BRITAIN'S NUCLEAR POWER INDUSTRY AND THE PROSPECT OF ITS REVIVAL

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February 20, 2024

Abstract

This paper recounts the history of the British nuclear industry from its inception to the present time. After the construction of a second generation of nuclear power stations had been completed, there was a long hiatus before it was recognised that a new generation of reactors was called for in order sustain the supply of electricity and to progress toward carbon-free electricity generation.

The Government failed to recognise that commercial enterprises could not be expected to bear the costs of constructing large nuclear power stations; and there has been a succession of projects that have failed to come to fruition. Now, there is an urgent need to expand the nuclear generating capacity.

The Government has failed to offer sufficient financial support to enable a timely revival of the nuclear industry. Sites need to be designated where new reactors can be tested; and the processes of certification must be expedited. The lack of support for our native enterprises makes it likely that, in future, Britain will have to rely on foreign suppliers of nuclear technology.

Contents

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1 First Generation of Nuclear Reactors

1.1 The Magnox Reactors

Calder Hall nuclear power station [3, 4, 5] was formally opened by the Queen on a bright autumn day in October 1956. It was described as the world's first full-scale civil nuclear power station. It had begun, in August, to feed 240 MWe (megawatts of electrical energy) into the national grid. In common with the Chapelcross station, which was its immediate successor, it contained four reactors, each contributing 60 MWe. All other Magnox stations contained two reactors. The decision to build the power station at Calder Hall had been taken in 1952. It is remarkable, in view of the time spent recently in designing and building nuclear power stations, that the entire process was completed in four years.

In fact, the Calder Hall reactor was not the first civil nuclear reactor to be commissioned. It had been preceded by the Obninsk Nuclear Power Plant, in the Soviet Union, which commenced operations in June 1954. Its electrical capacity had been a mere 6 MWe. This reactor was a forerunner of the notorious RBMK reactor, which was involved in the Chernobyl accident of 1986. Between 1956 and 1971, a fleet of 26 Magnox reactors were built in the UK at 11 sites. The reactors varied in their output, which rose in time to reach 490 MWe in the case of the station at Wylfa in Anglesey. This opened in 1971 and it was the last Magnox station to be connected to the grid. In 2015, it was the last to be shut down.

The Magnox reactors had the dual purpose of generating plutonium to serve Britain's nuclear weapons program and of generating electricity for the grid. The fuel for the reactors was natural uranium, which contains 0.711% uranium-235, 99.284% uranium-238, and a trace of uranium-234. A fissile isotope is one that is liable to split apart when stuck by a neutron of low energy. Within natural uranium, only the uranium-235 isotope is fissile. (uranium-233, which is bred from thorium, and plutonium-239, which are both created in nuclear reactors are also fissile.) In order to sustain a chain reaction in a uranium fuel with a small proportion of uranium-235, the kinetic energy of the neutrons created by its decay must be reduced or moderated to produce so-called thermal neutrons. Reducing their velocity increases their effectiveness in propagating the nuclear reaction. Neutrons that are too energetic will escape the nuclear pile without causing fission.

The Magnox reactors used graphite blocks to moderate the neutron flux. The efficiency of graphite as a moderator allowed the reactors to run using natural uranium fuel. The more common light water reactors require an enriched uranium, in which the proportion of the fissile uranium-235 isotope is increased to between 3 and 5%. The Magnox reactors used carbon dioxide as the coolant. This was pumped to a heat exchanger that transferred the heat to a steam circuit, which drove a turbine for generating the electrical power.

The carbon dioxide replaced the air that had served to cool the two graphite-moderated reactors at Windscale, described as the piles, which had been used, exclusively, to generate plutonium. Graphite will oxidise rapidly in air at high temperatures. This allowed one of the piles to catch fire. The fire burned for three days and it caused a radioactive fallout. This would have been much worse in the absence of the filters that had been installed at the tops of the chimneys at the insistence of John Cockcroft.

The name Magnox refers to the non-oxidizing magnesium-aluminum alloy from which the fuel canisters were formed. The reactivity of this material at higher temperatures limited the operating temperature of the reactors 360° C, which is too low for efficient steam generation. The Advanced Gas Cooled reactors (AGRs), which succeeded the Magnox reactors and which operated at a higher temperature, were expected to be more efficient.

1.2 Uranium and Plutonium

In the equation of a nuclear reaction, the elements are denoted by symbols that bear a leading superscript indicating the atomic weight, which is the number of neutrons and protons in its nucleus, and a leading subscript denoting the atomic number, which is the number of protons. The protons are normally accompanied by an equal number of electrons that surround the atom. The atomic number determines the position of the element in the periodic table. The fissile uranium-235 isotope is denoted by ${}^{235}_{92}U$.

Nuclear energy is released when the fission of a heavy nucleus, such as ${}^{235}_{92}U$, is induced by the absorption of a neutron. The fission products, in this case, are typically cesium-140, rubium-93, three neutrons and 200 MeV (200 million electron volts) of energy:

$$ {}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{140}_{55}Cs + {}^{93}_{37}Rb + 3{}^{1}_{0}n + 200 \text{ MeV}. $$

For comparison, one can note that the combustion of an atom of carbon to produce carbon dioxide generates 10 eV (10 electron volts) of energy.

The atoms of the non fissile uranium-238, which is the predominant element in the fuel of a thermal reactor, can absorb a neutron to become uranium-239, which then undergoes a radioactive decay to yield fissile plutonium-239. The conversion of uranium-238 to plutonium-239, via the intermediate neptunium Np-239 isotope, can be represented as follows:

$$ {}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \xrightarrow{\beta-} {}^{239}_{93}Np \xrightarrow{\beta-} {}^{239}_{94}Pu. $$

Thus, when uranium 238 absorbs neutrons in the reactor, it is transmuted into plutonium in a process that entails the beta decay of neutrons, which become protons by emitting beta particles, which are high-energy electrons in other words.

Plutonium-239 is a fissile isotope used in nuclear weapons, albeit that uranium-235 is also used. The grade of plutonium signifies the proportion of plutonium-240 that is present. This is a spontaneously fissile isotope; and, if a significant proportion is present, it might lead to a chain reaction in a large mass of plutonium. By definition, weapons grade plutonium cannot contain more than 7% of plutonium-240.

Some of the plutonium-239 that is created within a typical commercial nuclear reactor will be consumed, providing more than 1/3 of the total energy produced. A lengthy residence of the fuel rods within the reactor will lead to an excessive production of plutonium-240. To avoid this, reactors that are exploited to produce weapons grade plutonium must have the fuel rods replaced before this can happen, which may necessitate shutting down the reactor regularly. In any case, the efficiency of the reactor will be prejudiced.

The primary purpose of the Magnox reactor of Calder Hall was to produce weapons grade plutonium for Britain's nuclear weapons program. The Magnox reactors have contributed largely to the stock of plutonium that resides at Sellafield. In total, there are 140 tonnes of the material to which these reactors are estimated to have contributed 86 tonnes.

The plutonium was initially extracted from the spent fuel of the Magnox reactors via a first-generation process located at Windscale, which ran from 1951 to 1973. It was succeeded by a Magnox reprocessing facility, which ran from 1964 to 2022. A separate Thermal Oxide Reprocessing Plant (THORP) was devoted to reprocessing the spent fuel from the Advanced Gas Cooled Reactors (AGRs), which were the successors to the Magnox reactors.

The production of plutonium in the United Sates took place at the Hanford site in the state of Washington. The site was established in 1943 as part of the Manhattan Project, which undertook to construct the first atomic bombs. Abundant supplies of plutonium were produced, and the production reactors were shut down between 1964 and 1971.

2 The Nuclear Fuel Cycle

The nuclear fuel cycle embodies the stages of the creation, the deployment and the disposal of a nuclear fuel. The predominant source of the fuel employed in nuclear reactors is uranium, although thorium can also give rise to a nuclear fuel. Uranium leaves the mine as a concentrate consisting mainly of the stable oxide U_3O_8. Then, it is commonly converted to uranium hexafluoride UF_6, which is subject to an enrichment process that aims to increase the proportion of the fissile uranium-235 isotope. This is achieved by gaseous diffusion and with the aid of centrifuges. Following the enrichment, the uranium hexafluoride is de-converted into the uranium oxide UO_2, which enters a process of fuel fabrication. The finished fuel takes the form, typically, of a column of ceramic pellets of uranium oxide, sealed into zirconium alloy tubes.

The Magnox reactors were fuelled by natural uranium metal, which was contained within finned magnesium alloy tubes. The fuel was manufactured in the UK at the Springfields site in Preston, Lancashire. The fuel for the AGRs was in the form of uranium dioxide pellets, with the uranium-235 isotope enriched to 2.5–3.5%, contained in stainless steel tubes. This was also produced at the Springfields site, where it continues to be manufactured in small quantities alongside fuel for Pressurised Water Reactors (PWRs) for export to France. Springfields also manufactured the initial core and several reloads for the Sizewell B reactor, until British Nuclear Fuels (BNFL) lost the contract to Siemens in the early 2000's. It is proposed that the fuel for the EPR reactors at Hinkley C and the Sizewell C reactors that are in prospect will be supplied by Framatome in France, which is owned primarily by Électricité de France (EDF), who are the vendors of the reactors.

There has been a decline in the manufacture of nuclear fuels in the UK. However, within the Government's Civil Nuclear Roadmap of 2024 [6], there is proposal to revive the manufacture of fuels in preparation for the advent of a new generation of reactors. It is proposed that the Urenco Corporation, which has a British headquarters at Capenhurst in Cheshire, should develop facilities for manufacturing Low

Enriched Uranium Plus fuel (LEU+), with up to 10% of uranium-235, and High-Assay Low-Enriched Uranium (HALEU) fuel, which is enriched to between 10% and 20%. The Urenco Group is a British–German–Dutch nuclear fuel consortium operating several uranium enrichment plants in Germany, the Netherlands, United States and United Kingdom. Its enrichment technology depends largely on centrifuges. It is proposed that, at the Springfields site (which is managed by Westinghouse on a 150-year lease), facilities should re-established for converting both reprocessed uranium (RepU) and naturally occurring non-irradiated uranium (NIU) in readiness for the production of advanced fuels and that it should be responsible for manufacturing the fuel assemblies.

2.1 MOX fuels

MOX fuels are created by blending plutonium with depleted uranium. The depleted uranium is commonly obtained from the uranium hexafluoride discarded during the enrichment process. This is known as Hex Tails, and it contains about 0.25 % of uranium-235. There are vast inventories of this material, arising from decades of enrichment activities, which can be de-converted to the form UO_2. The uranium contents of these fuels could also be provided by RepU, which has been produced by reprocessing spent nuclear fuel and which also exists in large quantities. It is typically in the form of the uranium oxides U_3O_8 and UO_3. It would need to be converted to the UO_2 oxide before use. However, a facility that served this purpose, which was located in Russia, is no longer available to the West.

MOX fuels have been seen as a means of disposing of the surplus stocks of plutonium that have been created to serve nuclear weapons programs. These stocks are liable to contain a significant proportion of transuranic actinides, which are created from the uranium fuel by the absorption of neutrons. They may make it inappropriate to use the plutonium in MOX fuels intended for thermal reactors. However, their presence is no impediment to the use of the plutonium in fast reactors.

More than a decade ago, in 2012, the GE-Hitachi PRISM fast reactor was considered by the UK's Nuclear Decommissioning Authority (NDA), for the purpose of burning the surplus stocks of plutonium held at Sellafield. The PRISM (Power Reactor Innovative Small Module) [7] is a sodium-cooled fast reactor that would have been fuelled by a metallic alloy of plutonium and uranium. An obstacle to the proposal was the fear of a nuclear weapons proliferation that could arise if the plutonium were to fall into the wrong hands. The Canadian CANDU (Deuterium Uranium) reactor, which maintains a dense neutron flux, was also proposed for the purpose of disposing of the plutonium.

Fast neutron reactors could greatly reduce the volume and radiotoxicity of waste products that, otherwise, require long-term storage. The alternative means of disposing of nuclear waste, whether it has come directly from a reactor or whether it has been produced by reprocessing spent fuel, as in the case of the plutonium, is to bury it deeply in a Geological Disposal Facility (GDF) [8].

2.2 Reprocessing

The reprocessing of spent fuel ideally separates it into three streams consisting of plutonium, uranium and fission products, respectively. The fission products are described as nuclear ashes. They constitute a radioactive hazard and they also act as nuclear poisons that inhibit fission reactions.

Apart from the use of the separated plutonium in nuclear weapons, an original motive for reprocessing spent fuel was to reuse the uranium in thermal nuclear reactors. For this purpose, the separated uranium would need to be further processed in order to increase the concentration of the fissile uranium-235 relative to the non-fissile isotopes of uranium such as uranium-238, which is the predominant isotope within uranium ore. It was also proposed that the separated plutonium could be used in fast reactors.

When it transpired that the supply uranium ore was more abundant than had been expected, these motives for reprocessing spent fuel went largely into abeyance. However, use has been found for the separated plutonium in creating mixed oxide fuels, which combine the plutonium with depleted uranium. Mixed oxide (MOX) fuel provides almost 5% of the new nuclear fuel used today, and it fuels about 10% of France's fleet of reactors.

The large stockpile of Plutonium that has been generated by Britain's nuclear reactors resides at Sellafield [9]. How it should be treated is subject to debate [10]. On the one hand, it could be used as fuel for a new generation of fast reactors. On the other hand, it represents a nuclear hazard that must be contained or disposed of. The plutonium emits alpha radiation of which the particles consist of two protons and two neutrons bound together to form what is equivalent to a helium-4 nucleus. These particles are easily stopped in their tracks by light shielding. However, the plutonium comes mainly in the form of plutonium oxide PO_2, which is a fine powder. If this is ingested or inhaled, it can cause severe damage to human tissues.

Plutonium was extracted from the spent fuel of the original plutonium piles at Windscale by a First Generation Reprocessing Plant, designated B204, which operated from 1951 until 1964. It was later repurposed for extracting plutonium from the spent fuel of Magnox reactors. A second reprocessing plant, B205, was deployed from 1964 to 2022 for the purpose of extracting plutonium from the spent fuel of the Magnox and the AGR reactors. It used the chemical PUREX process to produce separate streams of plutonium, uranium and fission products.

A third nuclear reprocessing plant was operating at Sellafield between 1994 and 2018. This was the Thermal Oxide Reprocessing Plant (THORP). Its primary purpose was to generate from spent nuclear fuels the elements that could be used in manufacturing MOX. The difficult chemical processes of extraction and refinement were initially beset by technical problems, but, eventually, they were judged to be highly successful. However, the enterprise was predicated on an assumption that there would be a worldwide demand for the MOX fuel, and this never materialised. The enterprise also suffered when, in 1999, it was revealed that certain safety records had been falsified at the Sellafield plant. This led to the cancellation of foreign contracts and to the return to Sellafield of some of the material. The Fukushima nuclear accident, which began on March 11, 2011, led to a prolonged shutdown of Japanese nuclear reactors that had been recipients of the fuel manufactured at Sellafield's MOX plant. This led to the closure of the plant in 2011. The construction of the plant had begun in 1996 and it had become operational 2001

The unfortunate effect of these experiences with THORP is that the Government has become unwilling to contemplate a revival of the MOX enterprise. It is notable that neither the Hinkley C reactors not the Sizewell C reactors are being engineered to accept MOX fuels, although this is a possibility that could have been encompassed easily. This unwillingness to persist with MOX fuels is limiting the range of potential new nuclear technologies that the Government is liable to support, and it eliminates one route towards the disposal of nuclear waste. The remaining option for its disposal, in the absence of waste burning reactors, which could depend on MOX fuels, is the geological disposal of nuclear waste.

A Geological Disposal Facility (GDF) has been mooted for many years but, as yet, no site to accommodate it has been determined. A GDF that is soon to become operational is located at Olkiluoto in Finland, where several reactors, including a version of the European Pressurised Reactor, are located. These reactors satisfy 35% of Finland's electricity demand.

3 The Early Prospects

At the time of the opening of the Calder Hall power station, there was great enthusiasm for the civil use of nuclear energy and there was unbridled optimism at this prospect. According to a pronouncement of the time, the eventual consequence of generating electricity by nuclear power would be a supply so cheap and plentiful that it would not be worthwhile to meter it. This prediction was based on a fair appraisal of what the technology had to offer. It was envisaged that the next generation of nuclear power stations, using fast breeder fission reactors, would generate more fuel than they would consume. Their source of power would be self-replenishing.

3.1 Fast Breeder Reactors

Such a fast reactor needs no neutron moderator, but it requires a fuel that is relatively rich in fissile material, when compared to thermal neutron reactors, such as light water reactors. The fast, high energy, neutrons would be effective in converting the non-fissile 238-uranium within the nuclear fuel to the fissile 239-plutonium isotope. This, in turn, would undergo a fission process that would release the nuclear energy in the form of heat and γ rays. The fission products would be xenon and zirconium:

$$^{1}_{0}n + ^{239}_{94}Pu \longrightarrow ^{240}_{94}Pu \longrightarrow ^{134}_{55}Xe + ^{103}_{40}Zr + 3^{1}_{0}n.$$

In this way, the potential of the uranium could be fully exploited.

Eventually, the sources of uranium fuel would be depleted, but only in the distant future. However, another technology was in the offing, which would avert even this distant anxiety. Whereas the current generation of nuclear power stations was, effectively, harnessing the power of the atomic bomb, which was due to nuclear fission, a future generation would harness the power of the far more awesome hydrogen bomb, which came from nuclear fusion.

The depletion of the supplies of uranium, on which fission reactors depend, would no longer be a concern. Fusion reactors would use for their fuel one of the most abundant substances on earth. This is hydrogen, which is a constituent element of water.

3.2 Nuclear Fusion

Nuclear energy is released by the fusion of two light nuclei, as when two heavy hydrogen nuclei (deuterium) combine to produce a helium-3 atom and a free neutron and 3.2 MeV of energy:

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He + ^{1}_{0}n + 3.2MeV.$$

This is accompanied by another reaction that gives rise to tritium $^{3}_{1}H$ and an atom of hydrogen, consisting of one proton and one electron, which releases 4.03 MeV of energy. A reaction involving tritium $^{3}_{1}H$ and deuterium $^{2}_{1}H$ produces the $^{4}_{2}He$ helium isotope, a neutron and 17.6 MeV of energy. Fusion powers the sun. On earth, it occurs in H-bomb explosions.

By 1958, the U.K. Atomic Energy Authority had constructed a fusion device called ZETA: an acronym that stands for Zero Energy Thermonuclear Assembly. It had a small doughnut or ring-shaped chamber that was designed to contain a superheated gas plasma in which fusion would occur. Powerful electromagnetic forces induced by the coils surrounding the chamber would hold the plasma safely in its centre.

Unfortunately, the dream of nuclear fusion was a fantasy. The fusion of the neutrons that the scientists had observed was not thermonuclear. It was actually due to electromagnetic acceleration during a plasma instability. The effect cannot be scaled up to produce useful energy. Only recently, has a controlled fusion reaction succeeded in producing more energy that has been used in initiating it.

4 British Nuclear Research

The development of Britain's nuclear technologies was undertaken by a group of scientists and engineers located, principally, at the Atomic Energy Research Establishment at Harwell in Oxfordshire, which was owned and funded by the British Government. It gave rise to the United Kingdom Atomic Energy Authority (UKAEA). The Harwell facility operated from 1946 until the 1990s, when it was wound down. The ZETA fusion reactor was located at Harwell.

The Dounreay Nuclear Power Development Establishment, which was operated by the UKAEA, was formed in 1955. Its mission was to develop a civil fast breeder reactor (FBR) technology. The Dounreay Fast Reactor achieved criticality in November 1959. Power was exported to the National Grid from October 1962 until the reactor was taken offline in March 1977 to be decommissioned.

The UKAEA also operated a site at Winfrith in Dorset that hosted the Dragon experimental high temperature gas-cooled reactor, described as a pebble bed reactor, which operated from 1965 to 1976. The reactor used helium gas as the coolant and graphite as the neutron moderator. Fuel was formed into tiny spherical pellets and then coated with ceramics. Other countries have inherited this and other technologies developed under the auspices of the UKAEA.

5 The Second Generation of British Reactors

5.1 Advanced Gas-cooled Reactors

The second generation of British nuclear reactors where the Advanced Gas Cooled Reactors [11] (AGRs), which were developed from the Magnox reactor. They also use a graphite moderator and they are also cooled by carbon dioxide. They were originally intended to burn natural uranium. However, in the process of developing the design, the material of the fuel cladding was changed from beryllium to stainless steel, which absorbs more neutrons. Therefore, an enriched fuel, with between 2.5% and 3.5% of uraniun-235, was needed in order to provide a sufficient neutron flux.

The AGRs were intended to operate at a higher temperature than their predecessors, sufficient to generate steam to power the turbines that had been deployed in coal fired power stations. Given that they were no longer optimised for the production of plutonium, they could be run for longer periods before refuelling, which added to their efficiency.

There were hopes that the AGRs would create an export market. However, the design proved to be problematic. The reactor at Dungeness, which was the first to be embarked on in 1965, was intended for completion in 1970. It experienced many modifications; and it began generating electricity in 1983, which was 13 years late. Eventually, 14 reactors were completed at 5 sites between 1976 and 1988. In view of the difficulties that afflicted the design, the civil service and others developed a strong prejudice against it. Already, by 1977, a senior economic advisor to the Treasury, David Henderson, was declaring the AGR project to be a costly economic disaster, comparable, in his assessment, to that of the supersonic Concorde airliner.

5.2 The Sizewell B Reactor

A consequence of these experiences was that the next reactor to be built in Britain, which was the Sizewell B reactor, adopted an American Westinghouse design of a pressurised water reactor. The construction began in 1987 and the reactor was connected to the grid in 1995. A further consequence of these experiences was to contribute to the anti-nuclear sentiment that had been growing in Britain and elsewhere, which was compounded by the Chernobyl accident in 1986.

The majority of AGRs have already been decommissioned. Four reactors remain in operation. These are located at Torness, Hartlepool and Heysham, where there are two reactors. The Torness and the Heyshan 2 reactors are late versions of the design, from which most of the problems have been eliminated. They are scheduled for closure in 2028. The others are scheduled for closure in 2026, but all four reactors may be granted further life extensions. The dates of closure for these reactors are liable be determined by the condition of the graphite within the reactor cores, which is subject to weight loss and cracking, and which must, therefore, be monitored closely.

In 1979, the incoming Thatcher government announced a new long-term nuclear power programme. The existing state National Nuclear Corporation would complete the construction of the planned second generation AGR reactors. A new programme was proposed for building one Westinghouse designed Pressurised Water Reactor (PWR) per year for at least a decade from 1982, providing a generating capacity of about 15 GWe in total.

However, the program was called into question by reports from the Select Committee on Energy and the Monopolies and Mergers Committee. With the replacement of David Howell as Secretary of State for Energy by Nigel Lawson, support for the program declined. With the privatisation of the electricity industry via the Electricity Act of 1989, the nuclear industry, which remained under state ownership, was in an anomalous position. In the event, only the Sizewell B pressurised water reactor (PWR) was built, which was connected to the grid in 1995.

In 1996, the seven advanced gas-cooled reactors and the one pressurised water reactor were assigned to British Energy, which was a privatised company. The remaining Magnox reactors remained in public ownership under Magnox Electric. The first Magnox reactor to the shut down was at Berkelay in Gloucestershire. It ceased operation in 1989 after 27 years of grid connection. The Magnox reactor at Calder Hall was closed in March 2013, after it had been running for almost 57 years. The last of the Magnox reactors in the UK, which was located in Wylfa in Anglesey, was shut down in 2015.

6 The Demise of Nuclear Power

A Labour Government succeeded the Conservative Government in 1997. In 2002, Margaret Beckett, as Secretary of State for Environment, Food and Rural Affairs, rejected demands for an expansion of nuclear power. It was concluded by the Energy Review of that year that, given the ample generating capacity and in view of the price of fuels, there would be no need for new nuclear energy for at least 15 years. The review also suggested that the private sector could be relied upon to make proposals for building new nuclear power stations.

However, the case for new nuclear power stations was revived in a review of 2006 from the Nuclear Installations Inspectorate—the predecessor of the Office for Nuclear Regulation—which proposed a new process of Generic Design Assessment

(GDA) to examine nuclear designs. This is a protracted process, which is coupled with an assessment by the Environment Agency. The duration of the process is liable to exceed the time that it took to design and to build the Calder Hall power station. However, when the GDA was conceived, plenty of time seemed to be available. The assessment is liable to be made after the design has been completed. The GDA process could be hastened, if it were to become concurrent with the design process. This has been proposed in the Civil Nuclear Roadmap of 2024, which has indicated that any certification already achieved by foreign designs will be taken into account in order to expedite their assessments.

The Energy White Paper of 2007 [12] continued to assert that the private sector should be relied upon to bring forth plans for investing in new nuclear power stations. In January 2008, the Labour government gave the go-ahead for the building of a new generation of nuclear power stations. Whereas the Conservative opposition welcomed the proposal, the Liberal Democrats were equivocal in their support. The proposal for a nuclear revival relied on the willingness of private enterprise to undertake the construction of the new power stations; and two consortia, which were EDF–Centrica and RWE–E.ON, announced tentative plans to build a total of 12.5 GW of new nuclear capacity.

In the following year, in 2009, by paying £12.5 billion, Électricité de France (EDF), acquired the assets of British Energy, which was operating eight former UK state-owned nuclear power stations and one coal-fired power station. This acquisition included all of the extant nuclear power stations.

In October 2010, the Cameron–Clegg coalition took forward the previous Labour government's plans for private suppliers to construct up to eight new nuclear power plants. Proposals to build the power stations were made by a variety of companies and consortia, including E.ON–UK, RWE npower and Horizon Nuclear Power.

Eventually, each of these organisations relinquished their plans, leaving, EDF alone to pursue the construction of a large power station, which is Hinkley C. This implements a version of the European Pressurised Water Reactor (EPR). A second power station to the same design, which is Sizewell C, is in prospect; but the final investment decision is still pending.

7 Failed and Surviving Projects

The Electricity Act of 1989 and the Gas Act of 1986 made provision for the privatisation of Britain's energy supplies. Before the privatisation, there had been 14 regional public electricity suppliers and a single supplier of gas, which was British Gas. By the mid-2000s, the market was dominated by what became known as the Big Six energy suppliers. These were of British Gas, EDF Energy, E.ON, RWE npower, Scottish Power, and SSE. Of these, E.ON and RWE (Rheinisch–Westfälisches Elektrizitätswerk) are in German ownership and SSE (Scottish and Southern Energy) is a subsidiary of Iberdrola, which is a large Spanish and multinational energy consortium.

The privatised utilities began to invest in combined-cycle gas turbine electricity generating stations. These exploited the plentiful supplies of North Sea gas and they began to replace the coal-fired power stations. Their construction took no more than four years, and they were cheap to build. The same utilities were able, subsequently, to invest in wind power electricity generation.

These successful investments suggested to the government that the privatised utilities could be relied on to maintain the nation's energy infrastructure. The supposition was that they could also be encouraged to invest in nuclear power stations. A variety of commercial consortia were formed to answer to the purpose; but, eventually, most of them withdrew their proposals, leaving EDF as the only investor in nuclear power.

7.1 Horizon

Early in 2009, RWE npower combined with E.ON UK to established Horizon Nuclear Power. This consortium proposed to establish nuclear plants at Oldbury, Wylfa and Bradwell. There was slow progress with the venture, and, in October 2012, after E.ON and RWE had abandoned the project, Horizon became a subsidiary of Hitachi, which proposed to build two or three of the 1380 MWe Advanced Boiling Water Reactor (ABWR) units at each site. However, in January 2019, Hitachi announced that it was suspending work at Wylfa and Oldbury, having failed to agree terms on funding with the UK government. In September 2020, Hitachi abandoned the project to build nuclear reactors in the United Kingdom.

7.2 NuGeneration

The NuGeneration consortium was set up early in 2009. This was a joint venture of Iberdrola (which owns Scottish Power) with GDF Suez (now Engie). In October 2009, NuGeneration bought the Moorside site on the north side of Sellafield from the the Nuclear Decommissioning Agency (NDA) for £70 million. In December 2013, Iberdrola agreed to sell its share to Toshiba. In November 2018, after failing to find a buyer, Toshiba announced that it had decided that NuGen would be wound up from January 2019.

7.3 CGN

The Chinese General Nuclear Power Group (CGN) had been involved with EDF in the project to build the Hinkley C reactors. In conjunction with the China National Nuclear Corporation (CNNC), it had proposed, originally, to take a 50% stake in the project. EDF and CGN had collaborated in the building of an European Pressurised Water Reactor (EPR) in Taishan, China, which is to the same design as the Hinkley C reactor. Latterly, the British Government has keen to eliminate China's participation in British nuclear projects, for reasons of national security.

A further project, which was to be have been jointly owned by CGN and EDF, was proposed for the site at Bradwell. The Bradwell B reactor was of the Hualon One HPR1000 design, which is a Chinese derivative of a Westinghouse design. The proposal, which was first mooted in 2013, still requires approval from the Government, albeit that in 2022 the reactor design completed its Generic Design Assessment.

7.4 EDF

The only project that has endured is the construction of the Hinkley C power station. The reactor in question is the European Pressurized Reactor (EPR), which has been developed by a Franco–German consortium consisting, on the French side, of EDF and Framatome (now a part of the nationalised Areva company) and, on the German side, by Siemens, which later sold its nuclear business to Framatome. The EPR design has been realised in three other locations. In each instance, there have been problems with the design and in its construction, resulting in delays and cost inflation.

The first project to be undertaken was at Olkiluoto, where the construction began in 2005. The station was initially scheduled to go on line in 2009. Problems arose both with the design and with the construction work, which fell short of the standards appropriate to a nuclear installation.

The reactor attained nuclear criticality in December 2021 and it was connected to the grid in March 2022. Further snags arose before the regular operation of the power station began in April 2023. The initial cost of the station, as proposed in 2005, was €3.7 billion. By 2012, this has risen to more than €8 billion

The second station to be embarked upon was at Flamaville in Normandy, where the first concrete was poured in December 2007. A multitude of problems have affected the project. Many have concerned defective metal work and weldings. The fuel is now expected to be loaded in early 2024. Estimated total costs have increased through successive escalations to €13.2 billion.

The third station, of which the construction was undertaken jointly by EDF and the Chinese CGB corporation, is at Taishan. The project has benefitted from the experiences of the previous EPR projects. Construction of the first of two reactors began in November 2009 and their nuclear criticality was achieved in June 2017. Some ensuing technical problems affecting the fuel assembly delayed the full commercial operation of the power station until August 2022.

It is proposed that the lessons that have been learnt in the previous projects will ensure that the Hinkley C project will be relatively free from technical problems. Its delay has been the consequence of political indecision as well as an interruption caused by the Covid pandemic.

In 2010, the site was designated as one of eight locations destined to receive a new power station; and a site license was granted to EDF in 2012. In 2016, the board of EDF approved the project when 10 out of 17 directors voted in favour of the final investment decision. The internal dispute over the decision had led to the resignation of one of the directors.

Even then, there were doubts in the Government on whether to proceed, Some work in preparing the site had begun in 2008, but it was not until March 2017, after the Office for Nuclear Regulation (ONR) gave approval to start building, that EDF embarked on the building of the plant itself.

The work is scheduled to be completed by 2026 and the station is not scheduled to start generating power before June 2027. However, this is in doubt; and in December 2022, a new contract between the Government and EDF stipulated that Hinkley will still be funded even if it does not start operating until 2036. Its ultimate cost is expected to be between £33 billion, which represents a 30% increase relative to the estimates of 2015.

8 Financing the Projects

A difficulty in creating a large nuclear power station is in raising the necessary capital in the financial markets. The borrowings require payments of interest, which cannot be offset by earnings until the project is completed. The hiatus can last for more than a decade; and interest payments can account for as much as half of the cost of the project,

8.1 Contracts

It is proposed to finance the Hinkley C power station via a contract for difference. This guarantees a fixed albeit an index-inked return per unit of power delivered to the grid, which is described as the strike price. If the market price of electricity is less than the strike price, then a full supplement will be paid to the generator, whereas, if the market price exceeds the strike price, then the excess earnings will be claimed by the regulator. It has been proposed that the strike price should be determined by an auction; but, in this case, there was only a single bidder.

This arrangement has not provided a sufficient incentive for other consortia to persist with their projects. It is now proposed that it would be more appropriate to finance the building of nuclear power stations via an arrangement described as a regulated asset base. This will allow the constructor to impose a levy on consumers of electricity during the process of construction and prior to the operation of the facility. The arrangement is intended to avoid a long hiatus before any revenues are generated by the project.

A regulated asset base is the means by which it is proposed to finance the construction of an additional EPR power station to be designated as Sizewell C. It has been promised that a final investment decision will be made before the end of the current parliament, which must be before 17 December, 2024. This presupposes that the potential contractor, which is EDF, will continue to be interested in undertaking the task.

8.2 Costs and Benefits

According to a prominent political philosophy, all investment projects, whether they be for a private benefit or for the public benefit, should be judged according to commercial criteria. This is a motive and a justification for the insistence that projects to construct nuclear power stations should be capable of being financed by raising funds from the financial markets. A failure to achieve this could be taken to signify the non-viability of a project. On this basis, it could be asserted that a succession of nuclear projects have failed to demonstrate their worth.

In assessing the viability of investment projects, the UK Treasury adopts a quasi-commercial procedure of cost–benefit analysis in which future earnings and payments are reduced to their discounted present value. A project is judged to be viable if the discounted benefits exceed the discounted costs. In such procedure, the receipt of £100 in one year's time is valued at £100 × d, where $d < 1$ is the annual discount factor. This is defined as $d = 1/(1+r)$, where r is an annual rate of interest. The rate that is adopted by the Treasury is 3.5%, which leads to a discount rate of $d \simeq 0.966$.

One can imagine a project to construct a nuclear power station that takes ten years to complete, after which the station functions for 50 years, The discounted present value of £100 received when the station begins to generate electricity is

£100 × $d^{10} \simeq 79.89$. The discounted value of £100 received at the end of the station's life is £100 × $d^{60} \simeq 12.69$, which is almost a negligible amount. It is reasonable to question whether our own futures and those of our successors should be discounted in this manner.

A cost–benefit analysis of this nature may be ignoring the wider context in which the project to build the power station has arisen. It may have been undertaken in view of the cost to society that would be imposed by a future dearth of electrical power. It might have been inspired also by a desire to mitigate the effects of the climate change brought about by the burning of fossil fuels. The analysis is unlikely to take full account of such costs.

The difficulties in financing the construction of large nuclear power stations have given rise to proposals for small modular reactors (SMRs) that can be constructed in a shorter time using standardised factory-manufactured components. In Britain, Rolls–Royce made their first proposal for an SMR in 2015.

9 Renewable Power

Nuclear power must be compared with wind power and solar power as a means of generating electricity. To compensate for the variability or intermittence of their availability, these so-called renewable sources of power must be accompanied by an ancillary source. The true cost of using the renewable power must take account of the cost of the ancillary power. At present, the generation of electricity from renewable power is supported by gas-powered stations that are on standby. These burn an unabated fossil fuel, which is contributing to climate change. The gas is costly and its supply is increasingly insecure.

9.1 Energy Storage

If the renewable sources of power were to predominate, then they would need to be accompanied by a means of storing their energy. It is widely proposed that the energy should be stored in hydrogen gas contained in underground caverns. The hydrogen would be created via the electrolysis of water at times when the renewable energy is plentiful. At other times, it would be used to power turbines or reciprocating engines attached to electricity generators.

The necessary technology is not yet available; and its cost together with the cost of the electricity generated from renewable energy is liable to equal or to exceed that of nuclear power. If hydrogen is to be relied upon as a source of energy, then it could be produced most cheaply by high temperature electrolysis, using the heat and electricity generated by nuclear power. Alternative thermochemical processes are also being developed.

10 A Nuclear Revival

A light water reactor uses ordinary water both as the coolant and as the moderator of the neutron flux. These reactors, which predominate in nuclear power stations, have adopted a technology that was influenced by the military requirements of the Cold War. The reactors were deemed to be suitable for military applications in providing the power for nuclear submarines and aircraft carriers.

A seeming advantage of the military light water reactors was their compactness. The civil reactors that have inherited their technology are no longer compact, and some of them have grown to immense proportions. The danger that these reactors have posed on account of a meltdown, accompanied by a hydrogen explosion and a rupture of their pressure vessels, has caused them to be accompanied by safety systems that have become ever more elaborate and bulky.

An attempt has been made to reverse the process that has given rise to ever-larger nuclear power stations. This has led to proposals for small modular reactors (SMRs) that can be constructed in a shorter time using standardised factory-manufactured components. Numerous designs have been proposed but, as yet, few, if any of them, have been realised.

The designs that are capable of being realised the soonest are small modular light water reactors, Several of these are vying for support from the Government. Amongst them is the Rolls–Royce SMR. The SMR reactors employ what is described as third-generation technology. Such reactors are liable to be superseded by fourth generation reactors described as Advanced Modular Reactors (AMRs). These are of radically different designs. Three such reactors, which are proposing to be built in Britain, will be described at the end of this account.

10.1 The Rolls–Royce SMR

In Britain, the progress in developing small modular reactors has been affected by avoidable delays and by a lack of sufficient financial support from the Government. Rolls–Royce made their first proposal for an SMR in 2015. The company has provided the nuclear reactors that power Britain's fleet of submarines; and it has the experience that should assist it in rapidly developing a small civil light water reactor.

Reactors that power submarines typically use highly enriched fuel, often with more than 20% of uranium-235. This enables them to deliver a large amount of power and to operate for long periods before refuelling. The design of an SMR using a conventional uranium fuel will differ significantly from that of a military reactor, which cannot be adapted readily to civil purposes.

The definition of an SMR, according to the International Atomic Energy Agency (IAEA), is a reactor producing up to 300MWe, which is half the output of a British Advanced Gas Cooled Reactor and somewhat in excess of the 240MWe that was produced by Britain's first nuclear power station at Calder Hall. The Rolls–Royce reactor, which would be rated at 470MWe, is described, nevertheless, as an SMR. For comparison, the Hinkley Point C power station will generate 3,200 MWe (3.2 GWe) from two reactors.

In December 2017, the UK Government provided funding of up to £56 million over three years to support SMR research and development. In 2018, the UK SMR industry sought billions of pounds of government support to finance a putative first-of-a-kind project. In 2019, the Government announced its Low Cost Nuclear Challenge [12], which made commitment to invest up to £18 million to the development of an SMR.

In November 2021, the UK government provided funding of £210 million to Rolls–Royce to further develop the design, partly matched by £258 million of investment from Rolls–Royce Group, BNF Resources UK Limited and the American Exelon Generation Limited, amongst others. It was expected that the first unit would be completed in the early 2030. However, the commitment of the Government to the Rolls–Royce project is not unequivocal.

10.2 Great British Nuclear

In July 2023, the dormant company British Nuclear Fuels Limited (BNFL) was resurrected as Great British Nuclear (GBN); and it was given the task of overseeing the Government's long-term plan for nuclear energy, which proposes that 24 GW of nuclear power should be available in the UK by 2050. This would create a quarter of the electricity that is projected to be generated by that date.

GBN's first task is to administer a competitive process to select the best small modular reactor (SMR) technologies from around the world [13]. In October of 2023, it announced that six companies were to be invited to bid for UK government contracts in the next stage of the process [14]. The companies are EDF, GE Hitachi, Holtec, NuScale Power, Rolls–Royce SMR and Westinghouse. In November, doubts, were raised regarding the viability of the NuScale project on account of a failure to achieve commitments to the project from a sufficient number of municipalities in the US.

It should be observed that, of the six competitors, only one is a firm based primarily in the U.K. The thought arises that the Government may be happy to allow the costs of developing the technology to fall upon a foreign contractor, thereby avoiding a significant expenditure. If the Rolls–Royce reactor were not to find favour, then this would be to the severe detriment of Britain's nuclear industry and it would forestall the opportunity of developing an export market for a British SMR. However, GBN has implied that it might be willing to see as many as four projects continue through to the next stage. This could preserve the prospects of the Rolls–Royce SMR.

Within the remit of GBN is a program for bringing the next generation of advance modular reactors to fruition. However, there appears to have been little progress on this front, albeit that the Government is now giving support to foreign projects to develop high temperature gas-cooled reactors.

The Roadmap to 2050 for Civil Nuclear, issued by the Department for Energy Security & Net Zero, has been accompanied by a document titled Alternative Routes to Market for New Nuclear Projects [15]. This elicits responses from interested parties to a series of 23 questions concerning the future of nuclear power in the U.K.

The document declares that we need a more reliable energy supply "that does not leave us dependent on foreign energy imports." However, it states no inhibitions regarding our dependence on foreign suppliers of nuclear technology. It assumes that nuclear projects will be initiated, henceforth, by the private sector, and it states that "the Government is not currently considering introducing new Revenue Support Mechanisms beyond CfD (Contract for Difference) and RAB (Regulated Asset Base). This appears to be the limit to the support offered to native British projects.

11 Fourth Generation Nuclear Reactors

Generation IV reactors are envisaged as successors to Generation III reactors. They comprise a variety of technologies, and their common theme is that they fall within the remit of the Generation IV International Forum (GIF), which proposes to coordinate their development. Although there is no precise definition of what constitutes such a reactor, it is possible to identity six designs that are under consideration. These are the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very high-temperature reactor (VHTR).

11.1 High Temperature Gas Cooled Reactors

High Temperature Gas Cooled Reactors (HTGRs) have attracted some interest on the part of decision makers in the Government [16]. The Department for Energy Security and Net Zero has issued a document in 2022 titled Advanced Modular Reactor Research and Development [17], which proposes a competition for the sponsorship of advanced reactors in which the emphasis has been placed upon HTGRs. The attraction of the HTGRs for the Government may lie in the fact that they represent a natural progression from the AGRs. That progression was accomplished long ago by the Dragon reactor, which operated in Winfrith, Dorset, from 1965 to 1976.

The output of a conventional light-water reactor is at around 300°C and that of an Advanced Gas Reactor (AGR) is around 540°C. The temperature of the advanced HTGRs could be in the region of 700–950°C. They could provide the heat for a variety of high-temperature industrial processes.

HTGRs, in common with AGRs, use a uranium fuel, with a graphite moderator. They are cooled by helium as opposed to the carbon dioxide that is used in the AGRs; and the gas pressure could be in the region of 100 atmospheres. The fuel consists of tristructural-isotropic (TRISO) particles, which have a core of uranium oxide surrounded by layers of carbon and sealed by a shell of silicon carbide, also called carborundum. Various arrangements for the fuel have been proposed. In some designs, the TRISO particles form a pebble bed and in others they are inserted into graphite blocks.

A design for a mini reactor using this technology, described as the U-Battery, was proposed by the Delft University of Technology in the Netherlands and Manchester University in the United Kingdom. The reactor was rated at 10 MWth thermal power and 4 MWe electric power, and it would be ideal for small industrial applications. A small subvention to support this design was forthcoming from the UK Government. However, in the absence of sufficient commercial sponsorship, the project has been shelved.

Some of the key personnel of the U-battery project have been recruited by the US-based Ultra Safe Nuclear Corporation, which is developing a so-call Micro Modular Reactor. Others have been recruited by the National Nuclear Laboratory (NNL), which is collaborating with Ultra Safe on a supposedly joint project. This is a high-temperature gas-cooled reactor (HTGR) with a thermal capacity of 15 MWth and an electrical capacity of 5 MWe. In July 2023, the U.K's Department for Energy Security and Net Zero awarded Ultra Safe a grant of up to £22.5 million to support the project. The Government also announced £16 million funding for the National Nuclear Laboratory, to work with the Japanese Atomic Energy Agency, to develop the coated particle fuel required for HTGRs [18].

There is also an ongoing American project for the development of an HTGR, which is being undertaken by the X-Energy organisation. They have received sponsorship from the United States Department of Defence and from the Dow Chemical Company. It appears that, if it were to adopt this technology, then Britain might have to rely on a foreign supplier. This would be a matter of importing a technology to Britain that it has been responsible for developing.

11.2 Fast Reactors

Today's conventional light water reactors use less than 1% of the energy that is potentially available from their uranium fuel. At the outset of the nuclear industry, it was thought that the uranium fuel would be in scarce supply. Therefore, thoughts turned to the possibly of exploiting the fuel more efficiently.

Reactors were engineered to exploit the possibility of converting the non-fissile uranium-238, which is the predominant uranium isotope, into the fissile plutonium-239. This occurs when uranium-238 absorbs a neutron. As has been described above, the conversion entails some intermediate products. The fissile plutonium-241 isotope is also produced in this way. In a similar manner, the non-fissile thorium-232 isotope is converted by neutron capture into the fissile uranium-233. Both uranium-238 and thorium-232 are described as fertile isotopes on account of their potential conversions.

These conversions require a dense high-energy neutron flux. This can be provided, initially, by a uranium fuel of which no less than 20% must consist of the uranium-235 isotope. Thereafter, the process should be self sustaining. There is no moderator in a fast reactor and the coolant is chosen to avoid a moderating effect on the neutrons. Liquid sodium or liquid lead are the usual choices.

A fast reactor can be engineered to produce more fissile plutonium than the plutonium and uranium that it consumes. In that case, it is described as a breeder. Otherwise, if the ratio of fissile material produced to the amount consumed is less than one, then it is described as a burner. Apart from its fuel economy, a fast reactor has the advantage that it also consumes the radioactive actinides that constitute a large part of the hazard that is associated with the spent fuel of a light water reactor. These actinides are transuranic elements that are of greater atomic weight that the uranium from which they are derived by capturing neutrons.

A further advantage of a fast reactor is the high temperature at which it is liable to operate, which implies a greater thermodynamic efficiency than that of the light water reactors. The higher temperatures are appropriate to a variety of industrial applications. Whereas the use of a liquid metal as a coolant poses some engineering difficulties, it also means that the pressure in the reactors can be maintained at a low level, which improves their safety.

As time passed, the anxiety over the potential shortage of the uranium fuel was dispelled and the cost of engineering the fast reactors was no longer justified. However, the stage has now been reached where their fuel economy and the lesser problems of their waste management are seen as desirable features. The majority of the proposed Generation IV reactors are fast-neutron reactors.

11.3 Molten Salt

A molten salt reactor employs salt as the coolant. Its fuel is typically a mixture of the salt with a fissile material. The reactor has the advantage of safety. The salts of the reagent and of the cooling system operate under atmospheric pressure. If there were to be a rupture in the cooling circuit or in the core of the reactor, then the salts, which would run off into a containment vessel, would cool and solidify.

The operating temperature of the reactor would be in the region 700°C, whereas the salt would crystallise at around 500°C. The low pressure at which the reactor operates means that there is no need for robust and expensive containment. The gaseous fissile products, which are xenon Xe and krypton Kr, can be safely captured as they bubble off; and there is no danger of a hydrogen explosion such as accompanied the Chernobyl and Fukushima disasters. A molten salt reactor fuelled by thorium does not breed a burden of radioactive actinides, such as are present in the depleted fuel of a light water reactor. Therefore, this aspect of the problem of waste management can be alleviated. Other aspects of the management of the waste from these reactors remain to be addressed, albeit that some relevant research is being undertaken as part of the Moltex project.

The concept of the molten salt reactor is not new. In the 1950's, both military and civil applications of the reactor were proposed. The U.S. Aircraft Reactor Experiment, which was intended to asses the feasibility of powering a long distance bomber with a small reactor, tool place at the Oak Ridge National Laboratory in 1954. The Molten-Salt Reactor Experiment, which was also conducted at Oak Ridge, produced a civil version of the reactor that operated from 1966 until 1969.

A disadvantage of the molten salt reactor at the time was that it did not generate weapons grade plutonium. As a military reactor, it was in competition with the light water reactor that was employed in the U.S. nuclear submarines. This design was advocated by Admiral Hyman Rickover, who manifested considerable hostility toward Alvin Weinberg, who was the director of the Oak Ridge Laboratory and the advocate of the molten salt reactor.

11.4 The Thorium Fuel Cycle

In common with uranium-238, which is the predominant isotope in natural uranium, thorium-232 is described as a fertile material from which fissile material can be bred. In the thorium cycle, fuel is formed when the thorium ${}^{232}_{90}Th$ isotope captures a neutron (whether in a fast reactor or a thermal reactor) to become ${}^{233}_{90}Th$. This normally emits an electron and an anti-neutrino $\bar{v}$ by β^- decay to become the protactinium ${}^{233}_{91}Pa$ isotope. This then emits another electron and an anti-neutrino by a second β^- decay to become fissile uranium ${}^{233}_{90}U$ which is the fuel:

$${}^{1}_{0}n + {}^{232}_{90}Th \longrightarrow {}^{233}_{90}Th \xrightarrow{\beta-} {}^{233}_{91}Pa \xrightarrow{\beta-} {}^{233}_{92}U.$$

The intensity of the nuclear flux that is required in order to convert Thorium-232 to the fissile uranium-233 is less than that which is required for the conversion of uranium-238 to plutonium.

Thorium can be used as a component in the fuel of conventional reactors and of reactors of enhanced designs, such as the Canadian CANDU (Canadian Deuterium Uranium) reactor. This is a Canadian-invented, pressurised heavy water reactor, which uses a heavy-water (deuterium oxide) moderator that subtracts less energy from the neutron flux than does a light water or a graphite moderator.

Thorium has several potential advantages over uranium as a nuclear fuel. It is a much more abundant element than uranium. It is more easily handled than uranium and it avoids the complicated manufacturing process whereby the fissile component of the uranium is increased to produce an effective fuel. It also creates a lesser problem of nuclear waste. However, an enriched fissile fuel is required in order to initiate a thorium reaction.

12 British Projects

Each of the three projects that are described below, and which are being pursued partly in the U.K., has a foreign partner. There is a fear that, unless the Government offer modest financial subventions to these projects, then they are liable to go abroad or to pass into complete foreign ownership. The Government must also provide sites for the reactors, to enable the criticality tests to be conducted, and access to the regulatory processes. Otherwise, Britain might be in the invidious position of buying back some of the technology that has been developed in this country and from which the country could have expected to profit.

12.1 The Newcleo Fast Reactor

The Newlceo reactor is lead-cooled fast reactor (LFR), which intended to burn nuclear waste in the form of an uranium-plutonium oxide MOX fuel. It is being proposed by an Anglo-French-Italian consortium. The project was launched in September 2021. It has already raised €400 million by resorting twice to the financial markets. A requirement for up to €1 billion is envisaged in order to complete the development of a working commercial reactor in conjunction with a facility for manufacturing its fuel. The project has yet to receive any subventions from the British Government,

The first aim of the project is to build a small 30 MWe LFR to be deployed in France by 2030. This is to be followed, two years later, by a 200 MWe commercial unit in the UK. The project also envisages the creation of a MOX production plant in France, with another plant to follow later in the UK. The large stock of plutonium that resides in Sellafield in the UK could contribute to the production of the fuel in conjunction with the spent fuels from existing power stations. The project could reduce the cost of disposing of radioactive waste and, for a considerable period, it could avoid the need for newly mined uranium.

The compact design of the reactor, which stands at a height of six metres, will allow it to be produced in a factory before being assembled at its eventual sites. The design of the reactor has profited from the experience of the lead-cooled reactors that were used in Soviet Alfa class submarines of the 1970s. Much of their technical information reached the west during the period of detente that preceded the access to power of Vladimir Putin. The Russians are continuing with the development of lead cooled reactors with two designs know as the BREST-300 (rated at 300 MWe) and the BREST-1200 (rated at 1200 MWe).

A lead coolant has little tendency to absorb neutrons. However, its high density makes it very effective at absorbing gamma rays and other ionising radiation. This ensures that radiation fields outside the reactor are extremely low. The lead coolant is not pressurised. Therefore, no pressure vessel is required; and there is no need for exotic steels and alloys. The operating temperature of the reactor will be in the region of 500°C, which ensures a higher thermodynamic efficiency than a conventional reactor.

12.2 The Moltex Reactors

Moltex Energy Limited is proposing two versions of a molten salt reactor. The first of these is a small thermal neutron (moderated) reactor that is powered by a uranium fuel with a 5% enrichment of uranium-235. This is the FLEX reactor. The second version of the reactor is the Stable Salt Reactor–Wasteburner (SSR-W), which is fast-neutron modular reactor (SMR) that uses recycled nuclear waste as fuel. This reactor is being developed in conjunction with a sister company, Moltex Energy Canada, which has been in receipt of funding from the Canadian Government.

The FLEX reactor, which is rated at 60 MWth thermal energy and 24 MWe electrical energy, was originally proposed as a maritime reactor. Its operating temperature is at 700°C and it could serve the needs of high-temperature industrial processes. A battery 32 reactors could constitute a small power station delivering 1,920 MWth or 768 MWe. This could be allied to a heat store containing molten salt, which might be used to produce the steam to power additional electricity generators at times when there is a dearth of electrical power. In this way, the total output of the station could reach 2,304 MWe.

The nuclear fuel of the FLEX reactor, which is a mixture of uranium and salt, is contained in fuel tubes that would remain within the reactor for up to 15 years. A partial refuelling every five years would give the reactor a lifetime of 60 years. The tubes, which sit within a graphite matrix, are surrounded by a separate, non-radioactive, molten salt that transfers heat from the reactor core to heat exchangers. This cooling salt circulates within the reactor by a process of convection. No pumps or valves are needed to control the process.

The reactor operates at a normal atmospheric pressure, which contributes to its safety. Moreover, if the reactor vessel were to rupture, then the salt would run into a container in which it would crystallise at a temperature of 500°C.

The Stable Salt Reactor–Wasteburner (SSR-W), reactor shares many of its features with the FLEX reactor. It is allied to a WAste To Stable Salt (WATSS) process, which separates spent fuel into different output streams, thereby isolating the materials intended as fuel for the SSR-W. The process creates an alloy that contains plutonium, mixed with higher actinides and with lanthanides, which are their fission products. This forms the basis of the SSR-W fuel. The spent fuel from the SSR-W can be passed back through the WATSS process indefinitely, which further reduces the volume of high-level waste destined for long-term storage.

12.3 Copenhagen Atomics Thorium Molten Salt Reactor

Copenhagen Atomics and its subsidiary UK Atomics are working to deploy a thorium molten salt reactor that can be mass produced in a factory. Thorium-232, which is described as a fertile element, is converted by neutron bombardment into fissile uranium-233, which is capable of sustaining a nuclear reaction.

The initial conversion can be achieved by a low-energy neutron flux, which can be provided either by a fissile plutonium source, or by a concentrated fissile uranium-235 source. Thereafter, the reaction becomes self-sustaining. In this process, there is an opportunity to burn the spent fuel produced by conventional light water reactors. The neutron flux is moderated by deuterium oxide heavy water.

The Copenhagen reactor is of an onion-like construction. In the middle is the core containing the fissile elements. Surrounding the core is a blanket containing the thorium, which is in the process of being converted to the fissile uranium-233 isotope. The heat is taken from the fuel salt through a heat exchanger and it is transferred to a coolant salt and then to a nitrate salt that is connected to salt storage tank. The heat can then be conveyed to working machinery. This might be a steam powered electrical generator or some other industrial system equipment.

The organisation has adopted a strategy of the piecemeal development of the essential components of their reactor. This has entailed developing the loops for the cooling system, a coolant pump with magnetic bearings and the software for controlling these elements. These have been tested, initially, using non-radioactive salts, but a full radioactive test is imminent.

The commercial version of the reactor is designed to fit inside of a leak-tight, 40-foot, stainless steel shipping container. The heavy water moderator is thermally insulated from the salt and continuously drained and cooled to below 50° C.

The reactor units that are enclosed in shipping containers are intended to operate for five years, before being disconnected and stored in warehouse. There, they would reside for the time that it takes for enough of the residual radioactivity to dissipate to allow them to be dismantled.

The company wishes to conduct further development in the U.K., including an initial criticality test. It could then take advantage of the sophisticated British licensing and regulatory regime. In Denmark, it faces the inhibitions posed by a resolution of the Danish Parliament of 1985 [19] that decreed that no nuclear power plants should be built in that country.

However, in August 2023, a Gallup poll showed that 55% of Denmark's population favour nuclear power compared to 26% that oppose it. This suggests that the parliamentary resolution is liable to be rescinded in the near future. In that case, the motive for Copenhagen Atomics to come to Britain would be weakened.

13 Summary and Conclusions

The construction of the first and the second generations of British nuclear power stations, involving Magnox reactors and Advanced Gas Cooled Reactors (AGRs), respectively, was financed wholly by the Government, as was the later construction of the Sizewell B pressurised water reactor. In other countries, governments have carried most of the burden, if not the entire burden, of financing the construction of their nuclear power stations. However, when the construction of the Britain's next generation of reactors was being considered, the Government was intent on relying entirely on private consortia to raise the necessary finance from their own reserves and from the financial markets.

It should have been apparent, from the early abandonment of their project by E.ON and RWE in October of 2012, that this was an unreasonable expectation. Nevertheless, the Government persisted in their approach, until only one project remained, which was that of EDF, which has undertaken to construct a European Pressurised Reactor at Hinkley Point. It is notable that the reactors that were proposed in the projects that were abandoned were mainly of tried and tested designs. Even so, there was unwillingness on the part of private finance to support them. In view of this outcome, it is to be expected that there should be even less willingness on the part of the private sector to support projects that involve technological innovations.

In 2015, Rolls–Royce proposed their Small Modular Reactor as means of overcoming the difficulties in financing and constructing large nuclear power stations. At this stage, the Government was beginning to recognise that some support for this enterprise was necessary, but the support that has been forthcoming was initially negligible; and it has remained inadequate. The project has come close to collapse on several occasions.

The prospects of the Rolls–Royce SMR have been further confounded by the recent decision of the Government to commission Great British Nuclear to run a competition to select the best small modular reactor (SMR) technologies from around the world. The contenders have been reduced to a list of six, from which it is proposed to select a short list of four in the next phase of the competition. The financial support that might have devolved onto Rolls–Royce will now be dispersed amongst four contenders, some of which are liable to be in receipt of substantial funds from the various agencies of the U.S. Government. This would put Rolls–Royce at a distinct disadvantage.

The belief that the privatised energy utilities could be relied on to maintain Britain's energy infrastructure was fostered by their experience in constructing gas powered electricity generating stations, and subsequently in investing in wind farms. Some of the proponents of wind farms see them as the primary means of satisfying Britain's electricity requirements in future. It has been suggested, in various documents of the Government, that up to three quarters of the demand could be met in this way. Such a large proportion of renewable energy would have to be accompanied by a means of storing the energy, in order to compensate for the intermittence of its supply.

It is widely proposed that the energy should be stored as hydrogen to be generated by the electrolysis of water. This could be used in times of dearth to produce electricity by powering turbines or reciprocating engines attached to generators. Despite the proposals of the Government, it is doubtful whether private enterprise could be relied on to provide the necessary storage facilities, which would need to be commissioned and financed in large measure by the Government. When the costs of generating and storing the hydrogen and the costs of the ancillary means of generating the electricity are taken into account, this is no longer a cheap option.

If the nation is to consider generating electricity in the long run by nuclear power, then it must look towards the next generation of nuclear technologies. Here, there is cause for concern. Virtually no support has been given by the Government to fourth generation technologies, which include the three projects that have been described in the previous section of the present account. Without such support, they seem to be destined to pass into foreign ownership.

It appears that the government is no longer seeking to support a native version of the advanced high temperature gas cooled reactor. It has failed to support the U-battery project and it has allowed the intellectual capital and the personnel involved to pass into foreign control. It has even offered a modicum of support to the foreign enterprises that are pursuing this technology. But this support will be insufficient to enable the British nation to assert any ownership over what cannot be described as joint enterprises. Britain will have ceded its rights over a design that it originated and developed successfully several decades ago.

An enduring problem has been how to dispose of radioactive waste and of spent nuclear fuels. The thermal reactors, which predominate, consume only a small proportion of the uranium that is supplied to them, leaving as waste a mixture of non-fissile uranium, plutonium, transuranic actinides and nuclear ashes. At the inception of the nuclear age, it was envisaged that fast reactors would soon be deployed in order to make better use of the seemingly scarce uranium. When the supplies of uranium became abundant, the development of such reactors was abandoned.

The consequence has been an accumulation of waste from thermal reactors, together with stocks of plutonium that were generated to serve nuclear weapons programs. These are hazards that could be largely disposed of by consigning the waste and the plutonium to fast reactors, or to wasteburners. All three of the reactor projects that have been described in the previous section have the objective of burning spent nuclear fuels and plutonium. By such means, the demand for the geological disposal of these materials, which has not yet been met, could be greatly diminished.

An impediment that stands in the way of this recourse is the unwillingness of the Government to consider the reuse of the plutonium. The Nuclear Roadmap of 2024 assets that the Government is “committed *not* to support the use of plutonium stored at Sellafield by Advanced Nuclear Technologies whilst high-hazard reduction activities are prioritised at Sellafield.” The cladding of the stored plutonium has deteriorated; and the plutonium needs to be repackaged. The process of repackaging it should provide an opportunity for supplying it to the developers of fast reactors and of waste-burning reactors, which are capable of disposing of it. By not taking this opportunity, the Government, will be inhibiting the development in the U.K. of advanced nuclear technologies.

In summary, it seems that the Government’s policies are destined to bring about the collapse of the nation’s nuclear industry. They need to be replaced by policies that are much more supportive of the industry.

14 Bibliography

There are few available accounts of the history of nuclear technology in Britain. Exceptions are *The Fall and Rise of Nuclear Power in Britain* by Simon Taylor [1] and *An Atomic Empire* by Nick Hill [2]. Technical details of nuclear fuel and nuclear reactors can be gathered from the website of the World Nuclear Association `https://world-nuclear.org`. Wikipedia has provided plentiful information on many nuclear topics on the Web. The following is a sparce list of specific references that have been made in the text.

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