LECTURE 9

Nuclear Power and Britain's Energy Policy

Hope and Failure

On October 17, 1956, the ceremonial opening took place of the world's first nuclear power station at Calder Hall in Cumbria. It was a bright sunny autumn day. In front of a large white rectilinear building that glistened in the sunshine stood a small group of people that included an incongruous mixture of dignitaries and white-coated boffins. One of them was a young lady with scissors in her hand, poised to cut a ribbon. She was dressed in a long tailored coat with a nipped waist and padded shoulders, and she was perched insecurely on high-heeled shoes with rounded toes. She was the young queen.

This hopeful occasion occurred at the height of the cold war, when the threat of nuclear annihilation was becoming a dominant anxiety in the minds of many British citizens. The event heralded the peaceful use of atomic energy. 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 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.

Popular Opposition

The optimism that accompanied the dawn of the nuclear age has gradually faded. Today, there is widespread popular opposition to the nuclear industry in Europe and in the United States. This opposition has been stimulated by such events as the accident at Three Mile Island (March 28, 1979) and the catastrophe at Chernobyl (April 26, 1986). It is also a natural consequence of the association of nuclear power with nuclear weaponry. The anxieties surrounding the weapons are bound to effect our perception of nuclear power. In some cases, these are due to a rational assessment of the dangers of nuclear proliferation, but, in other cases, they are merely the emotional product of an irrational association.

It must also be acknowledged that the deceit and the misinformation that have surrounded the nuclear industry have contributed to its unpopularity. There has been a dawning recognition that the programme for the peaceful use of atomic energy has often concealed sinister purposes. An example is provided by the original nuclear power station at Calder Hall—now renamed Sellafield. Apart from its use in generating electricity, the reactor was intended as a source of weapons grade plutonium. The accidents that have beset Britain's nuclear installations have also been concealed from the public, beginning with an incident in 1957, which is now recognised to have been the worst nuclear accident before that of Chernobyl.

Evidence of a widespread nuclear phobia is provided by the difficulty in achieving the permanent disposal of nuclear waste. For this purpose, two conditions must be fulfilled. First, a site must be found where the waste can be buried deep underground in a manner that will prevent it from percolating into the water table or reaching the surface over time in some other manner. The second requirement is to find a region where the inhabitants are prepared to tolerate the presence of the nuclear waste.

In Britain, the Nirex (Nuclear Industry Radioactive Waste Executive) corporation, which was charged with the disposal of nuclear waste, was able to satisfy only one of these requirements. It chose, for the disposal of waste, the Sellafield site in Cumbria, where Britain's first nuclear power station had been located. The local population had become habituated to nuclear hazards. Unfortunately, this was a bad choice from the point of view of its geology. The rocks in which it was proposed to bury the waste are porous and fissured in way which would have exposed the waste containers to erosion by subterranean waters; and it was feared that the contamination would have eventually reached the surface. The government of the day, which was formed by the Conservative party, attempted to gain some credit, on the eve of the 1997 general election, by withdrawing its consent to the plan to investigate further the possibility of disposing of the waste at this site.

The End of a Dream

Many people now believe, erroneously, that the era of nuclear power generation has virtually been brought to an end. The misconception has been strengthened by recent events. On Monday 31st March 2003, the last of the four reactors at Calder Hall, which had come to the end of its economic life, was shut down. A small and sad ceremony marked the event. In reporting the event, the Guardian newspaper, conscious of the optimism that had marked the beginning of the era, asked in a headline "Is this the end of the dream?"

In August of 2003, it was announced that the THORP nuclear reprocessing plant at Sellafield was scheduled for closure in 2010. The so-called MOX plant was designed to create a nuclear fuel from uranium and plutonium, which are the waste products of a conventional reactor. It had been expected to make money by selling this fuel overseas. The hope has evaporated with the cancellation of the existing contracts and in the absence of any further demand. It might seem, therefore, that it remains only to dismantle the power stations and to clear up the nuclear contamination.

The problems of Britain's nuclear industry are compounded by the financial crisis that it is currently facing. An immediate factor in this is a fall in electricity prices in consequence of a temporary overcapacity in the power generating industry faced by an inelastic demand. Britain's nuclear power stations were ostensibly privatised in 1996, under the aegis of the British Energy Corporation; and since then, the industry has faced the rigours of price competition as never before.

In view of its financial difficulties, and in consequence of the costs that the industry faces in decommissioning the first generation of power stations, the Labour government undertook, in 2002, to underwrite its loses to the extent of almost 5 billion pounds. Much to the glee of its critics, some of who propose that it should be scrapped altogether, the industry continues to suffer large operating losses.

The Surival of the Industry

The idea that it might be possible to dispense with its output is one of the many illusions that surround the nuclear industry. The truth is that Britain continues to rely heavily upon nuclear power to generate its electricity. Some 28 percent of the electricity comes from this source. Not all of this electricity is generated within the country. Some unknown proportion of it is shipped in from France, where

Percentage of Electricity Generated by Nuclear Power

Lithuania	81.5
France	78.2
Belgium	60.1
Ukraine	46.8
Sweden	46.2
Bulgaria	45.4
Slovak Republic	44
Switzerland	40.6
Slovenia	39.9
Hungary	39.9
Japan	35.2
Republic of Korea	34.1
Germany	31.8
Finland	30.4
Spain	29.3
Taiwan	29.1
United Kingdom	27.5
Armenia	25.7
United States	20.1
Czech Republic	19.3
Canada	14.2
Russian Federation	13.6
Argentiania	11.4
Romania	9.7
South Africa	6.5
Netherlands	2.8
India	2.3
Brazil	1
China	0.8
Parkistan	0.6

Source: IAEA Bulletin 40/3/1998

78 percent of the electricity is generated by nuclear power. World-wide, some 18 percent of electricity is generated by nuclear power. The figures for 1998 are shown in an accompanying table.

Far from vanishing, nuclear power is set to become the primarily source of energy in replacement of the fossil fuels whose combustion has created the burden of atmospheric carbon dioxide that is causing global warming. In the perception of many experts, nuclear power represents the only viable alternative source of energy. The other sources of energy seem quite insufficient to satisfy our existing demands, let alone those that are envisaged in the future.

Such is the unpopularity of nuclear power that few politicians are prepared to acknowledge these realities in public. However, the tacit adherence of the British government to a policy of nuclear power generation is witnessed by their unwillingness, until recently, to envisage the closure of the THORP reprocessing plant. Its survival was seen as a token of the survival of the industry as a whole and as a security for meeting the energy needs of the future. However, it seems that this view was based upon a mistaken analysis since, in any circumstances, the reprocessing technology would not be needed for many years.

It is not difficult to envisage, even within ten years, a crisis in the U.K caused by a shortfall in the supply of energy. In 10 or 20 years, the demand for oil will outpace its supply and, in the same time span, the present generation of coal and oil-burning power generators will reach the end of their working lives. As the crisis approaches, politicians will be forced, eventually, to debate the future of the nuclear industry in an overt manner. For the moment, they are content, in the main, to disregard the need for a national energy policy. At dawn of the nuclear age, virtually all of the country's energy supply was under the control of the central government. Nowadays, it is in the hands of a privatised industry. It is out of sight and, therefore, out of mind, unless its financial exigencies are commanding attention.

Nevertheless, it is foolish for governments to pretend that they can ignore these matters. Unless we can staunch our demand for energy, which seems highly unlikely, we shall be forced into making a Faustian contract with nuclear power. If this is to be the case, then it is important that we should understand what the technology entails. We should begin our analysis with some simple facts of nuclear Physics.

Fission and Fusion

The 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 is denoted

$${}^{235}_{92}U$$

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 50 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 TOKOMAK 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 in Dounreay in Scotland. 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 U-283, 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.

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. The 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 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.

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. Althought 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 radionucleatides 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 know as MOX, which denotes a mixture of uranium and plutonium oxides. With low a 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 worldwide totals perhaps some 350; 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 known as Sizwell 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 has now entered the equation that has made the economic viability of the British reprocessing enterprise even more doubtful. This is 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, will be 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. It is clear that liquid metal fast breeder reactors (LMFBRS) 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 Super-Phenix, went into operation in France in 1984. A pilot plant was also constructed in Germany, but it was abandoned before the Super-Phenix was. There remains a small prototype LMFBR at Dounreay in Scotland. 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.

Five Decades of Mishaps

1947 Old munitions factory site at Windscale chosen for producing plutonium after Clement Atlee, the Prime Minister, takes the decision to mount a crash programme to build British atomic bomb.

1950 First plutonium production starts up. Site remains a secret. Anyone disclosing information about the plant liable to five years in jail. But newspapers arrive every day at the railway station marked for delivery to "The Atom Bomb Plant".

1956 Queen opens Britain's first commercial nuclear power station at Calder HaIl next to the plant, predicting a solution to the energy crisis as this new power "which has proved itself to be such a terrifying weapon of destruction, is harnessed for the first time for the common good".

1957 Fire rages out of control for four days in the world's worst nuclear accident before Chernoby. Full-scale disaster averted because of the installation of safety filters which trap the radioactivity. But 260 people are thought to have contracted cancer.

1977 Windscale Inquiry into building the Thorp plant to process modern reactor fuel after an accident contaminates 35 workers. Plant gets go-ahead, but not built for over a decade. In 1977 President Carter deferred indefnitely the recycling of "spent" nuclear fuel, citing proliferation risks.

1981 After more accidents name changed to Sellafield. Mishaps continue, giving Sellafield a yet worse name.

1983 discharge of radioactive waste contaminates coast. BNFL plays down incident, but TV documentary discovers high levels of leukemia in local children.

1993 John Gummer, then environment secretary, gives permission for Thorp to start on the basis of a report by Touche Ross that it would be profitable. Last year, *The Independent on Sunday* revealed this report had never existed. Thorp begins operation, but fails to reach targets.

1994 Main raison-d'etre for reprocessing nuclear fuel destroyed when the Conservative government scraps programme of fast breeder reactors, designed to be fuelled by plutonium.

1997 Another disaster for Sellafield. On the day the election is called, Mr Gummmer halts investigation into building a nuclear dump near the the complex after studies show that it is likely to leak.

1998 Britain agrees to cut discharges from Sellafeld to "close to zero" by 2020. Opponents say this would make reprocessing impossible. Ministers are asked to rule on application to start up a new plant at Sellafield to make fuel from plutonium. Opponents say this would put enough plutonium for 550 bombs onto the roads and railways each year.

1999 New German government says it will stop sending spent fuel to Sellafield for reprocessing.

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