THE DEMISE OF THE NUCLEAR POWER INDUSTRY AND THE PROSPECT OF ITS REVIVAL

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An account is given of the history of nuclear power generation, its technologies and the prospects of its revival.

It is proposed that a revival of nuclear power generation is the only way in which we can meet the existing and projected demands for energy, if we are not to continue to burn fossil fuels in a way that will lead to disastrous climate change.

The revival of the nuclear industry will depend, in the long run, on the exploitation of technologies that, for historic reasons, have been sidelined. It will also depend on our overcoming the phobias that have been stimulated by nuclear weaponry and which have been exacerbated by nuclear accidents that could have been avoided.

Introduction: Hope and Failure

The demise of the nuclear industry in the U.K. is a paradigm for the technological failures of the nation in the years from the Second World War to the present. Although the outcomes have been consistently bad over a wide range of activities, there are particular circumstances that affect each of these failures. Therefore, it may be worthwhile to give a brief account, in this introduction and in a subsequent section, of the history of the U.K.'s nuclear industry, while making reference to circumstances in the wider world.

The British public were alerted to the civil uses of nuclear power by the inauguration of the nuclear power station at Calder Hall. This occurred on a bright and cloudless day on the 17th of October 1956, and it was recorded in a *Movietone* newsreel film.

There is a familiar picture of this occasion, which shows the young queen surrounded by dignitaries and boffins who are clustered under a circular awning that reflects the modernistic design idiom of the Festival of Britain of the summer 1951, and of the Coronation of June 1953. (Presumably the awning was erected for fear of bad weather.) The Queen is about to pull a lever to begin the process of feeding nuclear-generated electricity into the national grid.

A remarkable fact that was reported in a contemporary issue of the *Engineer* is that the opening of Calder Hall occurred no more than three and a half years after the design team had begun work on their scheme. In her speech, the Queen declared that nuclear power, which had proved itself to be such a terrifying weapon of destruction, had been harnessed, for the first time, for the common good of the community. The event demonstrated the peaceful uses of this new source of power.

As we well know today, a primary purpose of the Calder Hall power station was to generate weapon's grade plutonium. Indeed, this was an objective that everywhere dominated the early years of civil nuclear power. As will be argued, it shaped the nuclear industry that we know today. Presumably, this secret purpose was common knowledge amongst the cognoscenti. The abstract to the aforementioned article of the *Engineer* openly stated that the reactor was designed for the production of plutonium as well as for the generation of electricity.

However, it is undeniable that there was great enthusiasm for the civil use of nuclear energy and there was unbridled optimism at this prospect. According to an unattributed pronouncement of the time, which is still well remembered, 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 accomplish the amazing feat of generating more fuel than they would consume. Their source of power would be self replenishing. Eventually, of course, the fuel would expire, 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 fissile 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. 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.

Practical power stations based on this improbable device were widely imagined. The artist of the *Illustrated London News* seized upon the image of the small toroidal chamber in which fusion was thought to have occurred and magnified it several times, surrounding it by industrial buildings and car-parks and placing the complex in a green field.

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. Even today, no one has succeeded in producing a controlled fusion reaction that has released more than a fraction of the energy that has been used in initiating it.

The Demise of the of the British Nuclear Power Industry

The demise of the British nuclear power industry is recorded in a recent report of the Select Committee on Science and Technology of the House of Lords on the subject of Nuclear Research and Development Capabilities. The report shows that there has been a virtual cessation of U.K. public sector funding for Research and Development concerning nuclear fission. The funding stood at £500 million per annum in 1970. By 1995, the funding was zero. The report also records the closure of laboratories and the depletion of the Research and Development workforce. The majority are facing imminent retirement. Soon none will remain.

The attitude of successive governments to matters of science and technology has been afflicted by the fallacy of outsourcing. It is believed that there is no need to maintain a scientific and a technical competence within government and the civil service. The functions that have previously been performed internally can be purchased as services from outside suppliers. Recent events serve to show how vulnerable to the whims of the market the U.K. energy policy has become. In the absence of a scientifically competent civil service, there is a lack of expert advice to guide this policy.

To understand the complex issues surrounding the deployment of nuclear technology, it is necessary to grasp some of the aspects of the underlying physics.

Fission and Fusion

An atom consists of a small, massive, positively charged core or nucleus surrounded by electrons. The nucleus, which contains most of the mass of the atom, is composed of neutrons and protons bound together by strong nuclear forces.

The generic atomic nucleus is denoted by

$$^{A}_{Z}K$$

A : the atomic mass = protons + neutrons,

Z : the atomic number = number of protons,

K : the symbol for a chemical element found in the periodic table.

An example is the uranium-235 isotope, 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 $200MeV$ (200 million electron volts) of energy:

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

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

Nuclear energy is also 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:

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

Fusion powers the sun. On earth, it occurs in H-bomb explosions. Controlled fusion has been attempted for almost 60 years without significant success. An early attempt, as we have already noted, occurred in the U.K. with the ZETA machine. The first successful controlled fusion was achieved by the TOKAMAK machine in the U.S.S.R. in the 1970's. The endeavour continues in the U.K. with the JET (Joint European Torus) machine, which is located at Culham, Oxfordshire. Fusion is very far from providing a practical means of generating energy; and it is debatable whether the endeavour will ever bear fruit. In the meanwhile, the nuclear industry depends upon a supply of mineral uranium and upon its radioactive products.

The power of a nuclear reactor depends upon a controlled chain reaction. For such a reaction to occur, it is necessary for at least one of the neutrons released during each fission to cause another fission event. The likelihood of this happening depends upon the proximity of other fissile uranium atoms and on the presence of neutron-absorbing materials, such as the uranium U-238 isotope, which are liable to inhibit the chain reaction.

The speed of the neutrons is also a factor in the process. To prevent them from escaping from the nuclear pile, the neutrons can be slowed down by the presence of a moderating substance. Thus, the probability that a fission neutron will itself induce fission can be increased by a factor of several hundred when the neutron is slowed down through a series of elastic collisions with the light non-fissionable nuclei of substances such as hydrogen, deuterium or carbon.

Uranium Nuclear Fuel

The radioactive U-235 isotope represents typically only 0.7 percent of natural mineral uranium. The majority of the mineral consists of the inactive U-238 isotope. Moreover, the quantity of the radioactive isotope is gradually diminishing in consequence of its decay. For the uranium to be effective in generating nuclear power within a reactor, the proportion of the radioactive isotope must be increased. There are no chemical means available for doing this. Instead, a method of enrichment must be employed that depends entirely on the weight differential of the 238 and 235 isotopes.

To produce the nuclear fuel, the mineral ore is first concentrated by milling. Then it is shipped to a enrichment plant where it is converted to uranium Hexafluoride gas UF_6. The gas is forced through a permeable membrane barrier that permits the lighter 235 isotope to diffuse more rapidly that the heavier isotope. By repeating the process, by means of multiple diffusion barriers, the degree of enrichment can be increased to an arbitrary level. The enriched gas product is sent to a fuel fabrication plant where it is converted to uranium oxide. This is usually incorporated in ceramic pellets that are loaded into fuel rods. The typical nuclear fuel contains about 3 percent of U-235, but some fuels, such as those intended for the small and powerful reactors that power nuclear submarines, contain more.

When the nuclear fuel is burned in a reactor, the percentage of fissile U-235 gradually declines until its concentration becomes subcritical. After a period of 3–6 years the percentage of U-235 drops to around 0.8 percent. In the process, some of the non-fissile U-238 that forms the preponderant mass of the original fuel will be converted into the fissile plutonium isotope Pu-239. The latter will account for about 1 percent of the spent fuel, which is an insufficient quantity to sustain the chain reaction. The conversion of U-238 to Pu-239, via the intermediate neptunium Np-239 isotope, can be represented as follows:

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

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

Reprocessing

Spent fuel, which has been removed from a reactor, generates heat and radioactivity, and it is generally stored underwater to provide radiation shielding and to cool the fuel rods. Although spent fuel can be stored safely for years, storage underwater is not a permanent solution. The options for dealing with the fuels include dry storage, deep underground disposal, conversion into a less harmful substance and reprocessing.

Reprocessing entails the separation of plutonium and uranium from the residue of the fission products, which are about 3 percent of the spent fuel and which account for most of the radioactivity. It is the presence of these radionuclides that causes reprocessing to be far more hazardous than the process of enriching the original uranium ore. Also, plutonium is more toxic and radioactive than fissile uranium.

Separated uranium and plutonium can be recycled into a useable nuclear fuel. This may require a further re-concentration of the fissile elements. The process is known as closing the fuel cycle. The fuel in question is generally known as MOX, which denotes a mixture of uranium and plutonium oxides. With a low concentration of plutonium, the MOX fuel can be used as a direct substitute for the enriched uranium fuels that light water reactors (LWR's) have been designed to use. With higher concentrations, some modifications are required to the control systems of the reactors.

The first use of MOX fuel was in 1963 in a Belgian LWR reactor. Large-scale use started in Germany in 1981 and in France in 1985. By 1999, 34 operating LWR's, 6 fast breeder reactors and one advanced thermal reactor had used MOX. The number of reactors in operation world-wide totals perhaps some 430; and not all of these are capable of burning the MOX fuels. In particular, only one of Britain's power generating reactors, the pressurised water reactor (PWR) known as Sizewell B, is capable of burning the fuel. The remaining reactors are either of the original Magnox design, now being decommissioned, or its replacement, the advanced gas-cooled reactor AGR.

The Sellafield Thermal Oxide Reprocessing Plant (THORP), which was established in 1994, was, therefore, intended, primarily, to satisfy an overseas demand that has evaporated, as well as a new generation of British LWR's that have not been constructed. A further element entered the equation that made the economic viability of the British reprocessing enterprise even more doubtful. This was the intention of the United States to convert a substantial proportion of its stockpile of redundant weapons grade plutonium into MOX fuels. The conversion, which involves the mixing of existing stocks of uranium and plutonium oxides, is much easier to accomplish than the reprocessing of spent nuclear fuels.

Fast Breeder Reactors

At the dawn of the nuclear era, the reprocessing of spent fuel was seen as a temporary expedient to be used in advance of the arrival of practical fast breeder reactors. These would be relied upon to make the fullest use of the available nuclear fuel; but, in the meanwhile, the fuel would be conserved by reprocessing. The fast breeder reactor is designed to convert most of the available non-fissile uranium-238 that accompanies the U-235 isotope into fissile plutonium Pu-239. It should then proceed to use the plutonium as its own abundant fuel.

In order to maximise the production of plutonium, the velocity of the neutrons causing fission must remain fast, with an energy at, or near, that of their initial release. Any moderating material that would slow the neutrons must be excluded from the reactor. For this reason, a molten metal, such as sodium, is used as a cooling liquid. Sodium melts at about 100 degrees C and it boils at 900 degrees C. However, it is chemically highly reactive and it combusts spontaneously in air and in contact with water. It is clear that liquid metal fast breeder reactors (LMFBR's) are difficult to engineer.

Although the development of the LMFBR began in the early 60's, it has never reached full fruition. The first large-scale plant of this type for generating electricity, called the Superphénix, went into operation in France in 1984. A pilot plant was also constructed in Germany, but it was abandoned before the Superphénix was. There was also small prototype LMFBR at Dounreay in Scotland. In 1961, it became the first fast reactor in the world to provide electricity to a national grid. It was closed down in 1977.

Notwithstanding the technical difficulties, the dream of the fast breeder reactor remains an alluring one. In an LMFBR, about 75 percent of the energy content of the natural uranium would be liberated, in contrast to the 1 percent in a LWR. It is likely that, when a severe shortfall in the supply of energy begins to threaten our way of life, the dream of the fast breeder reactor will be revived.

The Thorium Fuel Cycle

In common with uranium-238, thorium 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 was used in an early molten salt reactor at the Oak Ridge National Laboratory that demonstrated an alternative technology for nuclear power generation. It has been proposed, more recently, to use the thorium fuel cycle within liquid fluoride thorium reactors (LFTR's), which many see as the way forward, in the long run, for nuclear power generation.

Nuclear Reactors around the World

Russia

It is now clear that the world's first civilian power station was the Russian Obninsk Nuclear Power Plant. Construction started on January 1, 1951, and the first grid connection was made on June 26, 1954. This was more than two years before the connection of Britain's Calder Hall power station to the U.K.'s National Grid, which occurred on October 17th 1956. The Obninsk reactor used a graphite moderator and a water coolant. The total electrical capacity of the plant was 6MW, which is a negligible amount. It was a forerunner of the RBMK reactors, which became predominant throughout the USSR and its satellite counties.

The RBMK (Reaktor Bolshoy Moshchnosti Kanalniy, or "High Power Channel type Reactor"), which has been described as an early Generation II design, is a pressurised water-cooled reactor with a graphite moderator. This reactor, which was implicated in the Chernobyl disaster of 1986, embodies several design and safety flaws. It displays a dangerous instability at low power levels.

At Chernobyl, there was a sudden power output surge. An emergency shutdown was attempted too late to save the reactor, and superheated steam led to a reactor vessel rupture and to a series of explosions. The graphite moderator of the reactor was thereby exposed to the air, causing it to ignite. The resulting fire sent a plume of highly radioactive smoke into the atmosphere and the fallout covered an extensive geographical area. At least 11 RBMK reactors continue to operate in Russia.

Britain

Britain followed a very different approach to the other nuclear nations in the design of its original Magnox reactors. These were moderated by graphite and cooled by carbon dioxide. Boron-steel control rods were inserted into the pile in order to slow or to halt the reaction.

The Magnox reactors were considered at the time to have a considerable degree of inherent safety because of their simple design, their low power density and their gas coolant. Loss of coolant would not cause large-scale fuel failure, since the Magnox cladding would retain the bulk of the radioactive material. Assuming that the reactor was shut down rapidly, the decay heat could be removed by the natural circulation of air.

The Windscale fire of 10 October 1957, which was the worst nuclear accident in Great Britain's history, was not attributable to the Magnox rector. It was associated with a separate but adjacent facility for the production of weapon's grade plutonium. The misattribution of the accident, which is understandable in view of the secrecy surrounding the nuclear weapons programme, was bound to influence the British public's appraisal of the safety of nuclear power generation.

The reactors in question were graphite-moderated and air-cooled. They had a solid graphite core, with horizontal channels through which cartridges of uranium and other isotopes could be passed to expose them to neutron radiation from the uranium and to produce plutonium and radioisotopes.

Fuel and isotopes were fed into the channels in the front of the reactor, and spent fuel was then pushed all the way through the core and out of the back into a water duct for initial cooling, prior to retrieval and processing to extract the plutonium.

The chimneys that are visible in the pictures of Calder Hall were, in fact, the vents for the cooling air of this plutonium manufacturing facility. When the core caught fire, they spewed radioactive contamination into the surrounding area. The filters at the tops of the chimneys were an afterthought. They had been placed there at the insistence of Sir John Cockcroft, the director of the Atomic Energy Research Establishment (AERE) at Harwell, and they were instrumental in limiting the contamination.

The Magnox reactor was eventually succeeded in the U.K. by the advanced gas cooled reactor (AGR). This second generation reactor has many of the features of its predecessor. It operates at a higher gas temperature, thereby improving its thermal efficiency. It employs a uranium fuel with a degree of enrichment of 2.5–3.5%, which is higher than in the case of the Magnox reactor and which confers the benefit of less frequent refuelling.

The AGR was intended to be a superior British alternative to the American light water reactor designs. The first reactor at Dungeness B was ordered in 1965, with 1970 as its intended date of completion. It finally began generating electricity in 1983, which was 13 years late. The export orders never materialised; and the American industry, which supplied pressurised water reactors, dominated the export market.

These experiences must have convinced U.K. governments to withdraw their support from the nuclear industry. A state has now been reached where British nuclear power stations are owned and run by a foreign company, which is EDF (Electricité de France). In February 2012, EDF announced that it expects to extend the lives of the AGRs by 7 years on average.

The present government, which is aware of the impending shortfall in the U.K.'s provision off electrical power, has declared that it is prepared to allow any willing provider to bid for a contract to build new nuclear power stations. These would form part of a mixed portfolio of energy supply. It is becoming increasingly clear that there are no such willing providers.

In May 2012, EDF announced that it has deferred its uptake of the £1.2bn contract for a new nuclear power station to be built at Hinkley Point in Somerset. One reason for this has been the election to the French Presidency of François Hollande, who has declared himself to be sceptical about nuclear power. Other power companies, such as the German E.ON and RWE (Rheinisch –Westfälisches Elektrizitätswerk) and SSE (Scottish and Southern Energy), which is a branch of a large multinational energy consortium, have already dropped out. The German companies have been discouraged by the opposition of Angela Merkel to nuclear power.

The United States

Much of the science that underlies the technology of nuclear power generation was developed in the United States in connection with the atomic bomb project at Los Alamos. The science continued to develop apace, and the atom bomb was succeeded by the hydrogen bomb, which was first detonated in 1952.

The early developments of nuclear power generation in the US were vigourous and multifarious. They included the development of the Molten Salt Reactor Experiment (MSRE) at the Oak Ridge National Laboratory by a team led by Alvin Weinberg and the contemporaneous development of the pressurised light water reactor that powered the Nautilus nuclear submarine, which was authorised in 1951 and launched in 1954.

It seems fair to say that the naval demand for pressurised light water reactors has had a dominant effect on the designs of civil reactors in the United States. There are currently 69 pressurised water reactors (PWR's) and 35 boiling water reactors (BWR's) in operation. These have been provided, in the main, by the suppliers that have responded to the demands of the military, which are Westinghouse and General Electric.

The molten salt reactor, which showed great promise in its experimental stages, was discarded. This reactor avoids many of the problems associated with uranium scarcity and with the production of long-lived radioactive wastes. It could not have provided, amongst its waste products, an abundant supply of the much-needed weapon's grade plutonium.

Now that the priorities of the Cold War no longer dominate, there is every reason to attempt to revive this alternative technology. However, the American nuclear industry has been in abeyance for many years. Almost all the US nuclear generating capacity comes from reactors built between 1967 and 1990. There have been no new construction starts since 1977.

There have been two reasons for this hiatus. First, disregarding their environmental consequences, power stations fuelled by coal or by natural gas have been more economically attractive. Secondly, there have been heightened safety fears following the Three Mile Island nuclear accident in 1979.

Recently, there have been indications that the Obama administration, motivated by the fears of global warming, has been keen to renew the program of nuclear power generation. So far, there have been few indications of progress in this connection.

France

Nuclear power is the primary source of electricity in France. In 2004, 78.8% of the electricity was generated from nuclear power, which is the highest percentage in the world. As much as 18% of French electricity is exported to Italy, the Netherlands, Belgium, Britain and Germany.

France began its nuclear programme later than did other nuclear counties. The impetus was provided by the 1973 oil crisis, when French politicians became conscious of a heavy dependence on imports of oil for supplying power. A political philosophy that differs markedly from that of the United States has enabled the state to provide large subsidies to the nationalised power industry, which is in the hands of the EDF monopoly.

The first 8 French nuclear reactors were of the gas-cooled variety. Their development was pioneered by the French public sector company CEA. Subsequent reactors were of the pressurised water variety, which eventually became the dominant type. All of the gas-cooled reactors have been shut down.

Of all the nations that embarked on the experiment, France have persisted longest with its attempt to realise a viable form of sodium cooled fast breeder reactor. The prototype French fast breeder was the Phénix. Its construction began in November 1968. The first connection to the French national electricity grid was in December 1973. The Phénix reactor was finally shut down at the end of 2009.

The Superphénix was a larger, more ambitious, version of the fast breeder. Its construction was a protracted affair lasting from 1974 to 1981, and power production did not begin until 1985. Throughout its period of operation, the reactor was afflicted by problems of corrosion and leakage. Full output was achieved only in 1996, which was the year in which electricity production ceased. The plant was closed in 1998. Throughout its lifetime, the Superphénix attracted protest actions from the Green lobby.

The French have persisted with their fast-breeder dream. The ASTRID (Advanced Sodium Technical Reactor for Industrial Demonstration), which is

	In Operation		**Building**	
Country	Number	Output MW	Number	Output MW
Argentina	2	935	1	692
Armenia	1	375	–	–
Belgium	7	5,927	–	–
Bulgaria	2	1,906	2	1,906
Canada	18	12,604	–	–
China	16	11,816	26	26,620
Taiwan	6	5,018	2	2,600
Czech Republic	6	3,766	–	–
Finland	4	2,736	1	1,600
France	58	63,130	1	1,600
Germany	9	12,068	–	–
Hungary	4	1,889	–	–
India	20	4,391	7	4,824
Iran	1	915	–	–
Japan	50	44,215	2	2,650
South Korea	23	20,671	3	3,640
Mexico	2	1,300	–	–
Netherlands	1	482	–	–
Pakistan	3	725	1	315
Romania	2	1,300	–	–
Russian Fed.	33	23,643	10	8,203
Slovakia	4	1,816	2	782
Slovenia	1	688	–	–
South Africa	2	1,800	–	–
Spain	8	7,567	–	–
Sweden	10	9,326	–	–
Switzerland	5	3,263	–	–
Ukraine	15	13,107	2	1,900
United Kingdom	17	9,736	–	–
USA	104	101,240	1	1,165
Total	436	**370,494**	**63**	**60,057**

Table 1. Nuclear power plants world-wide, in operation and under construction, as of 30 March 2012 (IAEA 2012).

part of the international Generation IV reactor programme, is intended to succeed Phénix. It is envisaged that it will be built in the period 2015–2020.

Other Countries

Despite having suffered the effects of nuclear weapons in wartime, Japan has resorted to nuclear technology to provide a substantial portion of its electricity. In 2011, the country's 50 main reactors provided some 30% of the total electricity output.

Japan imported its first commercial nuclear power reactor from the U.K. This was a gas-cooled Magnox reactor built by Britain's GEC (General Electric Company), which has since been absorbed by British Aerospace to form BAE Systems. It began operating in July 1966 and it continued until March 1998. After this plant was completed, only light water reactors were constructed, which were boiling water reactors and pressurised water reactors.

However, following the Fukushima accident in October 2011, the Japanese government has begun to reappraise the country's dependency on nuclear energy. The outcome remains uncertain. Given Japan's energy demands and the country's lack of natural resources, it seems that it is bound to retain its nuclear industry.

Several other countries have a legacy of nuclear power generation, which has originated either from their erstwhile association with the USSR (Union of Soviet Socialist Republics) or from their affiliations to the U.S.A. The extent of the world's current nuclear generating capacity is recorded in Table 1, which also shows the capacity that is forthcoming.

The table illustrates the recent commitment of China to nuclear technology. As much as 80% of China's electricity is currently produced from coal. A further 15% is generated by hydropower, to which the Three Gorges Dam and the Yellow River make significant contributions. China's use of its massive coal reserves threatens to contribute largely to the problems of global warming. However, its emerging nuclear power industry may serve to mitigate these effects.

China has 14 nuclear power reactors in operation, more than 25 under construction, and more about to start construction soon. The nuclear technology has been drawn from France, Canada and Russia, the French contribution having been prominent. The latest technology acquisition has been from the USA, via Westinghouse, which is now owned by Japan's Toshiba, and from France. In the immediate future, the industry will rely on developments the Westinghouse technology.

China is rapidly becoming self-sufficient in reactor design and construction, as well as in aspects of the fuel cycle. There have been recent indications that China has become interested in the technology of molten salt reactors, which will be appropriate for using thorium as a fuel.

The table also illustrated the intention of India to pursue a nuclear future. Because of its nuclear weapons program, India is not a signatory to the Nuclear Non-Proliferation Treaty. Therefore, for many years, it has been largely excluded from trade in nuclear materials and nuclear technology. This has hampered its development of civil nuclear energy. Now India has begun to participate more actively in the world-wide technology, albeit that its nuclear power plants will retain much indigenous content.

Aspersions have often been made against the ramshackle nature of some of India's nuclear engineering. Nevertheless, India aspires to become a world leader in nuclear technology via its expertise in fast reactors and in the thorium fuel cycle. India adheres strongly to a vision of fast breeder reactors.

The Problems of the Existing Technology

The progress of nuclear power generation has been impeded by technical difficulties and by the threat of nuclear accidents. There is also the intractable issue of what should be done to dispose safely of the enduring waste products of nuclear power generation, which remain radioactive for many years.

It is also true that the anxieties surrounding nuclear weapons have affected people's perception of nuclear power. In some cases, these anxieties have been due to a rational assessment of the dangers of nuclear weapons proliferation, but, in other cases, they are merely the emotional product of an irrational association with nuclear weaponry.

Many persons, who have made a cool assessment of these matters, contend that the hazards of nuclear power have been exaggerated and that they are insignificant when compared with the dire consequences if the world continues to satisfy its energy demands by burning fossil fuels.

The hazards of nuclear power generation are inherent in the technologies that were adopted, in the early years, for reasons that were largely extraneous to the purpose. They could be largely avoided by the adoption of alternative technologies. The revival of the nuclear industry will depend, in the short run, on the existing well-developed technologies; but, in a longer run, these will need to be replaced.

The first of the problems with the existing technology concerns the fuel supply. The fissile uranium-235 element has to be extracted from the uranium ore and concentrated by processes that are protracted and difficult. When all is done, the fissile uranium isotope represents only a few percent of the gross mass of the fuel. When, in the process of burning the fuel, the percentage has fallen below a critical level, the fuel is exhausted.

This wastefulness has given rise to the pursuit of nuclear reprocessing, which aims to reconcentrate the spent fuel and to exploit the presence within it of a fissile plutonium isotope. This highly toxic substance makes reprocessing an expensive and a hazardous business.

The avoidance of waste has also inspired the dream of the fast breeder reactor, which has been realised using a liquid sodium moderator. The success of these reactors has been limited by the problems that are associated with this dangerous substance. However, as their technology has developed, the conventional reactors have become capable of breeding increasing proportions of their own fuel. The Canadian CANDU reactor, which might be described as a slow breeder, is a case in point.

A further problem with the existing technology concerns the use of water under very high pressure both as a coolant and as a moderator. The three most severe nuclear accidents, which have been at Three Mile Island (1979), at Chernobyl (1986) and at Fukushima (2011), have involved the loss of the water coolant from pressurised water reactors. In the cases of Chernobyl and Fukushima there were attendant hydrogen explosions.

The Promise of a New Technology

The opinion is strengthening that the way forward for the nuclear industry in the not-too-distant future is a wholescale conversion from conventional pressurised water reactors to liquid fluoride thorium reactors (LFTR's). These reactors use the thorium fuel cycle in a fluoride-based molten salt fuel to achieve high operating temperatures at atmospheric pressure. This technology was first investigated at the Oak Ridge National Laboratory in the Molten-Salt Reactor Experiment in the 1960's, under the direction of Alvin Weinberg.

A LFTR can be designed as a breeder reactor. It can breed enough new fissile fuel from fertile thorium to run almost indefinitely. The breeding of fuel via the uranium-plutonium fuel cycle requires the use of fast reactors such as those that employ a molten sodium coolant. With thorium, it is possible to breed the fissile material in a thermal reactor, which entails a neutron flux of a much lower energy.

There are two ways to configure a thorium reactor to do the required breeding. One can keep the fertile and the fissile fuel together, so that the breeding and the fission occur in the same place. Alternatively, fissile and fertile material can be separated to create a core-and-blanket reactor. The fissile core produces the heat and the neutrons, while the breeding occurs in the separate blanket.

The original Oak Ridge reactor, which ran successfully from 1965 to 1968, was a single core, or single fluid, design. The design of a two fluid, core-and-blanket, reactor was well advanced by the time that the Oak Ridge research was terminated in 1970 and Weinberg was fired.

There are several advantages in separating the core of the reactor from the surrounding blanket in which the thorium is converted to protactinium-233. This can be allowed to decay slowly and spontaneously to the fissile U-233 fuel. Since blanket is isolated from the core, an accumulation of fission products cannot inhibit the efficiency of the fuel that is being generated therein.

Because the fissile material is contained in a small core, the overall size of the reactor can remain small. Finally, since there is virtually no fission occurring in the blanket, there can be an efficient use of a limited neutron flux, and the need for shielding is reduced.

The molten salt reactor has some considerable safety advantages. As the fuel heats up, its neutron absorbency increases. This leaves fewer neutrons to continue the chain reaction, thereby reducing the power. Next is the important fact that, as it is heated, the salt expands, thereby pushing the fuel out of the active core and reducing the chain reaction. At no stage is there a possibility of an explosive build-up of pressure, as there is in a conventional reactor.

A final safety feature can be engineered by placing a plug of solid salt in the reactor vessel, which can melt if the temperature exceeds a critical level. This will allow the fuel to run out of the reactor, which will effectively close it down.

It is ironic that one of the features that prevented the early adoption of the molten salt thorium reactor is today one of its principal advantages. There are few fissile elements amongst its waste products. It fails to produce the fissile plutonium that was required during the years of the Cold War for the production of nuclear bombs and warheads. Such reactors could now be used to dispose of the stockpiles of plutonium and the quantities of nuclear waste that have accumulated since the beginning of the nuclear age. They could be burned as fuel and rendered virtually harmless.

An unanswered question remains of how long it would take to make this alternative technology fully operational. It must be admitted that, nowadays, things move much more slowly than they did in the years immediately following the Second World War. One is reminded that it took only three and a half years to design and to build Britain's first civil nuclear reactor at Calder Hall. This should provide a measure of the effort that it would take to realise the thorium based nuclear technology, even if it does no tell us how long it would take.

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