A Review of Nuclear Power in the United Kingdom

by FRANCIS TOMBS
Chairman, The Electricity Council

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A REVIEW OF NUCLEAR POWER IN THE UNITED KINGDOM

Ever since scientists realised that there was a large amount of energy locked up in the nucleus of heavy atoms they have directed their efforts to releasing that energy in a usable way. British scientists played a leading part in the research for nuclear energy which has been going on in this country at least since the beginning of the present century. Many of the early experiments which paved the way for the present applications of nuclear power took place in British universities. It was at the Cavendish Laboratory, Cambridge, in 1897 that J. J. Thomson proved the existence of the electron, and in 1919 that Rutherford announced the transmutation of nitrogen. In 1932 Chadwick identified the neutron, a very important nuclear particle that has no charge, which was to play a vital role in chain reactions. In the same year, 1932, Cockcroft and Walton achieved the ambition of most physicists in those days, the splitting of the atom, which for centuries was considered to be the smallest part of matter, and indivisible.

From then on nuclear physicists knew that they were well on the road to controlled release of the energy in the nucleus of heavy atoms. In the spring of 1941 a group of scientists in Britain reported on the feasibility of using nuclear energy as a source of power. Objective and truthful as scientists are, they reported at the same time that nuclear energy could also be used as an explosive. The British scientists' report was conveyed to the US government and it gave considerable impetus to the US atomic energy plans, which soon took shape in the "Manhattan Project". It was unfortunate that because the democratic countries were in a deadly struggle at the time, priority was given to the development of nuclear weapons. From 1943 a substantial number of British scientists were engaged in the intensive work on the atomic bomb project in the USA. Some of them were sent to Canada to work on nuclear power research at Chalk River, where a heavy-water-moderated reactor was built. This work led to a rapid increase in knowledge of the processes of nuclear fission and the technology of building, controlling and using nuclear reactors.

At the end of the war in 1945 the British scientists were withdrawn from the US project, and most of those working in Canada returned to work on the development of nuclear power in this country.

Let us now look at the basic principles of "chain reaction", and nuclear power. When a uranium atom U235 is hit by a neutron with the right energy, the U235 is split into two lighter elements, or fission is said to take place. The important point to note is that at the same time some neutrons are released from the nucleus and are available to cause fission of other U235 atoms. These new-born neutrons have high energies and therefore high velocities. At these high energies they could pass very close to the nucleus of a U235 atom without being captured by it to cause fission. Therefore the neutrons have to be slowed down, or moderated, as it is called. There are three practical moderators: ordinary water, graphite and heavy water. Water is a very effective moderator and slows down neutrons in a short distance but unfortunately it also captures some of the neutrons so that there are fewer neutrons available to cause fission of the U235 atoms. Graphite and heavy water slow down the neutrons over longer distances, but they capture far fewer neutrons, and therefore more neutrons are available to cause fission.

Natural uranium has only 0.7% of the isotope U235; 99.3% of it consists of the isotope U238. When this isotope is hit by a neutron, fission does not take place. With graphite and heavy water moderators, 0.7% concentration of U235 is sufficient to sustain a chain reaction so that the fission process can continue. With ordinary light water 0.7% concentration is not sufficient and a chain reaction cannot be sustained. A higher concentration of U235 is necessary. This means that the U235 content has to be increased, or the uranium has to be "enriched", as it is called. At the end of the war the only uranium enrichment plant was in the USA but in the post war years the UK and Russia also built their own enrichment plants. Much later France also built such a plant.

The enrichment required in light water reactors is about 2-3% of the U235, against the 0.7% in natural uranium. The enrichment process is not one of making more U235; that is not possible. The process in fact removes some of the U238 from natural uranium, so that the remaining material has the right percentage of U235. The U238 removed is called depleted uranium.

Enrichment plants are very costly to build and consume large amounts of electricity. It was said that the first American enrichment plant consumed as much electricity as the total consumption in the UK after the war.

Before we leave this rather simplified explanation of chain reaction, let us note another very important process that takes place. Some of the neutrons are captured by the U238 atoms, and through a series of radio-active processes, turn into another element that is not found in nature: Plutonium. The importance of plutonium is that like U235, fission takes place when hit by a neutron. It is therefore an extremely important and useful material in the energy supplies of the future. The quantity of uranium in the world is finite and only 0.7% of it can provide us with energy, but if we can turn all the U238 into plutonium, we can extract about 100 times as much energy from the uranium reserves.

After the war, when it was decided to exploit nuclear energy for the generation of electricity in the UK, there was no spare uranium enrichment capacity for civil use, so a natural uranium reactor had to be adopted. In the USA, as there was sufficient enriched uranium available, they opted for an enriched uranium reactor using light water. We had a choice of moderator: graphite or heavy water. Graphite is a relatively cheap material. Heavy water forms about 140 parts per million of ordinary water. It has to be separated out by a cascade distillation process and is quite costly; therefore a graphite-moderated natural uranium reactor was chosen.

The heat generated in the uranium fuel has to be utilised to generate steam for the turbines, as a boiler does in a coal or oil station. This is done by removing the heat from the uranium fuel by means of a suitable coolant and transferring it to a heat exchanger in which steam is generated. The next choice for the British reactor was the coolant. We have seen already that it could not be water, as it captures neutrons. It had to be a gas. Air was used in the original Windscale reactors. Because of the oxygen however, the operating temperatures are severely restricted, which means that the heat that can be generated per tonne of fuel is low and the economics are very poor. Helium would be an extremely good coolant as it is chemically inert but it is not readily available in this country. (It is found in certain gas fields in the USA and Canada, but at the time there was a restriction on the export of large quantities of it.) Carbon dioxide was therefore chosen as coolant and in order to increase the heat transfer it is used under pressure.

In the post-war years the Government set up a large organisation in the Ministry of Supply to build various nuclear plants necessary for defence purposes. These consisted of uranium ore processing, uranium enrichment, fuel element fabrication, reactors for plutonium production and fuel reprocessing, in which the spent fuel from reactors is chemically treated to separate the unused uranium, the plutonium and the radio-active waste products. A very important part of the organisation was a powerful research group with very extensive research facilities, probably second to none in the nuclear field, under the personal direction of Sir John Cockcroft, the first man to split the atom – in 1932. The engineering design and construction group of the organisation, equally powerful, was under the direction of Sir Christopher Hinton, now Lord Hinton. The successes of this group are now legion. They built reactors and nuclear plants all novel, with no direct experience to draw on, with minimal delays. They have all been highly successful in operation. All who have worked with Hinton realise his engineering ability, his clear thinking, his drive, his broad vision and far-sightedness. A biographical memoir of Cockcroft published by the Royal Society records that Hinton, when accepting his appointment in 1946 to build the nuclear plant for military purposes, made the condition that if it were possible to evolve civil applications for nuclear power, the engineering development should be the responsibility of the group he was being asked to set up. Obviously Hinton could already forsee nuclear power as a practical concept and was intending to make organisational provision to that end. Within a few years he was convinced that nuclear power was a reality and he managed to convince others. An opportunity was provided in 1951, when there was an increased need for plutonium for defence purposes. It was decided to build reactors capable of producing both plutonium and electricity. Calder Hall in Cumberland – now Cumbria – was chosen as the site for a nuclear power station of 4×35 MW (e) units. The first unit was commissioned in 1956 and became the world's first nuclear power station of a commercial size.

No time was wasted by the Government or the atomic energy organisation that had been set up to promote the commercial exploitation of atomic energy. Four groups of industrial companies were invited to set up teams to design and construct atomic power stations. Industry responded with enthusiasm and great speed. Four consortia were formed for this purpose, each including a turbo- generator manufacturer and a boiler maker. Some included a civil engineering contractor also. The turbo-generator manufacturer took the lead in each consortium and it is interesting to consider why this happened. It was not strictly logical because a nuclear reactor is in fact a "nuclear boiler", taking the place of the fossil fuel-fired boiler in a conventional station, and therefore is a competitor of conventional boilers. It would appear to be more logical for the boiler makers to have taken the lead in the consortia, because if nuclear power could be developed successfully, it would replace conventional boilers, and the boiler makers would find themselves without their traditional work. On the other hand turbo-generators are required in nuclear stations as well as in conventional stations, and therefore their business would not be seriously affected. I believe the generally accepted reason for the turbo-generator manufacturers taking the lead is that the design and development of reactors requires considerable engineering and metallurgical research and development facilities. The turbo-generator manufacturers were a part of electrical companies which had extensive R. & D. facilities. It is interesting to note that in other countries also, the turbo-generator makers entered the nuclear reactor business. In the USA some boiler makers entered this field as well as the turbo-generator manufacturers.

In the UK the basic design and information was to be provided by the Government's atomic energy team, which at the time was still a part of the Ministry of Supply. In order to facilitate closer contact and co-operation with industry, responsibility for nuclear energy was transferred from the Ministry of Supply to a non-departmental organisation under the Atomic Energy Authority Act, 1954. Hinton's Group helped the consortia to set up the appropriate teams to design and construct nuclear power stations on a turnkey basis – that is, a single contract placed with a main contractor, who takes full contractual responsibility for the design and construction of the complete station and places his own sub-contracts for the supply of the necessary components and services. Hinton's Group provided the consortia with the basic nuclear data and engineering information from the Calder Hall reactors. Events were moving very fast and in February 1955, a Government White Paper was issued which stated that construction of two nuclear power stations would start in 1957 followed by two more in 1958-59 and a further four in 1960, and that they would be owned and operated by the supply authority. It appears that events were moving so fast that the owners and operators to be, the Central Electricity Authority, as they were then, were hardly consulted. Sir Stanley Brown, the then Chairman of the Central Electricity Generating Board records in his Cockcroft Memorial Lecture to the British Nuclear Energy Society in 1970 that before the publication of the White Paper barely half a dozen or so people in the CEA had taken any part in discussions and they, in the light of the tight security arrangements on nuclear matters, had been unable to disseminate such information as they had. The concept of turnkey contracts was new to the CEA. The newly formed Atomic Energy Authority considered that such an arrangement was necessary to optimise and co-ordinate the designs of the reactor and the turbo-generator, and to comply with the nuclear safety requirements. Sir Stanley Brown says that as far as he could ascertain there was no consultation with the CEA on this important topic, which was such a basic change to the practice of the supply industry. However, Sir Stanley records his belief that the supply industry was well served by the consortia in the majority of the contracts, and that the adoption of the turnkey contract system in this country made a major contribution to the early successes of nuclear power.

If the CEA had been left breathless with the Government's and AEA's speed of action, they showed their own paces when it came to finding the first two sites. Within two months after the issue of the White Paper a series of aerial surveys had been undertaken and 24 sites inspected. Within three months trial borings had commenced, and within seven months six sites were selected, which included Berkeley and Bradwell. Sir Stanley, looking back, concludes that "the choices were sound and that speed had no evil effects." In his view the normal procedures that take at least twice as long lead to no better results.

After the selection of sites came the next hurdle. The CEA were faced with purchasing and operating a type of station of which they had virtually no knowledge. The AEA extended to the supply industry the training they gave to engineers and scientists from the consortia. Sufficient engineers had been trained to enable the CEA to write the first enquiry specifications for a turnkey nuclear power station by early 1956 and issue them to the consortia. They were, of course, assisted by the AEA on the reactor sections of the enquiry.

In parallel with the AEA's and CEA's activities, one of the most exciting developments in the history of the heavy plant industry was taking place. The four consortia were building up almost from scratch, broadly based teams of mechanical, electrical and civil design engineers; development engineers; physicists, mathematicians, metallurgists, and chemists; project engineers, contract engineers and site resident engineers. Such a collection of disciplines under a single control was new to the heavy plant industry. It is to the credit of the leaders of the consortia that they built up such teams, and they were powerful teams, so quickly. I am sure they will be the first to agree that they were helped in this recruitment of staff by the general attitudes to nuclear power in those days. There was some romance about it. Young men were eager to enter the new industry at its birth, and to shape its destiny. There was a great deal of pioneering work to be done, and there were many enthusiastic people ready to take up the challenge. Within a matter of months these teams, in competition with each other, went to the heart of the Magnox reactor, and made improvements to the heat transfer from the fuel to the gas, compared to the Calder Hall fuel, by ingenious designs of fins. This increased the output from each tonne of fuel and therefore from a given size of reactor. The White Paper had visualised a reactor size of about 75 MW and a station output of 150 MW from two reactors. In fact, the very first designs of the consortia were for about 300 MW output from a twin reactor station. The consortia then set about preparing their tenders in great detail, backing each item of novel design with analytical and experimental evidence. The tenders were voluminous documents weighing many hundredweights. They were submitted in October 1956. The assessments were completed and the first three contracts awarded in December, 1956. Site work at Berkeley and Bradwell began within a few weeks, in January, 1957. Hunterston was delayed, as the Reporter who held the public enquiry died suddenly before he submitted his report, and a fresh enquiry had to be held.

Early in 1956, a medium term coal shortage had been forecast. The NCB had reported that only 53M tons of coal would be available in 1965 for electricity generation by the CEA and SSEB against an estimated demand of 68M tons. The government had requested the supply industry to convert some coal-fired stations to oil burning. In October 1956 came the Suez crisis which raised the gravest doubts as to the security of the necessary oil supplies. As a result the Government announced in March, 1957, an expansion of the nuclear programme from about 2000 MW to 5000 MW.

There was the usual controversy about the relative economics of nuclear and fossil-fuel stations. The AEA were optimistic. Money was cheap: the interest rate was 5%. They had assumed the capital cost of conventional stations to be around £70/kW, although Stanley Brown had pointed out at a symposium in Calder Hall in November, 1956, that technological advances in the design and size of turbo-generators were in the pipe-line and that costs would fall. Based on the AEA's assumptions, and by attributing a credit of £5000 per kg to the plutonium produced in the fuel, nuclear power was expected to be competitive right at the outset. However, fate was unkind to the newly born nuclear power industry. Interest rates soon began to climb. Nuclear stations being capital intensive are more sensitive to interest rates than conventional stations. The cost of conventional stations began to fall: at one stage to about £35/kW. The NCB discovered that they had much more coal for power stations than they had forecast in 1956. Suez had not after all proved to be a threat to oil supplies; on the contrary, there was a rapid expansion of oil production and oil prices fell. In fact, to encourage the use of coal, the Government imposed a tax on heavy fuel oil and paid compensation to the supply industry for the use of uneconomic coal in lieu of oil. In this new situation revised estimates in 1960 showed that the cost of electricity from conventional stations would be about

25% less than that from contemporary nuclear stations. It was believed, however, that nuclear stations being more inflation-proof due to their very much lower fuel cost, would produce cheaper electricity by 1970. That belief at least has been fully justified, as we shall see later.

During the construction and commissioning of the Magnox stations, there were the usual design changes and teething troubles associated with a new technology and novel designs. Although the Calder Hall reactors were a useful reference for the consortia, the design parameters had to be pushed to the limit in order to reduce the unit cost. The operating temperatures, the gas pressure, the size of the units were increased. These changes required entirely new design of components. It was also decided to change fuel on load; The Calder reactors are shut down for this purpose, which involves an economic penalty. All the problems were systematically overcome. The construction of the Berkeley and Bradwell stations was completed in 1960, in about 3½ years, and the commissioning took another year. A remarkable achievement for a young and inexperienced industry.

The first seven commercial Magnox stations used steel pressure vessels, as at Calder Hall. For the Oldbury station, one of the consortia put forward an entirely different concept of layout, with the whole of the primary circuit, the reactor core and the steam generators contained in a prestressed concrete pressure vessel. This was a major advance in the safety of gas-cooled reactors. With a steel pressure vessel there is a probability, albeit extremely small, of a brittle fracture. A prestressed concrete pressure vessel removes even that small probability. In such a design there are many thousands of cables, and they cannot all fail at the same time. Since Oldbury, all gas-cooled reactors in this country, Magnox and later Advanced Gas-Cooled Reactors, have been built in prestressed concrete pressure vessels. In France and the USA also, all gas-cooled reactors since Oldbury have been based on the same concept.

Altogether nine Magnox stations – 18 reactors – have been built in the UK, one in Italy and one in Japan. They have been operating very well. One basic shortcoming however, was discovered after a few years' operation, which marred their excellent performance. It was found that in the carbon dioxide atmosphere, there is breakaway corrosion of mild steel at temperatures above 360°C. This was not foreseen when the stations were designed and built. It has been necessary, therefore, to reduce the maximum temperatures of the gas, which has resulted in some reduction in output. The actual reduction varies, depending on the partcular reactor design. For instance, Berkeley was hardly affected, whereas Oldbury suffered a big reduction, as its design parameters were more advanced. The average reduction in output was about 10%. Even after taking this de-rating into account, the cheapest electricity in the country is now being produced by nuclear stations. This is due to the large increases in oil and coal prices, demonstrating that nuclear stations are more inflation-proof than fossil-fuel stations.

While the Magnox stations were being built by the consortia, the AEA developed a more advanced design, called the Advanced Gas-Cooled Reactor – the AGR. In order to increase the rating of the fuel and reduce the size of the reactor for a given output, a cluster of fuel pins was used, each pin canned in stainless steel. The geometry of the AGR fuel necessitates the use of enriched uranium. By then, there was sufficient enrichment capacity in the country to supply the required fuel. The AEA decided to build a 30 MW AGR for the main purpose of proving the new fuel element . It was considered that the engineering features of the new reactor were close enough to the Magnox reactors being built not to warrant the building of a large-scale prototype. Events many years later showed this to be a serious error of judgment, for which the whole nuclear industry must accept some responsibility.

The order for the Wylfa station at Anglesey completed the first nuclear power programme of 5000 MW. In 1964 the Government published their White Paper "The Second Nuclear Power Programme" for a further 5000 MW. In brief, this stated that a more highly rated reactor system than the Magnox would have a lower capital cost and would therefore be preferable for the next nuclear power programme. As enriched uranium would be required for the AGR, it was decided to invite tenders for other enriched uranium reactors of proven design. In practice this meant American companies' designs, as by then they had built a number of Light Water Reactors. Some of the consortia offered both the AGR and a water reactor based on an associate American company's design. The AGR offered by one of the consortia was assessed to be the lowest tender. There was some controversy about the assessment, so the CEGB took the unprecedented step of publishing their assessment of the winning AGR tender and of the second-lowest tender, which was based on the BWR. The site for the station was Dungeness "B" and the contract was placed in 1965. Dungeness "B" station is not yet complete; it has had a most unfortunate history, largely due to the weakness of the particular consortium, which was eventually relieved of the contract and went out of business. Dungeness "B" being the first AGR station, the failure of the contractor inevitably cast doubts on the reactor system itself. This is where a large-size prototype instead of the 30 MW fuel element test-bed reactor would have played an important part and the contractor would have been able to draw on the experience of the prototype. Fortunately for all concerned, including the reactor system itself, the following two AGR orders, for Hinkley Point "B" and Hunterston "B", placed in 1967 with another consortium, have been successfully completed and have been in operation for nearly two years. There were delays at these stations also, as they turned out to be prototypes. They are nevertheless producing the cheapest electricity in the UK, even after taking into account the cost of the delays. Their performance so far has been satisfactory.

Gas-cooled reactors have a very high degree of intrinsic safety, expose the operators to very low radition, and produce low radio-active discharge, compared to water reactors. The next nuclear power programme is now under consideration. The decision in 1974 to embark upon a limited programme of Steam Generating Heavy Water Reactors is likely to be changed. The reasons for this stem mainly from the changes in conditions since that date. The predictions then of an early need for large quantities of nuclear power have not been fulfilled and the grave concern about the problems in design and construction of the AGRs have been largely overcome by the successful commissioning of Hinkley Point and Hunterston. Additionally, progress with the design of the SGHWR has been disappointing, largely because of attempts to produce operator radiation dose levels and loss of coolant accident analyses to a much higher standard than can be offered by other water reactors.

The performance of the AGR is now supported by 18 months' satisfactory experience but some people believe it would have poor prospects of sales overseas in competition with light water reactors. I doubt whether this view is right, because the safety criteria in all countries are getting more onerous. People are looking for safer-than-safe reactors. Although the light water reactors are perfectly acceptable on safety ground rules, the AGR has more to offer and we should be able to sell it just because it is different from water reactors. Whereas, if we adopted a light water reactor in the UK, and tried to sell it overseas, we would simply be trying to compete for the same product with other companies which have been in the business for many years.

I would now like to look to the future and discuss the contribution nuclear power can make to our energy needs. Historically there has been a relationship between the standard of living in highly industrialised countries and their energy consumption per capita. For instance in the USA the energy consumption per capita is about 11,500 kg.c.e. whereas in this country, Germany and France, it is about half that figure. In contrast the developing countries of Africa and Asia consume only a few hundred kg.c.e. per capita. It may be argued that people in the USA use energy wastefully, and that they could go on improving their standard of living without increasing their energy consumption per capita. Only time will show whether that is true. But it is clear that many countries will require a great deal more energy than they are using today even if their population did not increase. But the population of the world will continue to increase for many decades, because the age distribution in the developing countries looks like a triangle, with young people at the base. The world's population today is around 4×10^9. Some estimates put the population in the year 2000 at 6×10^9, and a levelling off at 13×10^9 in the 22nd century. The increased population will require an equivalent increase in energy. If the world is to limit its energy consumption to the existing level, then either the richer countries will have to use very much less than they do today or the poorer countries must get poorer and poorer. Obviously they would not accept such a situation, nor indeed would the developed countries wish this to happen on moral and ethical grounds as well as on economic grounds. At the present time nearly three-quarters of the world's energy requirements comes from oil and gas. Estimates of the reserves vary, as it is not possible to be precise. The consensus of informed opinion in many countries is that there is enough to last at current rates of consumption for about 40 years or, with some growth, for about 30 years. But a crisis will occur much sooner when production can no longer expand to meet the increasing demand. That time is put at about 15 years from now, well before the end of the century.

That is the global picture. The position in each country is different. In the UK we are more fortunate than countries like Germany, France, Japan and Italy, thanks to the North Sea oil and gas. In comparison with the world's reserves, however, ours are minute. Production is estimated to peak in the 1980's. There is a real danger in the UK that the abundance of oil and gas for a few years will give us a false sense of security regarding our long-term energy supplies and our balance of payments. It will be tempting to increase oil and gas production even more, first for our own use instead of developing energetically alternative sources of energy for the future, and secondly to sell more oil overseas to pay for our imports, instead of improving our industry to sell more of our manufactured products. If we are foolish enough to adopt such a policy, we shall be faced with an economic crisis worse than anything we have yet experienced when the North Sea production begins to decline.

What are the alternative sources of energy available to us in the foreseeable future, say by the end of the century? We must rule out the use of oil and gas for any new projects. Their use from now on should be restricted for those applications for which they are essential. Oil, for instance, for transportation. We have large reserves of coal that would last for at least 300 years but its production presents social and economic problems. The NCB in their Plan 2000 say that by investing about £10 bn, they could increase annual production to 150 M–170 Mte by the year 2000.

Research and development is going on in the fields of wave power, solar energy, wind power. Some people who are not close enough to these developments believe that more money should be devoted to them to accelerate development. But development has to be carried out in stages, and at this stage of these developments a massive injection of funds would not increase the rate of progress. Of these alternative sources, wave energy, if the formidable engineering problems can be solved, could be very large. Because of this possibility three independent projects aiming to harness wave energy are being funded. In addition to the engineering problems there are environmental amenity problems. To produce half the electricity we use today would require installations about 300 miles long 15 miles off the North-West coast of Scotland. Most of the power would have to be transmitted to England. If this is to be done electrically it would require overhead transmission lines on an unprecedented scale, which would almost certainly be opposed by the environmentalists. Wind power is unlikely to provide large amounts of dependable energy to make a significant impact on our energy needs. Solar power to heat the domestic water supply is here now and its use should be encouraged if we can afford it. Insulation of existing houses would effect worthwhile savings of energy in the short-term. In future careful attention must be paid to the proper insulation of new houses. We must also look at the use of energy in industry and try to use it more effectively. But this is not likely to result in significant savings as industry reviews its processes and improves them whenever this is possible.

All these measures and the use of coal and alternative sources of energy will not provide us with enough fuel to live comfortably, to supply our industry, and to run our transport. As I mentioned earlier according to the NCB, we cannot expect more than 170 Mte of coal by the end of the century. Our total energy consumption at present is about 330 Mte c.e. With a modest growth in the economy, which is essential if we are to reduce unemployment to an acceptable figure, the energy demand at the end of the century is likely to be around 450-500 Mte c.e. According to a Department of Energy document, which considered the contribution that might be expected from the alternative sources of energy, we cannot rely on them for more than 10% of our needs. So there is a large gap to be filled. The only assured source of energy that can fill it is nuclear power. Those who have the responsibility of ensuring that sufficient energy is available at all times for our needs can count only on coal and nuclear power in the long term: coal to provide us with substitute liquid fuels for transportation and for use as a chemical feed stock: nuclear power to provide us with abundant electricity for space and industrial heating, and all those applications which can use electricity.

Large-scale and world-wide use of nuclear power would require large quantities of uranium if we continued to use the type of reactors we are using today which can extract only about 1% of the energy in natural uranium. But there is another type of reactor which converts more of the U238 isotope into plutonium than the U235 it uses. This kind of reactor is called a Breeder Reactor. It has no moderator to slow down the neutron, so to give it its full name, it is a Fast Breeder Reactor. A small 15 MWe experimental Fast Breeder Reactor operated satisfactorily at Dounreay for about 17 years. It served its purpose and was closed down earlier this year. A 250 MW prototype of such a reactor is now working at Dounreay. In view of the AGR experience I mentioned, we should build a full-size unit, 1300 MW, to prove all the engineering features and components before embarking on a large-scale programme of such reactors, which I believe will be necessary early in the next century. One or two units ought to be in operation in the last decade of this century, to give us the necessary practical experience.

During the last few years, there has been a growing opposition to nuclear power. It is significant that this opposition does not come from the people who work and live near nuclear power stations and installations. They know how clean and safe these plants are. The health record of the nuclear industry is second to none. The majority of the objectors appear to be people with only a superficial knowledge of the subject. The 6th Report of the Royal Commission on Environmental Pollution probably assesssed the objection to nuclear power correctly when it said: "We have no doubt that some who attack it are primarily motivated by antipathy to the basic nature of industrial society, and see in nuclear power an opportunity to attack that society where it seems likely to be most vulnerable, in energy supply." It is evident that some people do not hesitate to distort facts and to exaggerate the trivial, and to make wild statements with little foundation. I would like to deal with the main points which are made repeatedly by the anti-nuclear lobby, although they have been answered many times.

One of their bogies is the possibility of theft of plutonium by terrorists and of their making it into a bomb on a "kitchen table" and holding society to ransom. This is fanciful in the extreme, but it cannot be said that it could not happen, any more than that a Jumbo Jet would not crash on St. Paul's. The anti-nuclear lobby confuse possibility with probability. Plutonium in a form suitable for nuclear weapons has been available in a number of countries for many years. There have been no thefts, and no threats. It is not clear why the Fast Reactor fuel, a mixture of plutonium oxide and uranium oxide, requiring a special plant to extract the plutonium, would be more attractive to terrorists.

Of course, the material must be properly guarded in the nuclear installations and in transit. We are asked, by some, to believe that the arming of the guards, and security screening of the workers at the sensitive installations, will lead to loss of civil liberties and even undermine our democratic system. The guards are Special Constables under the 1923 Act. The 1976 Act authorises them to possess firearms without a certificate. The Secretary of State for Energy has undertaken to answer to Parliament for the actions of these Special Constables. There is no threat to our way of life by these measures. What concerns us more is the kind of direct action taken at Brockdorff, West Germany, and Creys-Malville, France, by a minority who are determined to impose their own will on the nation.

Another aspect of nuclear power that has caught the imagination of the public is the ultimate disposal of the radioactive waste. I must say in passing that President Carter's decision to stop reprocessing, and thereby accumulate large quantities of spent fuel, does not help the ultimate disposal problem. Reprocessing separates the relatively small quantities of radio-active waste from the bulk of the uranium and plutonium fuel. It is the separated radio-active waste that would be glassified in a form suitable for ultimate disposal. Without reprocessing, the bulk to be disposed of would be very much larger, and would contain relatively large quantities of plutonium.

Three basic schemes of storage or disposal have been considered:

(1) To store the glassified waste in tanks, in a somewhat similar manner to the storage of radio-active waste today. This would require some surveillance for hundreds of thousands of years.

(2) To bury the glassified waste in suitable rock formation in areas of the world that have been geologically stable and without water for tens of millions of

years. This would require minimal surveillance to ensure that the area was not dug up again for hundreds of thousands of years, until the activity had completely decayed. The objection raised by the environmentalists to this method is that unexpected geological changes may take place, even after millions of years of stability, and underground water may get to the waste, leach it and bring it to the surface or carry it into drinking water. Again the anti-nuclear lobby confuse possibility with probability. Even so, some preliminary studies by Dr. Bernard Cohen, of the University of Pittsburg, indicate that if leaching started soon after burial the probability of total cumulative deaths by the time the activity decayed would be less than two!

(3) To bury the glassified waste in stainless steel containers at the bottom of the oceans at depths of more than 10,000 ft. In this method, which would require no surveillance, the waste would gradually dissolve and would be dispersed and very much diluted by the natural currents at those depths.

More work needs to be done on all the possible methods to be able to predict more accurately the migration of heavy atoms under all conceivable conditions. The matter is not urgent. We need have no fear that the future generations would be less capable of dealing with such problems than our own. Mankind has progressed through the centuries by accepting problems and solving them.

Much concern has been expressed about the possibility of terrorists diverting nuclear materials for the manufacture of weapons. This would be a hazardous and uncertain procedure involving considerable risks for the terrorists with unpredictable and long drawn out results. One wonders why an intelligent terrorist should undertake such a task when there are readily available much more certain and less dangerous ways of blackmailing a population.

We may note that terrorists do not seem to have tried to hi-jack any of the many nuclear weapons in the world which do not suffer from these disadvantages to the terrorists. The answer can only be that security has been adequate, and if this is so then surely similar measures combined with the inherent disadvantages I have referred to should provide adequate protection for nuclear materials in a civil nuclear programme.

In any event the production of fissile material does not require the existence of a civil nuclear programme and nations determined to acquire a nuclear capability will be able to do so.

The solution to this problem is political and international. Great progress has been made through the International Atomic Energy Agency of the United Nations and the Non-Proliferation Treaty has been signed and ratified by an encouraging number of countries. In my view, achieving the maximum degree of acceptance of the Non-Proliferation Treaty remains the most important objective in nuclear power. The Non-Proliferation Treaty may not be perfect but it is a major step in the right direction.