Nuclear Energy
Past, Present and Future
Reflections

The whole story of the early days of nuclear research is both an exciting and a sobering one. It shows the thrills and the problems of being the first country in the world to exploit a new technology. Some of the early fears, about the shortage of oil in particular, have proved not to be as urgent as was assumed in 1947. The early pioneers through their wish to create a better world have created an option which now plays a part in global energy production, one which the world may come to value more and more as demand for energy grows, as traditional sources run short and as fears about climate change continue to increase.

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The period since World War II has been one of unparalleled technological change in our society. Advances such as television, computers, new farming and medical techniques, cheap air travel and the proliferation of cars have revolutionised the way we live. One of the new technologies is nuclear energy. Nuclear energy now produces about a third of the electricity in the European Union, where it is the biggest single source of power, and about one sixth of the world’s electricity – a total of over 2,500 TWh per year, rather more than the total amount of electricity that the world was using when Calder Hall, the first commercial-scale power station, began operating in the UK in 1956. (One TWh, or Terawatt-hour, is the equivalent of running one million 1 kW bar-fires for 1,000 hours.)

Nuclear energy can be used in two broad ways: civil and military. In the early days these two areas were closely connected. The civil nuclear energy programme grew out of the nuclear weapons programme, and it is therefore right that we should pay some regard to nuclear weapons.

In the popular mind, the nuclear age began with the bombs at Hiroshima and Nagasaki in August 1945. However, the story is older than that. Radioactivity was discovered in 1896 by Henri Bequerel, and soon afterwards, in 1905, Einstein formulated his famous equation: E=mc² which showed that, in theory, a very small amount of matter could be converted into a very large amount of energy. The challenge was how to do it in practice, but the idea occurred to many – reputable scientists as well as futurologists – that science had now discovered a way of providing unlimited energy.
Nuclear fission

Nuclear power depends on a phenomenon known as fission.

Everything in the universe is made up of ‘atoms’. At first scientists thought that atoms were the smallest fragments of anything that could exist – the word derives from the Greek word meaning ‘indivisible’. In fact, we now know that atoms themselves are made up of smaller components – a very dense nucleus, made up of ‘protons’ which have a positive electrical charge and ‘neutrons’ which are uncharged, surrounded by a very much lighter cloud of ‘electrons’, which are negatively charged.

The chemical behaviour of matter is determined by the electrons, but here we are much more interested in changes in the nucleus. Hydrogen is the lightest atom, consisting of just one proton (and one electron), while uranium is the heaviest naturally occurring atom, its nucleus consisting of 92 protons and a variable number of neutrons (146 and 143 in the two commonest forms, known as uranium-238 and uranium-235).

In recent years, a number of other atoms, which do not occur naturally on earth, have been produced, of which perhaps plutonium, with 94 protons and usually 145 to 148 neutrons, is the most well known. There are always a small number of free neutrons around in the environment, some of which come from outer space.

Usually when neutrons strike the nucleus of an atom, they either just bounce off or they become absorbed by the nucleus in question. However, the nuclei of a very small group of large atoms, such as ‘uranium- 235’, behave in a very different way if a neutron strikes them while moving at the right speed.

These easily fissionable (or fissile) materials break up into two smaller atoms, giving off two or three more loose neutrons and a quite extraordinary amount of heat. This process is called ‘nuclear fission’. In principle, each of the neutrons which are produced could then hit another uranium atom and cause another fission, so creating a chain reaction.
set up. The UK government announced the intention to build an Atomic Energy Research Establishment at Harwell in Oxfordshire, and a number of other sites were devoted to the nuclear programme, notably Windscale in Cumbria.

The first UK research reactor – in fact the first in Europe – the Graphite Low Energy Experimental Pile (GLEEP) at Harwell started up in 1947, and in the same year work began on two air-cooled plutonium producing reactors (or piles) at Windscale. These began production in 1950 and 1951 respectively, but were never designed to produce electricity.

In 1949 it was decided that the next plutonium producing reactors, to replace the Windscale piles in due course, should also be capable of generating electricity. This decision marks the start of civil nuclear energy in Britain. The first of four such reactors, which were built at Calder Hall near Windscale in Cumbria, was opened by the Queen in 1956. Four more were constructed at Chapelcross, 70 miles away in Dumfries and Galloway, and opened in 1959. Calder Hall and Chapelcross had long and successful operating lives (for most of which they were used solely as electricity producers) until closure in 2003 and 2005 respectively.

If we do nothing to control the reaction and there is sufficient uranium-235 present, then in some circumstances it might accelerate rapidly. One fission may produce three neutrons, which could, in theory, cause three more fission reactions, giving nine neutrons, which could cause nine more fissions giving twenty-seven neutrons, and so on. This is in effect what happens in an atom bomb. In practice, quite a few of the neutrons are lost at the edges of the material or absorbed harmlessly by other material present. (In a nuclear power reactor, for example, quite a lot of neutrons are absorbed by the more passive kind of uranium, known as uranium-238, which makes up the main part of the fuel.)

If, on the other hand, all the neutrons get lost or are absorbed somehow, the reaction will stop altogether. The interesting case from the point of view of power production is when all of the neutrons from each fission are absorbed except for one. This one will cause one more fission, and one neutron from this will cause one more fission, and so on. So it is possible to have a controlled fission reaction which will go on for as long as there is enough fissile material present. This is the process that occurs in a nuclear power reactor.

The phenomenon which is now known as fission of uranium was first reported in Berlin in December 1938. Four years later, on 2nd December 1942, the famous Italian-American physicist Enrico Fermi started the world’s first fission reactor in a Chicago squash court, and it is perhaps this moment that can most fairly be called the beginning of the nuclear age.

Post-war developments

The remarkable developments of the seven years from 1938 to 1945 could perhaps only have been achieved under wartime conditions. However, the ending of the war did not seem to result in any slowing of the pace of research. By the end of 1945 the Canadians were running a research reactor and the French Commissariat de l’Energie Atomique (CEA) had been...
How fission reactors work

The centre of a nuclear power station is the nuclear reactor. Uranium or plutonium fuel is formed into fuel rods which are arranged within the reactor ‘core’ to ensure that enough neutrons are captured by the uranium to establish a fission chain reaction. The neutrons released during fission move so quickly that they tend to bounce off other uranium atoms, so the fuel rods are surrounded by a ‘moderator’ to slow them down. This is usually water or graphite.

The amount of energy released inside a nuclear reactor can be controlled by using ‘control rods’. These are made from substances such as boron steel or silver and fit between the fuel rods. They can be lowered or raised. These control rods absorb neutrons, so lowering them reduces the number of neutrons available to cause fission of uranium. If they are lowered completely, the reactor will shut down. The heat energy released by the nuclear fission process is continually removed from the reactor core by a ‘coolant’. The coolant flows at a high temperature from the core to a heat exchanger (or ‘boiler’), where it converts water into steam.

The most common coolants are:

- ‘light’ water, used in most of the world’s reactors
- pressurised carbon dioxide gas, used in British Magnox and Advanced Gas-cooled Reactors (AGRs)
- ‘heavy’ water, used in the Canadian CANDU® design
- helium, not used today, but which has the advantage that it can be used to drive a turbine directly and does not require a boiling water stage, so making it more efficient

From this point onwards, nuclear reactors are just like coal-fired or gas-fired power stations – the steam (or hot helium) goes to drive large wheels called turbines – and the electricity that is produced is exactly the same. Uranium is an extraordinarily efficient fuel – one tonne of uranium fuel used in a modern nuclear reactor (without recycling) produces the same amount of electricity as about 20,000 tonnes of coal.
Unfortunately, the smaller atomic fragments from the process - known as ‘fission products’ - are highly radioactive, so the used or ‘spent’ fuel needs careful handling. Radioactive waste management is discussed in the booklet *Nuclear Energy in the Environment*, and the effects of radiation are considered in *Radiation, Health and Nuclear Safety*.

**The first UK nuclear energy programme**

In 1955 the first phase of the UK nuclear energy programme was announced, based on a gas-cooled, graphite-moderated reactor in which the fuel was kept in a non-oxidising magnesium alloy (Magnox) can. Apart from Calder Hall and Chapelcross, the UK Magnox programme consisted of nine stations, each consisting of two reactors, with a combined capacity of over 4,000MW. Construction of the first two, at Berkeley (Gloucestershire) and Bradwell (Essex), began in 1956; the last, at Wylfa, on the Isle of Anglesey was commissioned in 1971. The first closure came in 1989, and the rest will be closed by 2010. In addition, two Magnox stations were exported, to Japan and to Italy, though both have now been stopped operating.

It was declared at the outset that electricity generated from Magnox stations would be more expensive than that generated by burning coal. However, a number of factors combined to make nuclear energy attractive at that time. There was recognition of the importance of developing new ways of making energy, a topic discussed in *Energy, Society and the Nuclear Alternative*. It was also believed that in due course nuclear energy would become rather cheaper than other options (with the exception of hydropower). All of this was before the discovery of North Sea oil and gas. Furthermore, nuclear energy was seen as being rather kinder to the environment: in 1952, less than five years before the opening of Calder Hall, the great London smog, caused by burning coal in the capital, had killed 3,900 people in a fortnight. There was also a determination among scientists that the potentially devastating destructive force of the atom which had been unleashed should be balanced by using this energy as a force for good.

In 1957 there was a fire in one of the military plutonium piles at Windscale. Both Windscale piles, which were reaching the end of their design lives,
were closed down after the incident, and in 1959 what is now the Nuclear Installations Inspectorate (NII), part of the Health and Safety Executive, was set up as the independent government watchdog on the industry. Though the Windscale fire did relatively little real damage, it did mark the end of the early euphoria which had accompanied developments up to that point.

The second UK nuclear energy programme

By the late 1950s, with the Magnox programme under construction, the UKAEA turned its attention to a successor. This heralded a time of many different research programmes, but the logical progression from Magnox seemed to be the Advanced Gas-cooled Reactor (AGR), which, rather than using natural uranium metal, used a ceramic fuel in which the proportion of the active uranium-235 was increased from natural levels of 0.7% to around 3% in a process called ‘enrichment’. This both reduced the amount of fuel needed, and therefore waste produced, per unit of electricity manufactured, and allowed the reactor to operate at a higher temperature, which is more efficient.

Seven AGR stations were built in the UK to four different designs. Experience of the programme has been very mixed – most have operated reasonably well, although the first, Dungeness B, ordered in 1965, only began working properly in 1993, and ran heavily over time and cost, while others had a slow start. After a good period the programme was to run into further technical difficulties in the first decade of the 21st century.

In fact, the UK was the only country which pursued gas-cooled reactors at this stage. Most countries, including France and Japan, chose to follow the US lead and use ordinary water as the cooling agent in their reactors, mainly in pressurised water reactors (PWRs) or in boiling...
water reactors (BWRs). The UK therefore found itself rather isolated from the global mainstream. One result was that the costs of building were higher, as very few individual units were built compared to PWR or BWR; another was that there was no international experience of solving the kind of operating problems that might arise with AGR technology.

Prevention of nuclear weapons proliferation

The United States’ monopoly in nuclear weapons at the end of the Second World War did not last long. The Soviet Union, in 1949, and the UK, in 1951, carried out nuclear weapons tests, and there were fears that nuclear weapons would spread. Yet at the same time, the potential benefits of nuclear energy were becoming clear. President Eisenhower’s famous ‘Atoms for Peace’ speech to the UN General Assembly in December 1953 led to the first effective step in the drive to allow countries to develop nuclear energy if they wished, while at the same time limiting the spread of nuclear weapons. This was the founding of the International Atomic Energy Agency (IAEA), based in Vienna in 1957. Any country which was a member of the IAEA would be offered help in developing nuclear energy, but would have to promise not to develop nuclear weapons if it did not already have them. The IAEA established a system of ‘safeguards’ and employed inspectors to check that countries were sticking to this promise.

Successful as the IAEA’s programme of safeguards was, fears remained. They were fuelled by concerns about the effects of carrying out nuclear weapons tests above ground level, and by the deepening of the Cold War, the most notable nuclear scare being the Cuban missile crisis in 1962. Further efforts to control the arms race led to the Nuclear Non-Proliferation Treaty (NPT) coming into force in 1970. The NPT accepted that there were five countries with nuclear weapons (the ‘Weapons States’) at that time, including France which tested a nuclear device in 1962, and China in 1964, but declared a goal of preventing any more from joining them. By signing the Treaty, a country agrees to allow IAEA weapons inspectors to check as often as they think fit that material or equipment from nuclear energy programmes are not being diverted towards military uses. The Weapons States were ‘to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament’.

At first the NPT had its critics. It treated the countries which already had nuclear weapons differently from those which did not, and there was suspicion that inspectors might gain access to issues of vital national security. However, things improved with the success of the Strategic Arms Limitation Talks (SALT) in the 1980s and the end of the Cold War after the collapse of the Soviet Union in 1989–90. France and China both signed the Treaty in 1992. By the start of the new century only India, Pakistan, Israel and Cuba (which later joined) were not signatories. In 2002 North Korea became the only country to withdraw from the NPT. The NPT has been very successful in preventing the spread of nuclear weapons. At the time of the Cuban missile
The relationship between the uses of nuclear science for energy and for weapons is a complex one. Both are based on the fission of uranium, although nuclear fuel is very different from ‘weapons grade material’ and it is a difficult (and easily detectable) industrial process to convert one into the other. It follows that it is perfectly possible for a country to have nuclear energy without nuclear weapons, or vice versa. In fact, four of the five weapons states developed their nuclear weapons well before using nuclear power (the exception being France), and in three cases before there was any nuclear electricity anywhere in the world. There are many countries with nuclear power stations (Belgium, Canada, Brazil, Germany, Sweden, Japan and South Korea, to name just a few) and no nuclear weapons. In practice, all the countries which have developed nuclear weapons have done so through a specific programme largely unconnected with the use of nuclear energy. Ever since they started, the IAEA’s inspectors have had great success in limiting the spread of nuclear weapons or the use of nuclear energy materials for military purposes. However, in the new century, attention has to an extent turned to preventing countries or terrorist groups getting hold of highly radioactive materials, say from hospital radiology departments or from old research reactors, and releasing them in such a way as to threaten people’s health or peace of mind. Though not connected with the use of nuclear energy, these threats are likely to require IAEA involvement for the foreseeable future.

Types of reactor

As noted earlier, gas-cooled reactors have produced most of our nuclear electricity in the UK. Magnox reactors and AGRs are cooled by carbon dioxide and moderated by graphite.

However, gas-cooled reactors only make up about 8% of the world’s nuclear capacity today. The Pressurised Water Reactor (PWR) is the most common nuclear reactor design used in the world (accounting for over 60% of the world’s nuclear power stations), and the UK’s only PWR so far built is at Sizewell B in Suffolk. PWRs use water as both coolant and moderator. Water is...
pumped under high pressure (to prevent boiling) through the core of the reactor, reaching a high temperature. It is then used to boil other water in a separate circuit, to make steam.

There are other types of reactor in use in the world today. Boiling Water Reactors allow the water to boil in the reactor circuit and drive turbines directly without using heat exchangers and a separate water circuit. There are other types of thermal reactor, like the Canadian-designed CANDU®, and the RBMK, a design unique to the former Soviet Union which became infamous after the accident at Chernobyl in 1986.

Until 1994 an experimental ‘fast reactor’ operated at Dounreay in Scotland. Fast reactors use a plutonium-uranium mix of fuel, produced from the reprocessing of used reactor fuel from normal (‘thermal’) reactors. Because there is no need for moderators to slow neutrons down (hence the name ‘fast’ reactor), these reactors can be more compact, and they are more fuel-efficient than thermal reactors. They can be used to ‘breed’ more plutonium from otherwise useless uranium-238, but can also be used as a net plutonium burner. Fast reactors could, for example, be used to destroy the world’s stockpile of military plutonium. However, they are rather more expensive to build than thermal reactors. Few operational fast reactors have been built (in France, Japan, the UK, Germany and the former Soviet Union) and global experience has been generally disappointing, although countries like Japan, India and Kazakhstan remain committed to their development.

Uranium resources

Uranium was discovered in Germany in 1789. For a hundred and fifty years no large-scale constructive use was found for it and so little effort was put into finding new reserves. At the time its uses as a fissile material were first recognised it was assumed that uranium was a very rare element. In fact this proved not to be the case – it is commoner for example than tin or zinc. Furthermore it is much more widely distributed than
oil or gas, being found in countries and areas as diverse as the USA, Canada, Australia, the former Soviet Union and south and west Africa. There were once uranium mines in Cornwall.

Even were nuclear energy use to increase significantly known uranium reserves would last around 100 years. As the price rises the incentive for looking for more grows and it is likely, if uranium proves to be like the vast majority of other minerals, that there are very major deposits still to be detected.

If the uranium price does increase significantly, the cost of electricity generated in nuclear power stations does not increase proportionately. Unlike, say, electricity generated using gas, where most of the cost is the cost of the gas itself, uranium represents a very small proportion of nuclear generating costs (typically below about 3%) so rises in the cost of the fuel are less important.

Reprocessing

When ‘spent’ nuclear fuel comes out of the reactor it consists of about 96% unused uranium, 1% plutonium which could be used in other kinds of fuel, and about 3% highly active waste products (‘fission products’) and heavy metals.

There are two broad options – either the spent fuel can be stored with a view to disposing of it as it is, or it can be recycled into its separate components. As with all recycling, there are arguments for and against.

Initially, reprocessing was introduced to extract plutonium from spent nuclear fuel for use in nuclear weapons. It was also recognised that spent Magnox fuel, made mainly of natural uranium metal, could not be stored under water for long periods of time (as was then the practice) as it would corrode. In principle, reprocessing reduces the amount of fresh uranium which has to be mined, so extending the lifetime of uranium reserves and reducing local environmental impact. Reprocessing also cuts the volume of highly radioactive material for eventual disposal.

Against it, reprocessing involves the use of chemicals and plant which become contaminated with radioactivity and causes emission of radioactive materials into the environment (although recent technological advances have reduced such emissions a hundred fold to very low levels). It also produces free plutonium which could represent a risk regarding the proliferation of nuclear weapons. It was initially assumed that plutonium would be needed to fuel a growing number of fast reactors, but this has not so far proved to be the case, both because there is more uranium than was realised and because the growth of nuclear energy lowered significantly in the 1990s and early 2000s. Another way of addressing the issue would be to convert plutonium into mixed oxide fuel (MOX) as soon as it was separated. MOX can be used in pressurised water reactors as an alternative to fresh uranium fuel.
Several countries have licensed reactors to use MOX fuel, notably France which has over 20 reactors so licensed.

Finally, reprocessing does involve costs and therefore its economics depend on the price of fresh uranium. For much of the 1990s and early 2000s the uranium price was low, by historical standards, but it increased in the middle and early years of the new century to levels which caused some countries to look again at reprocessing as an option. This being said, as noted earlier, increases in uranium prices have less of an effect on the costs of generating electricity than increases in coal or gas prices.

Since there are arguments for and against, some countries have decided to pursue a reprocessing route and some have not. The USA, since the Carter administration (1977–81), has exerted considerable pressure on countries not to reprocess spent fuel, for fear of it helping countries to develop nuclear weapons, although recently there has been a debate about reversing this stance. The UK is one of a small group of countries, France being the main competitor, which can offer the business of reprocessing to other countries through the facility at Sellafield in Cumbria, owned by the Nuclear Decommissioning Agency (NDA). In all contracts signed since 1976, the country which owns the fuel will eventually have to take away all waste products, as well as the reusable uranium and plutonium.

**Liberalised energy markets**

In the 1980s it was decided to turn to the PWR for the next stage of nuclear development in the UK. The government of the day had plans for a family of four identical PWRs, the first of which, Sizewell B in Suffolk, began operating in 1995. Planning permission for a second, Hinkley Point C in Somerset, was granted in 1990.

However, there were significant developments elsewhere which were to affect the nuclear industry. The two most important were the development of the combined-cycle gas turbine (CCGT) which allowed vast, newly discovered gas reserves to be converted into electricity far more cheaply than had previously been the case; and the introduction of competition into the electricity supply industry.

After the oil price shocks of the 1970s, fuel prices had fallen significantly, in part because of significant oil discoveries outside the OPEC region. There were also major new discoveries of natural gas. As a result, governments in many countries no longer felt that secure energy supplies were under threat, and turned their attention to other aspects of energy policy, and especially to reducing energy costs. The Europe-wide ban on using gas for electricity was lifted in 1990, and private companies in competition replaced the state owned electricity monopolies like the Central Electricity Generating Board (CEGB) in the UK.

The monopolistic CEGB had been given a duty to supply power to any consumer who required it, in return for being able to pass the costs of an investment needed on to their captive customers. The CEGB had proved very effective in keeping the lights on, for example, during the miners’ strike of 1984–5 and after the storms of 1987. However, the government of the day believed that power costs were higher than they should have been because of the absence of competitive pressures, which meant that the CEGB did not necessarily operate as efficiently as possible. The CEGB was therefore broken up into four parts. Two companies with fossil-fuel power stations were privatised in 1990, but the nuclear industry remained in state hands until 1996, when the AGRs and Sizewell B
were privatised. (The National Grid, which had been part of the CEGB, was separated from the generation of electricity and became an independent company). The Magnox stations were not privatised, as they were near to the end of their lives. There would not be enough time to raise the finances needed to deal with their decommissioning and waste management costs, which are high, before they closed down. (As might be expected for the world’s first attempt at nuclear power stations, they were not as efficient as modern nuclear stations like Sizewell B, and therefore produced considerably more waste per unit of electricity than did their successors.)

In 1989 the plans to build more nuclear stations, including Hinkley Point C, were in effect abandoned. This was partly as a result of the disappointing experience of nuclear construction projects in some countries, but also because of changes in the electricity supply market. The accident at Chernobyl in 1986 undoubtedly had important repercussions as well.

In the CEGB days, investment in nuclear energy looked attractive. Nuclear plants did not use much fuel – a tonne of uranium fuel in an AGR is worth about 20,000 tonnes of coal – so their costs would not go up much if fuel costs went up. As previously noted, instead of being concentrated in a small number of countries, global uranium reserves are widespread, being found for example in the USA, Canada, Australia and Africa, so it was unlikely that supplies would be disrupted. Nuclear stations did not contribute to acid rain, one of the main environmental concerns of the 1970s and 1980s. And although it was expensive to build the stations, this investment could be recouped over a long period of time, as customers could not go anywhere else for their power.

The introduction of competition had two important effects. First, because nobody had a guaranteed market, investment was more risky in an economic sense. So instead of potential investors being happy with a 5% rate of return on their very safe investment, as they would have been in the monopoly days, they began to demand higher rates of return – 10% or even more. This is more damaging to a technology which is expensive to build but relatively cheap to run, nuclear energy, than it is for one which is cheap to build but more expensive to run, like CCGT. Second, since nobody has a guaranteed market at attractive prices for their output for very long, investors want their money back as quickly as possible. CCGTs can be built in 18 months (as opposed to about five years for a traditional nuclear station) at about a quarter to a third of the cost, so the financial risk to the investor is far less, even though they are more expensive to run. As a result, investment in traditional nuclear power plant declined radically in the developed world, although in countries like those of the Asia-Pacific region, with growing demands for electricity and problems in providing enough coal from their distant coal fields, nuclear investment continues to look attractive.

However, the introduction of competition into power markets has also had benefits for nuclear energy. Under the discipline of liberalised markets, the output from the UK nuclear power stations has increased significantly (though subsequent technical problems reversed this trend to an extent) Globalisation of nuclear energy markets raises the possibility of an international market in plant designs and components, rather than each country ploughing its own path at greater expense. And the plant designers themselves have responded to changing market conditions by developing simpler nuclear designs, which will both be cheaper and quicker to build and more reliable, especially in the early days of operation, than previous models. By 2009 two designs had emerged as candidates for a new programme of nuclear stations in the UK - the evolutionary power reactor (EPR) from EDF/Areva (France/Germany) and the AP1000 PWR from Mitsubishi/Westinghouse (Japan/USA). Nuclear stations with many of these features have been built successfully in the Asia-Pacific region, and the plant sellers believe that a series of new nuclear power stations could produce electricity as cheaply as CCGTs using moderately priced gas. Companies also came forward wishing to pay for new build. French power
firm EdF bought British Energy, the main nuclear generating company in the UK, in 2008, while European giants like RWE and E.On (Germany), Vattenfall (Sweden), GdF Suez (France) and Iberdrola (Spain), as well as UK-owned Scottish & Southern electricity, all announced interest in funding a new programme of nuclear stations in the UK.

Future developments

The global experience of liberalisation has been mixed. In some cases competitive markets do seem to have delivered lower power prices, but not in all. Major power cuts in several industrial countries and states (including Australia, California, Scandinavia, Germany, New York, Canada, the UK and Italy) have raised some concerns about whether liberalised markets can deliver reliable power supplies. In the UK, power prices fell so low in the early years of the new century that it proved very difficult to make a reasonable living even out of running existing plants, and there were certainly no spare resources to invest in new ones – hardly any new power stations of any description were opened between 2000 and 2008. Many power companies, including nuclear operator British Energy, faced financial problems at that time. However, power prices rose considerably in the middle years of the decade and interest in building new plants, including nuclear power stations, returned.

There is also a question over how to ensure that environmental objectives are met. Renewable operators are being offered very large subsidies, but even these may not be enough to encourage the enormous levels of investment needed to reach government targets. Furthermore, our ‘baseload requirements’ – the need for electricity to run our water systems, railways and so on – need to be served by sources of energy we can rely on and which will not be unavailable, say, if the wind is not blowing at the right speed, the sun is in or the tide is out. For baseload the real choice is likely to be between coal or gas – both major sources of greenhouse gases - or nuclear.

Given these uncertainties, several commercial companies expressed an interest in investing in a new programme of nuclear power stations. In 2008 the British government announce that it would not stand in the way of these companies and that planning and licensing of new plants could begin as soon as the resources were in place. A similar revival of interest was seen in a range of other countries, notably the USA, Finland, France and Canada, as well as others which had not previously used nuclear energy.

Fusion

What about the longer-term future?

Fusion is the opposite of fission, joining light atoms together rather than splitting heavy ones apart. The sun and stars are powered by fusion.

We can reproduce the effect on earth by bringing together two forms (or ‘isotopes’) of hydrogen called deuterium and tritium. The nuclei naturally want to push away from each other because they are both positively charged and repel each other. But if the isotopes are heated to temperatures of millions of degrees – much hotter than the surface of the sun – there is enough energy to force nuclei so close together that they fuse.

At very high temperatures matter turns into a new form known as ‘plasma’, where the electrons are stripped away from the nuclei. Plasma cannot be held in a normal container, so the mixture has to be held in what is called a ‘magnetic bottle’, a very strong magnetic field which prevents it escaping. The mixture is heated with a blast of electric current, and at a certain point the nuclei begin to fuse. The products of this fusion are nuclei of helium atoms and neutrons which travel extremely fast (at speeds comparable to the speed of light). The trick will be to capture these neutrons and use their energy to create electricity. If a substance like lithium is used to trap the neutrons, tritium is produced which can be used as fuel for more fusion. In due course fusion could, in theory, become another energy option to go alongside fission, renewables and fossil fuels. Deuterium is very
widespread in nature, and is found anywhere there is water. Lithium exists in rocks almost everywhere – the name is derived from the Greek word for ‘stone’. Tritium is expensive to make at present but, as noted above could be produced by neutrons hitting lithium atoms.

Fusion offers striking advantages. At any moment a fusion reactor would only require very small amounts of fuel – all of it could escape without being detectable nearby, so there isn’t even a theoretical danger of a major accident such as a ‘melt-down’. There is no long-lived radioactive waste, although the reactor itself does become radioactive over time. And like nuclear fission, it will not contribute significantly to climate change or rely on limited fossil fuels with other potentially beneficial uses.

Research into fusion is well established – the European project, JET (Joint European Torus, the last word referring to the doughnut-shaped reactor) was established in 1978 at Culham in Oxfordshire, and there have been major ventures in the USA, Japan and Russia. These projects have proved that fusion can be made to happen on earth – in other words they have demonstrated the physics of the process.

However, that is not the end of it. Indeed, engineers often claim that ‘the science is the easy bit!’ The next stage will be to develop and build a design which can sustain a self-supporting fusion reaction (so far all terrestrial fusion which has taken place has absorbed more energy than it has produced, simply because the reactors are too small for self-sustaining reactions), and which can then generate electricity. This stage will be known as International Thermonuclear Experimental Reactor (ITER). In 2006 it was announced that the project, expecting to cost some $10 billion and be carried out over 30 years, would be based at Cadarache in France with a major support facility at Rokkasho in Japan. Initially there were seven partners – China, the European Union, India, Japan, the Russian Federation, South Korea and USA, with other countries showing an interest in joining in due course. However, late in 2007 the US Congress cut the US contribution to the project.

Assuming the engineering challenges can be met, it will then be necessary to build a commercial prototype which will reveal the economics of the technology. It is far too early to speculate what the results may be, and even if a commercially attractive design should then be available, it would take some time before it established itself as a major source of world energy. Many people today believe it unlikely that fusion will be a major contributor by the year 2050, but it could become an important source of power after that if the technical and economic challenges can be met.
Glossary

AECL Atomic Energy of Canada Limited, a nuclear design and engineering company which owns the CANDU® design.

AGR Advanced gas-cooled reactor, used in UK.

AP1000 BNFL-Westinghouse’s Advanced Passive 1000 MW reactor design.

Atoms Building blocks of nature, made up of protons, neutrons and electrons.

BNFL British Nuclear Fuels plc, a UK company which offers nuclear fuel cycle and plant design services.

British Energy A private company which owns the UK’s AGRs and PWR.

BWR Boiling water reactor.

CANDU® A Canadian reactor design using heavy water as moderator and coolant.

Chernobyl Site in Ukraine of the world’s worst nuclear accident in 1986.

Coolant Material, such as water or pressurised gas, that transfers heat from the core of a reactor to the boilers to make steam.

CCGT Combined-cycle gas turbine for making electricity from natural gas.

CEGB Central Electricity Generating Board, broken up in 1990.

Deuterium An isotope of hydrogen with one neutron as well as one proton.

Electron A very small negatively charged particle which surrounds the nucleus of an atom, and can also exist in a free state for short periods of time.

Fast reactor A type of nuclear power reactor which uses plutonium and ‘fast’ (not moderated) neutrons.

Fission Splitting large atoms up into smaller atoms, producing free neutrons and large amounts of energy.

Fission products The smaller atoms produced when a large atom undergoes fission.

Fossil fuels Coal, oil and gas.

Fusion The joining up of atoms such as hydrogen, producing vast amounts of energy – the source of energy from stars.

Heavy water A form of water in which normal hydrogen is replaced with heavier deuterium, which is used as a moderator and coolant in CANDU® reactors.

Isotopes Atoms of the same element which have the same number of protons but different numbers of neutrons.

ITER International Thermonuclear Experimental Reactor, the next stage in fusion research.

JET Joint European Torus fusion research programme based in Culham, Oxfordshire.

Magnox The first commercial nuclear reactors built in the UK, named after the non-oxidising Magnox alloy used for the fuel cans.

Moderator A substance which slows neutrons down in a thermal reactor.

NDA Nuclear Decommissioning Agency. The government’s body for dealing with ‘legacy wastes’, the waste created by the early years of nuclear technology in the UK, arising from decommissioning these facilities.

Nucleus The very dense centre of an atom, consisting of protons and neutrons.

Neutron Uncharged particles found in the nucleus of atoms, which can cause fission in some atoms.

NII Nuclear Installations Inspectorate (UK).

OPEC Organisation of Petroleum Exporting Countries.

Plutonium An element which is not found in nature, but which is formed in a nuclear reactor and can be used to make energy.

Proton Positively charged particles found in the nucleus of atoms.

PWR Pressurised water reactor.

Radiation Particles of energy given off by the nuclei of unstable atoms.

Radioactivity The process of emitting radiation.

RBMK A Russian water-cooled graphite-moderated reactor design which suffered a major accident at Chernobyl but which was never built outside the former Soviet Union.

Reactor A plant in which reactions take place to produce heat and electricity.

Reprocessing Recycling of spent nuclear fuel into reusable uranium, plutonium and fission products.

Spent fuel Fuel which has been used in a nuclear power station and contains plutonium and waste products as well as unused uranium.

Thermal reactor A reactor which uses moderated neutrons, e.g. AGR, PWR, Magnox.

Tritium An isotope of hydrogen which contains two neutrons as well as one proton.

UKAEA United Kingdom Atomic Energy Authority.

Uranium The heaviest known naturally occurring element, consisting of two isotopes: uranium-235, which undergoes fission, and uranium-238 which does not.