to nuclear power, three of them dictated by national assets. As Fermi and the British research workers in 1940–41 realized, the only moderators which could be used with natural uranium were carbon and heavy water: light water absorbs neutrons 500 times more strongly than heavy water and this loss of neutrons was sufficient to prevent a chain reaction. The British war-time work was moved to Canada where large reactors moderated and cooled by heavy water have since been built, and Canada is now pursuing the path to nuclear power using natural uranium, and heavy water as moderator.

America had set up a large gaseous diffusion plant to separate the uranium isotopes on a massive scale to make the atomic bombs during the war and has thus chosen to use relatively cheap enriched fuel to overcome losses in ordinary water thereby gaining compactness, and the main American power reactors are moderated and cooled by light water. In Great Britain, where, after the war and for many years later, there was no enriched fuel, ordinary uranium with graphite moderator and gas cooling has set the pattern of our progress. All these reactors burn the uranium-235 and convert some uranium-238 to plutonium, the breeding coefficient for plutonium being less than unity. In addition to these three if the fuel is rich in uranium-235 the moderator can be dispensed with and the fast neutrons emitted from a core of uranium-235 can be used to convert uranium-238 in a surrounding blanket into plutonium (or thorium into uranium-233, likewise fissile) with a breeding coefficient greater than unity; in this way uranium-238 would become available for energy production thereby increasing a hundredfold the total atomic energy available from uranium (as clearly foreseen by E. O. Lawrence in 1941): large breeder reactors are operating in several countries.

The development of the graphite moderated power reactor in Great Britain has been pursued with a single-mindedness of purpose which has yielded remarkable results. Within twelve years of the start of operation of the first Calder Hall reactor nearly 5000 MW(e) of electrical generating capacity will have been installed and at that date, 1968, will be providing electricity equivalent to the consumption of over 20 million tons of coal a year replacing about one-fifth of the fossil fuel we should then need in power stations. So well was the first reactor at Calder Hall conceived and constructed that this goal will have been reached as a result of only one major technological advance—namely the improvement of the construction of pressure vessels containing the reactors—although innumerable important improvements have been made arising from the work of scientists and engineers in the Atomic Energy Authority, the Central Electricity Generating Board, and in industry. The concept of changing fuel elements while the reactor is on load appears simple but the achievement of this has been remarkable, and all the civil power stations have adopted it; time alone will show what pitfalls lie in store. The existence of eight reactors of the Calder type has been of immense benefit to the development of the power reactors, especially the fuel elements and there is now well founded confidence that these will give an average yield of over 3000 MWd per ton of uranium
(by which time the uranium-235 has fallen to 0.4% and there is a net yield of 0.2% plutonium in the fuel).

The pressure vessel for the Calder reactor was made from 2 in. mild-steel plate welded to form a cylinder 37 ft. in diameter, 70 ft. high with domed ends; after welding, the vessel was stress-relieved at 600 °C. This vessel operates at a pressure of 100 Lb./in.² and the coolant gas, carbon dioxide, removes 180 MW of heat from the reactor at an outlet temperature of 330 °C. From the experience gained in the construction of this vessel larger industrial reactors were made, that at Berkeley being a 50 ft. diameter cylinder 80 ft. high, and at Bradwell a spherical vessel 67 ft. in. diameter and 3 in. steel plate was used, achieving a modest increase in pressure to 130 Lb./in.² and temperature to 390 °C. At Dungeness 4 in. steel was used and pressures were doubled, 268 Lb./in.². The closest possible inspection has been given to the structure of these vessels and the huge ducts which connect them to the boilers, all welds have been radiographed, vessels have been annealed and tested to well in excess of the working load. To avoid brittle fracture the temperature of the steel when under load must be kept well above the brittle/ductile transition temperature which, for the kind of steel used in the Berkeley vessel is near 0 °C. This transition temperature, however, has been found to rise under the influence of fast neutron irradiation which causes a loss of ductility in steel. The maximum fast flux escaping from the Berkeley vessel is $2.8 \times 10^{10} \text{n cm}^{-2} \text{s}^{-1}$, which, integrated over 20 years is nearly $2 \times 10^{19}$; such a flux increases the transition temperature by nearly 100 °C so whenever the vessel is on load its temperature will exceed 50 °C; and this minimum figure will rise as the years of irradiation pass by. Good engineering, however, calls for second lines of defence and though the risk of failure of the pressure vessel is believed to be almost negligible, steps have been taken to prevent the escape of fission products: there will be a very rapid scram if pressure is lost, a sudden continuous flushing with carbon dioxide, and fuel elements have been designed so that the Magnox can shall not melt when the gas flow ceases.

One important cause of the fall in costs of the nuclear stations built since Berkeley and Bradwell has been the increase in their size and as it seemed impossible to exceed 300 MW(e) from one reactor contained in a steel vessel, reinforced concrete vessels have now been designed to withstand much higher pressures. The first, at Oldbury, will deliver no more power than the Dungeness reactors but will operate at 30% higher pressure and the vessel will contain the heat exchangers and blowers spaced closely around the reactor, thus eliminating gas ducts and expansion bellows and all the risk of sudden loss of coolant, for there is no conceivable way in which the vessel can fail catastrophically, not even under earthquake conditions. At Wylfa two single 600 MW(e) reactors in concrete vessels will be built and engineers consider it feasible to build a 1000 MW(e) reactor as one unit. The Oldbury vessel is 78 ft. in inside diameter and 62 ft. high with walls 15 ft. thick and flat end slabs 22 ft. thick prestressed with a labyrinth of steel cables threading through tubes embedded in the concrete, following nearly straight paths in the end slabs and helical paths of low radii in the cylindrical walls, both clockwise and anticlockwise. The ends of the steel cables are accessible from galleries above and below the reactor and are
tensioned to keep the vessel under strain at operating gas pressure. They could be replaced if it were necessary but they are so well shielded from fast neutron flux that deterioration can be ignored; to safeguard against rust, the tubes containing them will be filled with inert gas. The vessel is lined for gas tightness with thin \( \frac{1}{2} \) in. sheet steel anchored to the concrete in many places to prevent buckling as the vessel is placed under stress, and this liner and the concrete are water cooled. The reactor itself is surrounded by a steel and graphite sleeve 1 m thick to reduce the neutron flux at the boilers placed on the outside of this shield. Gas leaving the top of the reactor passes down the heat exchangers below which are the four blowers forcing the gas through openings in the shield to the bottom of the reactor in this way keeping the length of the gas circuit to a minimum. This integral design of the whole reactor system in a concrete pressure vessel is probably safer than the combination of a large steel reactor vessel and boilers all placed in a large steel containment vessel, for it is conceivable that severe accident to the steel reactor vessel might puncture the containment vessel also.

The fuel elements designed for Calder have also proved to be most satisfactory and only relatively small changes have been necessary. Their freedom from failure may be judged from the fact that Calder type reactors have achieved overall annual load factors of 94\% including refuelling (off load) and maintenance, and 98 \% between refuelling. In 37 reactor years of operation only one fuel element in 10000 has given trouble from fission gas leakage. The highest importance has been attached to reliability and a secondary goal is the achievement of long life set, if possible, by loss of reactivity rather than by failure of the can. There are two main problems: the growth of the fuel under irradiation and the change in the properties of the canning material. Uranium is anisotropic, expanding on one crystalline axis and contracting on the others; the ‘thermal spikes’ caused by fission fragments encourage interstitial atoms and vacancies to move in the directions in which they can best be accommodated and this results in a net transfer of atoms in the direction of lowest thermal expansion; a single crystal grows enormously in one direction while shrinking in the others. To avoid overall dimensional changes the metal is quenched from the \( \beta \)-phase to produce randomly oriented small crystals, and nucleation and grain refinement can be assisted by adding traces of aluminium and iron. When random orientation is not perfect the outer skin extends and the core contracts, but the interplay of these depends on the temperature of the fuel; at the ends of the bars growth predominates. The alloyed fuel—'adjusted fuel' (0-05 \% Fe 0-1 \% Al) is used in all the power reactors as it has greater dimensional stability. Later in the life of the fuel element another phenomenon develops, swelling due to the entrapment of the insoluble fission product gases and the solid fission fragments. Small bubbles of gas have been observed (with the electron microscope) 10\(^{-5}\) cm in diameter and these migrate randomly or under the influence of a temperature gradient; if they meet they coalesce and occupy more volume than their original conjoint volumes (the radius increases by \( \sqrt{2} \) instead of \( \sqrt[3]{2} \)) because the volume occupied is governed by surface tension forces. It has recently been shown that small precipitates tend to anchor the small bubbles and so prevent coalescence into large bubbles. This may be the cause of the observed small swelling of the adjusted
uranium compared with the pure metal. Certainly after some such specimens had
suffered high burn-ups the bubbles were found to be finely dispersed and less than
$4 \times 10^{-5}$ cm in diameter. With bubbles as small as this, increase in volume of the
metal after 0.7% burn-up should be only 3%, and a further 1.7% due to the solid
fission products. Expansion beyond this may be due to cracks and voids and work is
directed to reducing these.

The canning material Magnox (0.8% Al) has been very satisfactory for the
Calder reactors; out of several hundred thousand fuel elements, only seven have
failed suddenly and all these have been traced to faulty welds or damage while
handling, usually damage at the welded cap. If carbon dioxide gas enters the can,
the growth of uranium dioxide precipitately bursts the can. Helium leak detection
is now used to check welding faults. Cavitation of the Magnox has been observed to
develop in the cooler regions of the reactor where ductility has been insufficient to
match fuel growth. For the power reactors, heat transfer studies showed that a great
improvement could be made with helical fins on the cans, and these are now extruded,
twisted, and then pressurized on to the fuel in such a way as to result in a much finer
gained structure having three times the ductility of the coarser grained Calder
cans. Simple mechanical braces have been used to support the fuel elements
so that they do not suffer the compressional forces from fuel elements stacked above
them and these braces also prevent vibration due to aerodynamic forces which nearly
levitate the fuel. Life tests have had to be made to evolve satisfactory designs
to withstand these large forces. Finally, there is evidence of creep due to thermal
cycling. The coefficient of expansion of uranium is 50% higher than that of Magnox
and it has been estimated that fuel will experience some millions of temperature
cycles of a degree or two, as well as many cycles of larger temperature change.
Extensive tests now indicate that thermal fatigue is unlikely to be troublesome.
Many fuel elements of the Berkeley design but slightly enriched to simulate the
power rating in Berkeley were put in one of the Calder reactors in 1959 and have
achieved a burn-up of 3000 MW days/ton and are still being irradiated.

The cost of electricity from these gas-cooled reactors will depend considerably
on the performance of the on-load fuel-changing mechanism for if this is satisfactory
the reactors will operate for as many hours in the year as possible to spread the high
amortization charges. There are many ways of approaching equilibrium of opera­tion
of the fuel reloading cycle though some forms of initial transient is inescapable—
in its crudest form it necessitates starting to replace some fuel elements almost
immediately after the reactor has begun to operate, and thus losing half of the first
load of fuel, which must be paid for on the capital account of the station. But if
the fuel-changing machinery proves to be very reliable then the start of fuel
changing can be delayed for the first and subsequent changes, and if the elements
themselves can be handled satisfactorily several times, interchange of position
from low-flux regions to high-flux regions might be practicable, fuel elements in the
central flux-flattened region of the core might be left to burn up 5000 MW days/ton
while those in the perimeter deficient in reactivity were changed. Such procedures,
however, must await operating experience and it will be a few years before the most
economical methods of fuel burning emerge. There is every indication that fuel
costs will be one-half or one-third of the equivalent cost of coal and as the base load in Great Britain in 1968 will be well above the nuclear power station output there is every incentive to achieve the highest load factor from these stations.

One further point might be noted about the advance in design in the later stations. The mean temperature of the gas passing from all the channels in the reactor has been increased by 80 degC (Calder 330 °C, Oldbury 410 °C) the inlet gas temperatures by 110 degC (Calder 135 °C, Oldbury 245 °C). This has had two effects, increased efficiency of a steam cycle, and increased average temperature of the core, and hence less Wigner energy stored in the core. In the earlier reactors the fuel elements at the cool end of the reactor were sleeved with graphite insulated from the moderator so that the moderator temperature would be maintained high enough; now the input temperature is adequate. The efficiency at these temperatures, 33·5 %, is almost as high as the best existing coal-fired station. Thin plate-type fuel elements are now being tested; with their higher surface/volume ratio a larger heat extraction rate per channel can be obtained and this might result in a further 20 % fall in capital cost per kilowatt.

The heat rating of the Calder fuel elements was 2 MW/ton. Within a year of Calder operating, a design was being evolved by the A.E.A. for a similar reactor but using oxide fuel elements at a much higher temperature, and the design has resulted in the advanced gas-cooled reactor which has been working at full power for over a year, with a mean fuel rating of 8 MW/ton of uranium. The oxide is far more stable under neutron bombardment than is uranium metal and in sintered form does not give up the gaseous fission products readily below 1600 °C. Its operating temperature is therefore set by the material of the can, and stainless steel was chosen in preference to beryllium in spite of its neutron absorption being 90 times that of beryllium; steel has better core resistance, greater ductility and could operate at higher temperatures (850 °C) in CO₂; furthermore, beryllium exhibited some incompatibility with UO₂. The surface temperature of 850 °C is set by compatibility with CO₂; a nominal maximum surface temperature of 650 °C was chosen, and when an allowance is made for the temperature drop between the surface of the fuel and the can, the diameter of the fuel element is limited to 0·4 in, if the centre is to remain below 1500 °C. This gives an increase in surface area over Magnox per unit weight of metal of 7:1 neglecting the fins on the Magnox cans, and with the increased temperature of the fuel the overall fuel rating is 3 to 4 times greater than the most advanced of the Magnox reactors. The thickness of the steel can is chosen so that it has not collapsed, by creep, on to the fuel at the end of fuel life—heat is carried from the fuel to the can by helium, and the outside of the can is slightly corrugated to break up streamline flow and increase turbulence. The fuel elements are made up in clusters inside graphite tubes which take the weight of other elements placed above them, and the lattice pitch is adjusted to give the same neutron thermalization as in the Magnox reactors: the volume of the core is roughly half the volume of a Magnox station of comparable power, and early estimates of the probable capital cost of the first of this kind of reactor fall somewhat below the cost of the latest Magnox stations.*

* I have dealt briefly with costs of these stations in the Sir Jadadis Bose Lecture, Calcutta, 23 January 1964.
Neutron absorption in the steel cans must be provided for by the use of enriched fuel: 2.5% $^{235}$U is used in the a.g.r. now operating but this reactor is experimental, and for a larger and simpler reactor 1.8% enrichment is considered to be sufficient to provide for an average burn up of 12000 MW days/ton and on this basis the fuel cost is nearly as low as natural uranium lasting only 3000 MW days/ton; and for such a reactor with a gas outlet temperature of over 600 °C the steam cycle efficiency is expected to be 40%.

The increase in temperature of the moderator brings a new factor into consideration, the dissociation of CO$_2$ under irradiation by neutrons or γ-rays, creating nascent oxygen which then unites with carbon of the moderator to form CO$_2$; it has been found that if CO is added to the CO$_2$ gas the attack on the carbon is greatly reduced. It is suggested that the added CO may be adsorbed on the graphite so that the O + CO reaction occurs preferentially to the O + C reaction. If carbon were first removed and then precipitated the strength of the graphite would be reduced; this is not observed. However, the subject is still far from being exhausted; there may be side effects due to catalysts. At present the addition of a small percentage of CO seems to ensure adequate life to the moderator and in due time graphite of lower porosity and improved dimensional stability may be evolved.

The main technical contribution of the U.S.A. to the development of power reactors has been the use of ordinary water as moderator and coolant. Moderator distances of only 2 in. suffice to thermalize neutrons compared with the 7 in. for graphite and water can remove 20 MW of heat from a ton of fuel in the form which has been evolved over the decade so that the volume of a water cooled and water moderated core is only 1% of that of the gas cooled graphite core for a reactor of the same heat output. Water moderation necessitates enrichment of which the Americans appear to have had abundant supplies. The small size of the core makes this design immediately acceptable for ship propulsion hence its early use in submarines, in the Russian ice-breaker Lenin, and in the U.S. merchant ship Savannah. In the earliest designs, the reactor operated at such a pressure that ebullition was prevented—hence the description ‘pressurized water’ (p.w.) reactors and heat energy was transferred to a boiler outside the reactor, but following many experiments to test the safety of the system, a new system was evolved in which the water was allowed to boil as it flowed up between the plates of fuel elements, hence the name ‘boiling water’ reactors (b.w.r.); the creation of steam bubbles diminishes the moderation and hence reduces fission; this negative temperature coefficient of the b.w.r. is the cause of its great safety. In some designs of the b.w.r. the steam is passed to a heat exchanger, but in others the steam is passed direct to the turbine, and experience has shown that very little radioactivity is carried over from the reactor even after some of the fuel elements have developed faults.

The first industrial power p.w. reactor Shippingport, of 60 MW(e), has been in operation for six years; the second, Yankee, 142 MW(e), has been operating for three years, and the third, Indian Point, 151 MW(e), a year, these later two may be compared in output with Berkeley and Bradwell. The first power b.w. reactor, Dresden, 184 MW(e), has been in operation for four years, three smaller reactors are also in use, and in Italy the S.E.N.N. reactor of 150 MW(e) similar to Dresden,
from America has begun to operate. No attempt has been made to design any of these for on-load fuel changing: the short distance between fuel elements makes this difficult and the number of penetrations through the steel pressure vessel are very restricted on account of the extremely high pressures employed, around 2000 lb./in.² for p.w.r. and 1000 to 1500 lb./in.² for b.w.r. Instead, the reactor is shut down for a completely new core replacement, or for fuel shuffling. Many variants of fuel element design and reactor overall design have been proposed, and nearly all the reactors so far built differ from one another very considerably, more so than in the first 14 power reactors built in Great Britain.

The pressure vessels for the largest of these reactors are small enough to be fabricated and heat treated in the factory. The Yankee p.w. vessel is made mainly from 8 in. steel and is 31 ft. high and 10 ft. 6 in. outside diameter; the Dresden b.w. vessel is made mainly from 5-5 in. steel and is 40 ft. high and 13 ft. in diameter; the Bodega Bay 310 MW(e) vessel is 50 ft. high and 15 ft. in diameter but even larger vessels have been proposed to operate at 2200 lb./in.², and deliver 400 MW(e). The radiation flux reaching the walls of the Shippingport reactor amounts to $6 \times 10^{19} n/cm^2$ in 20 years of full operation and therefore precautions against brittle fracture must be taken; in due course the vessel will not be fully pressured until its temperature exceeds 150 °C, and in all the high-pressure reactors the material used will remain under constant observation during irradiation. The vessels are lined with stainless steel to avoid rust formation and embrittlement due to nascent hydrogen caused by knock-on processes, and all the interconnecting pipes and those in the heat exchangers are of stainless steel. The worst effect of rust is deposition on fuel elements which causes a lowering of heat transfer: the original experimental b.w. reactor suffered from this. The temperature variations in the heat exchangers are very small, for example, in the large Yankee p.w.r. the water leaves at 276 °C and enters at 260 °C, for Dresden b.w.r. the water temperatures are 286 and 262 °C and there is little chance of increasing these figures without superheat by oil or nuclear, so efficiencies are below the later gas-cooled reactors. The oil-fired superheating of the output steam in the Indian Point p.w.r. is to provide an attractive price for the power produced during these formative years of reactor experience; in the long run, if superheating can be achieved by passing the steam through channels in the reactor this would be preferable to oil firing.

All the light-water-moderated reactors use enriched uranium fuel elements, mostly in the form of oxide and mostly clad in a zirconium alloy (zircalloy 2, a 1-5 % Sn, 0-1 % Fe, Cr, and Ni alloy of zirconium from which the hafnium has been removed). Where metallic uranium has been used as in the Shippingport and naval reactors, it has been alloyed with a high percentage of zirconium; without this, ordinary metallic uranium is unsafe to use in water reactors on account of the violent reaction with water leading to release of fission products if failure of a fuel can occurs. Oxide fuel elements were used in the earliest b.w.r. at the Argonne Laboratory in 1956; a large amount of experience has been gained from their use. They have operated with faulty cans without notable loss of fission products. The oxide is sintered to a density of 96 % but even at this density thermal conductivity is low so rods have to be of small diameter. The cracking which occurs due to high
temperature gradients of nearly 2000 degC/cm does not adversely influence the fuel element behaviour as the cans are filled with helium but internal maximum temperatures must be kept below 1500 to 1600 °C; above this temperature grain growth becomes pronounced and this releases fission products which then cause swelling. Some fuel elements have been made by ultrasonic vibration packing of the oxide, this can reach a density of 95% and life tests are in progress.

The zircalloy cladding is very stable in the presence of radiation and nascent hydrogen, and has a lower neutron absorption than stainless steel, but it cannot be used in gas-cooled reactors because its corrosion resistance in CO₂ is inadequate. Although initially protected by a thin oxide layer, some corrosion of the zirconium occurs and hydrogen is absorbed causing embrittlement, unimportant during the life of a fuel element at present, but if very long burn-up periods are regularly achieved such as 20 to 40 kW days/ton and if fuel elements were handled excessively in fuel shuffling, this feature might be a serious limitation, but improved alloys are being developed. Many of the original zircalloy-clad fuel elements in the Shippingport reactor have completed 30 to 40 kW days/ton and zircalloy has been chosen for the next core in which all the fuel elements will be of the flat plate type of the kind familiar to users of research reactors, the fuel only 0·1 in. thickness. In this way higher thermal ratings will be obtainable. In the later p.w. and b.w. reactors stainless steel seems to have been used in preference to zircalloy, possibly for its cheapness or to avoid completely the hydrogen embrittlement. In the latest p.w. reactor Indian Point smaller diameter rods, 0·3 in. in diameter, have been used to increase surface area/volume ratio to achieve higher thermal rating. Protagonists of both these types of water reactors are satisfied with the economic potentialities and envisage larger reactors than those at present under construction: the Bodega Bay b.w. (310 MW(e)) reactor recently ordered and due for completion next year will have a larger electrical output than any of the gas-cooled reactors then operating but not so high as the two gas-cooled reactors at Wylfa (560 MW(e)).

In the p.w. reactors an improved method of reactivity control under consideration is the use of boric acid injected into the system, particularly during the start-up phase before xenon poisoning is significant. Its use as a shim offers a more uniform flux distribution than can be obtained by the use of a multitude of control rods and its injection and removal appears to be economically justified. In the original experimental b.w. reactor ‘Borax V’ the use of boric acid has been studied; apparently if water drops are not carried over into the turbine with the steam the amount of boric acid leaving the reactor is set by its volatility and is a small fraction of the total; however, this form of control has not yet been used on the b.w. power reactors.

Another way of avoiding flux disturbance introduced by control rods, and also of avoiding neutron absorption by boron has been suggested, namely, by undermoderating the neutrons in the early life of a reactor core, thus releasing more neutrons to breed fissile fuel, and, as reactivity of the core falls, to alter the moderator gradually to compensate for this. In the case of the p.w. reactor it is suggested that the moderator at first should contain four times as much heavy water as light, and then be diluted until at the end of 25000 MW days/ton irradiation the heavy water content
should have fallen to a few per cent. The gain in breeding coefficient and fuel utilization if thorium and uranium-235 are used—it is claimed—would more than compensate for the renewal of the moderator with each new core. Of course control rods are available for safety shut down.

If the cooling of the fuel is physically separated from the moderator two alternative designs of reactor of great potentiality are practicable and have been well developed in Canada and Russia and a whole family of so-called pressure-tube reactors are being considered; moreover, in separate pressure tubes nuclear superheating of steam might become practicable, and thus result in higher turbine efficiency. The Canadian reactors moderate with heavy water, the Russian with graphite; neither moderator is under high pressure so there is no very serious limitation of size of the reactor. The first Canadian reactor (N.P.D.) has been operating at 22 MW(e) for a year and the second, the Douglas Bay reactor, 200 MW(e), is due to operate this year: in India you have decided to build a 200 MW(e) reactor at Tarapur operating on almost the same principles. The great attraction of these reactors is that they use natural uranium, and fuel elements can be ‘shuffled’ naturally so that all have nearly the same burn-up before being discarded, also the moderator is relatively cool so that resonance capture is at a minimum; the penalty is the high expense of heavy water, but economic assessment shows that the cost of power is still low from this type of reactor. The first Russian reactor, at Obnernisk, has been operating since 1954 at 5 MW(e) and several 100 MW(e) reactors at Troitsk have been operating for a few years; their great attraction is the cheapness of the graphite moderator but enriched fuel has to be used. The pressure tubes which thread through the moderator must be capable of withstanding the 1000 to 2000 Lb./in.² either indefinitely or for the life of the fuel, and may be at the temperature of the coolant or the moderator. Cooling of tube-type reactors can be done with heavy or light water, or steam or gas, or an organic fluid; or in the extreme, a liquid metal in which case the pressure is barely above atmospheric.

The attractive features of the Canadian heavy-water moderated and cooled reactors are the fuel cycle and handling. The moderator is in a metal calandria, aluminium for N.P.D., steel for CANDU, threaded with 4 in. aluminium (or zircalloy) tubes on a 10 in. pitch. Through these tubes are threaded the high-pressure tubes of zircalloy 3½ in. in inside diameter, wall thickness 0.5 in. which must withstand 1200 Lb./in.² at 280 °C in the maximum neutron flux. These tubes have already been given increased strength by the cold work done on them in the final drawing process, and tensile and creep properties will improve under neutron irradiation; corrosion from hydrogen pick-up should be small within the lifetime of these thick tubes, and in the event of suspicion the tubes can be removed. They are insulated from the cool aluminium tubes by stagnant air.

In these tubes are pushed from either end the bundles of oxide fuel in very thin zircalloy cans which collapse onto the fuel under pressure. They are thin because very long life is not expected of them, the fuel being unenriched. As fuel rods are pushed in at one end others are extracted from the far end, and in adjacent tubes loading occurs from opposite ends. In this way mean lifetime should almost be synonymous with maximum lifetime and neutron losses are so small that fuel is
expected to yield 8000 MW days/ton. The fuel rods are separated from one another by thin zircalloy rods welded helically on to the elements so that good turbulence of the water occurs. The operating experience gained so far is meagre, and is concerned chiefly with heavy-water leakage and the fuelling machines. To avoid neutron loss there are no control rods, no soluble poisons and no burnable poisons: control and scram is exercised by moderator height in the calandria; 0.3% reactivity can be lost in 1 s and all the moderator dumped in 30 s.

The Douglas Bay 200 MW(e) reactor does not differ significantly from N.P.D. The calandria of stainless steel is 20 ft. in diameter, and the calandria tubes are of zircalloy instead of aluminium and great emphasis is placed on cutting thicknesses to the minimum to save neutron loss.

At the expense of using enrichment the Canadian concept can be modified by cooling the fuel with light water, and then following the b.w.r. concept, the heat exchangers can be eliminated. The reactor is then also in a suitable state for experimenting with the superheating of some of the stream. The construction of a British steam generating heavy-water moderated reactor for 100 MW(e) on these principles has just been started.

The Russian reactor at Obnerisk was first operated as a p.w. tube reactor and then some of the tubes were converted to allow boiling of water to occur; and finally some were used to superheat saturated steam, and as a result of these experiments the first superheated power-producing reactors were designed. The graphite core 30 ft. in diameter 30 ft. high is encased in a relatively thin steel shell filled with nitrogen and through the top plate the thin walled water-cooled fuel elements hang in cylindrical graphite sleeves. Three-quarters of the 1000 fuel elements are cooled with water which is boiling and the balance are superheating the steam to 500 °C. Each fuel element consists of a central stainless-steel tube which carries the coolant to the bottom of the element; here the coolant flows up six thin tubes spaced around the central tube, and uranium metallic alloy sleeves fit tightly on these six tubes. Many graphite disks pierced with the seven holes fill up the space around these tubes and all are encased in the outermost gas-tight steel tube. The large amount of constructional tubing originally necessitated a 5% enrichment in the Obnerisk experimental reactor, but the power reactors only need a 1-3% enriched fuel. To convert to superheating no changes appear to have been necessary to the fuel elements; all the central channels are first brought to boiling point and when the steam pressure has risen in the separator to 1500 Lb./in.² steam starts to replace water in the fuel assembles. As the moderator is graphite, and graphite even separates the individual uranium cylinders in a fuel element the change in moderation by replacing boiling water with steam causes very little neutron flux peaking, the operation is inherently safe as the change reduces reactivity by undermoderating. Details of the fuel heat balance with steam have not been given.

There have been some experiments on the conversion of channels in American boiling water reactors to superheat and two medium-sized reactors are now being built incorporating two different concepts. In the Vallecitos b.w. experimental reactor a hollow fuel element rather similar to the Russian elements was introduced into one of the 3 in. x 3 in. standard fuel elements; and steam from the dome of the
reactor was passed down the outside of the hollow fuel elements and up their inside—the outer stainless-steel tube was 1\(\frac{3}{8}\) in. in diameter, the inner 3 in. in diameter and the outer was in thermal contact with the moderator and so provided adequate cooling if the steam supply failed. The amount of steam circulating could be independently controlled. Failure of several stainless-steel inner tubes, the hottest being 600 to 700 °C, was due to attack by chlorine in the wet stream and the conclusion is drawn that at these higher temperatures either other materials must be used or chlorine concentration must be greatly reduced. Many satisfactory tests were then made with iron-nickel alloys (of the Inconel type) replacing stainless steel and heat removal by the stream of about 20 kW/kg (about half that removed by boiling water) was achieved. Now a complete core had been assembled to test superheating very thoroughly, the steam being supplied from an exterior boiler to avoid nuclear problems arising from two-region cores. Vacuum refined stainless-steel will be compared with the Inconel metals in these tests. The super-heat fuel elements in one of the small power reactors are placed in the centre of the core, thus acting as a flux flattener, in the other they had placed around the b.w. core and higher enrichment has to be used. It will be several years before superheating has been thoroughly tried and economically assessed; the integrated boiler and super-heater has many complications in it which a separate superheater would not have, and in the meantime other reactors might achieve such temperatures that superheating of steam would not be required.

If no moderator is used, fission takes place primarily by fast neutrons and with fast neutrons uranium-238 is fissile, other losses of neutrons are low and it is possible to breed more fissile atoms than the number undergoing fission. This fact was verified fifteen years ago and the first reactor to produce electricity was the experimental breeder reactor at the Argonne Laboratory in 1951. Several moderately large breeders have now been built, the one at Dounreay is generating electricity at its designed output and is working very satisfactorily so far. The relatively slow progress made with all these has been due to the novelty of materials employed and great complexity of the design, and the need for extreme precautions against nuclear accident with highly enriched fuel. In addition there has not been the urgent need to produce a power reactor of this type. However, progress now has been so good that its future is seen, first, as probably the best type of reactor to use the plutonium now being produced in the present generation of power reactors, and then, if as expected, it should prove to be a low capital cost reactor, it might be suitable for supplying some of the electrical energy over and above the base load of a country.

The complexity of the design arises because the thermal rating of the core of a breeder reactor is high, e.g. 14000 kW/cu.ft. of the Dounreay core compared with say 2000 kW/cu.ft. of the core of a water cooled reactor, and liquid metal must be used to remove heat at this rate. Although liquid metals such as sodium have been used for cooling turbine blades they have not been needed in the extreme purity of a few parts per million required in the reactor and the quest for purity has proved long and arduous. The molten metal—sodium, or a sodium potassium alloy—scavenges oxide from many solid metals and concentrations of oxide in the Dounreay reactors...
have clogged cooler parts of the complicated sodium circuits. The use of sodium as a coolant restricted the choice of fuel-cladding material; niobium and vanadium were shown to be compatible with the coolant and with the uranium-molybdenum alloy, chosen for the cores of the American and British reactors. There have been many other problems at Dounreay, notably gas entrapment in the liquid metal stream, and there are still many nuclear physics problems to solve, but the reactor is working so well that plans for the next engineering step forward are being prepared.

Only the main engineering developments have been reviewed. There are almost countless smaller variants to the main lines of progress; some have been dropped, some have experienced difficulties and others are very new. At an early stage it was hoped that the fuel might be used in fluid form so that the continuous removal of fission poisons could be achieved, but difficulties have been very great. Organic liquid, terphenyl was used instead of water, but decomposition under irradiation proved serious; if this can be overcome the attraction is the avoidance of very high pressures while achieving reasonably high temperatures. Another low-pressure graphite moderated reactor is the sodium reactor in California but this too has been beset by very great difficulties of manufacture and operation.

The future for the large central station reactor seems now to be well assessed, and based on experience the economies of the large reactor, gas-cooled, or water-cooled and moderated now seems to be able to compete with the fossil-fuel station. The really important new ideas ought to result in economies of 20% after one or two stations have been built. What is not yet so clear is the preferred design for a small reactor, say 100 MW(e) to operate on a load factor of 50 to 70% and therefore the less developed countries have small incentive as yet to embark on a nuclear power programme. However, they already have a long-term programme before them, the training of a generation of scientists, engineers and technicians needed for industrialization and for this the many research reactors are invaluable so that one can look forward to the 1970's for a rapid upsurge of nuclear power production.

In more ways than one this fantastic manifestation of nuclear energy has come to our generation in the nick of time. On the military front it speeded the finish of the war; and together with the hydrogen to helium fusion reaction which Rutherford discovered may have prevented a Third World War and heralded in a thousand years of peace. It has come in time for the renaissance of many nations all needing electricity to perform Herculean tasks. We, in England, would have needed half our 200 million tons of coal per annum for electrical generating stations ten years from now and would have been very anxious about the supply of fuel for the following ten years.

All this industrial progress has stemmed from the work of a few scientists of whom Rutherford was the outstanding genius and of him perhaps you could say:

‘Never in the realm of human endeavour in physics has so much been owed by so many to one man.’