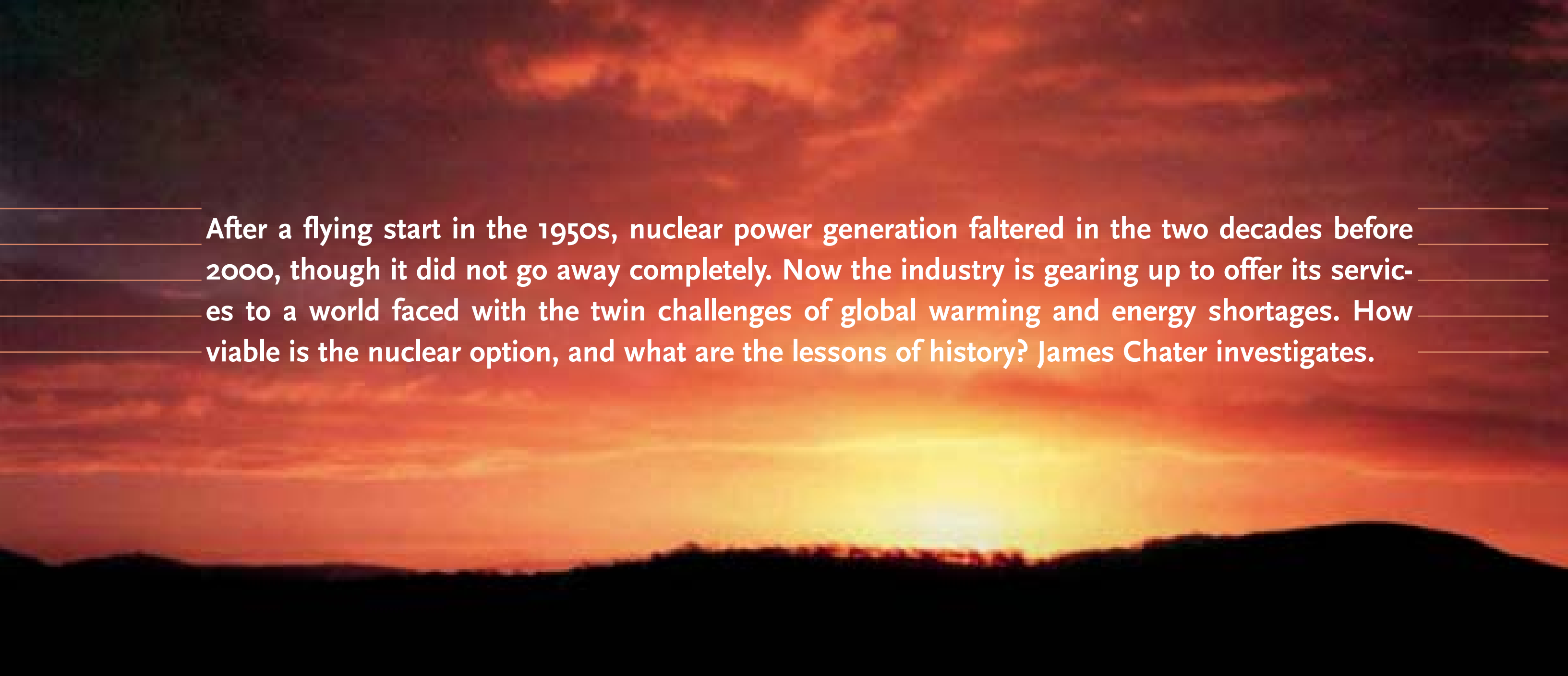

After a flying start in the 1950s, nuclear power generation faltered in the two decades before 2000, though it did not go away completely. Now the industry is gearing up to offer its services to a world faced with the twin challenges of global warming and energy shortages. How viable is the nuclear option, and what are the lessons of history? James Chater investigates.

A history of nuclear power

By James Chater

"Think of me ten per cent," says the nuclear plant engineer to the journalist in "The China Syndrome", the 1979 film starring Jack Lemmon and Jane Fonda. This referred to the percentage of energy derived from nuclear power in the USA at the time the film was released; now it is more like 20 per cent. In the rest of world, too, reliance on nuclear power has been increasing. Several industrial countries have come to depend on it for at least part of their energy supply. Nuclear power and the technology behind it are inextricably bound up with several scientific and social developments in the twentieth century: not only power generation, but also medicine, warfare and a number of other applications. After massive growth in the period 1960s and 1970s, the nuclear industry fell out of favour for two decades, mainly because of safety and cost considerations. But with mounting concerns about global warming and a possible energy crunch, nuclear is back on the agenda. How viable is the nuclear option? What mistakes were made, and what lessons have we learnt? By examining the past and projecting into the future, we may hope to attempt some answers.

Hidden powers

The first nuclear accident was the discovery of radioactivity. As far back as 79AD pottery makers used uranium oxide to give a yellow tint to their ceramic glazes, but for centuries uranium's properties remained unknown. Its radioactive properties were discovered by accident. Antoine Henri Becquerel was carrying out some experiments with fluorescence and phosphorescence when in 1896 he made a remarkable discovery: after putting some wrapped photographic plates away in a darkened drawer, along with some crystals containing uranium, he found the plates had been exposed by invisible emanations from the uranium. Becquerel's accidental discovery was termed "radioactivity" by his successor, Marie Sklodowska Curie, who together with her husband Pierre Curie investigated the properties of uranium and discovered other radioactive substances such as polonium and radium. Marie hypothesised that the emission of rays by uranium compounds could be an atomic property of the element uranium. This and the contemporary discovery of the electron – which showed that the atom was divisible – triggered a revolution in physics. After Pierre's death in 1903 Marie took over her husband's teaching job at the Sorbonne, the first female teacher in its 650-year history. Marie Curie gave her life to her work in a literal sense: she died in 1934, probably from the effects of radiation.

Moonshine?

The discoveries of Marie and Pierre Curie had wide ramifications, leading to advances in, for instance, medicine and geology. But the most far-reaching developments in atomic research came from Ernest Rutherford. Together with Frederick Soddy, Rutherford showed that elements such as uranium and thorium became different elements through the process of radioactive decay. He worked out the planetary structure of the atom (work later built on by the Danish physicist Niels Bohr), and was able to demonstrate the enormous, hitherto undreamt of power of the atom. Interestingly though, Rutherford was sceptical about nuclear power. In 1933 he wrote: “The energy produced by breaking down the atom is a very poor kind of thing. Anyone who expects a source of power from the transformations of these atoms is talking moonshine.”

Fission

Contemporary newspaper accounts talked of Rutherford having “split the atom.” However, actual nuclear fission was first achieved only in 1938, one year after Rutherford’s death. Two German physicists, Otto Hahn and Fritz Strassman, bombarded the nucleus of a uranium atom with neutrons, causing it to split and release energy. From there it was but a small step to start a chain reaction, and therefore to build a powerful bomb. A year later the world was plunged into World War II, and the USA and Germany raced to build the first atomic bomb. Alfred Einstein, whose own researches had provided a theoretical framework for the atomic bomb, warned President Roosevelt that it would soon be possible to build a nuclear bomb. As a result, a massive research and product pro-

Marie Sklodowska Curie

gramme was launched, the Manhattan Project. Enrico Fermi demonstrated the first self-sustaining nuclear reaction, while a team of scientists led by Robert Oppenheimer built and tested the first nuclear bomb at Los Alamos, New Mexico, USA. Sites were set up to produce refined uranium and plutonium. The net result of all this activity was the manufacture of the atomic bombs dropped on Hiroshima and Nagasaki in 1945.

The nuclear age

The bombs’ devastating effects cast a fearsome shadow over the new era of peace and prosperity. This fear was intensified by the spread of nuclear secrets to Russia and China, anti-Communist paranoia, Cold War tensions and the increasing power of the secretive military-industrial complex. Secrecy was indeed the order of the day: in the UK Clement Atlee’s Labour government (1945-51) built an atomic bomb without informing or even seeking the approval of Parliament.

Nuclear science had started to develop its own momentum, and East-West rivalry fuelled an arms race which international treaties have slowed down but failed to stop. The 1950s saw the further testing and the spread of the atomic bomb and the invention of the hydrogen bomb, developed by Edward Teller from the principle of nuclear fusion. Two military developments with important implications for power generation were the nuclear submarine and the nuclear-power aircraft carrier. Both of these used the Pressure Water Reactor or PWR, which was to become the most widely used reactor type in civil nuclear power.

Birth of nuclear power

In 1953 President Eisenhower addressed the United Nations in 1953 in his “Atoms for Peace” speech, calling for international co-operation in the development of nuclear technology for peaceful purposes. Even as he spoke, the Soviet Union, the UK, the USA, France and Canada were already busy developing their nuclear power programmes out of their weapons programmes. The Soviet Union developed the RBMK (“very powerful reactor of the channel type”) – a graphite-moderated, water-cooled reactor fuelled by natural uranium – and in 1954 a power plant of this type was connected to the Soviet power

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Crushed uranium ore, also known as “yellow cake” grid at Obninsk, the world's first nuclear power station designed for commercial use. In the West, this kind of reactor has never been considered viable or safe owing to the lack of containment. The reactor that exploded at Chernobyl in 1986 was of this type.

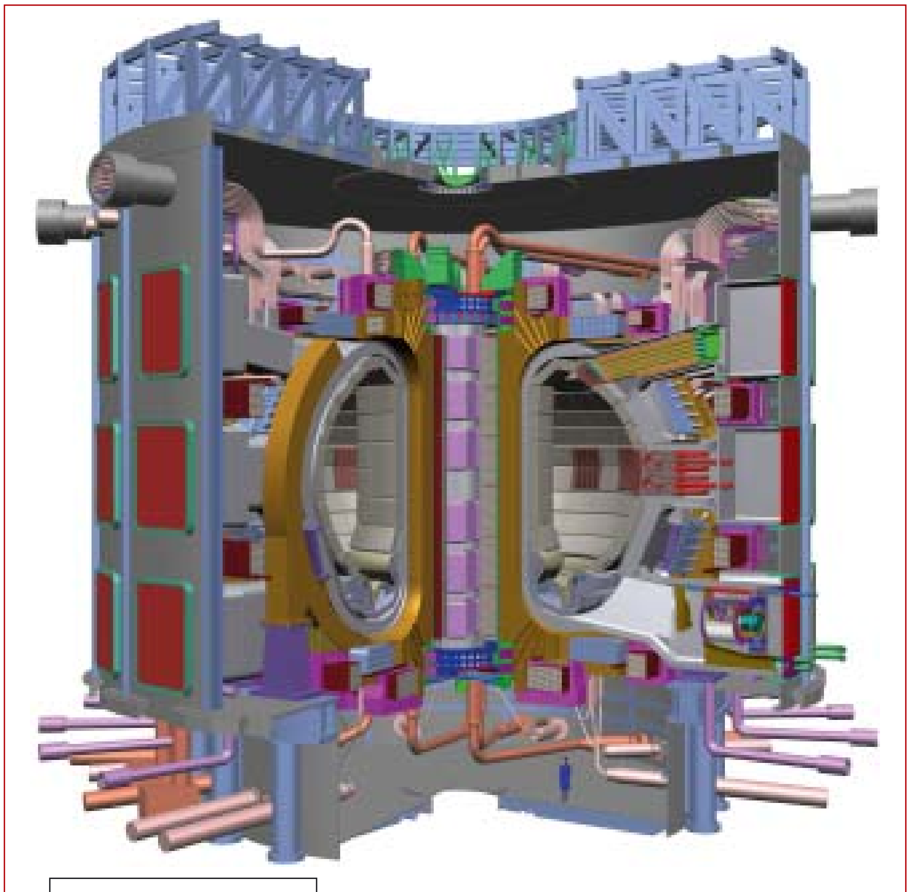
In the UK, plutonium for weapons had been produced at Windscale, Cumbria, in England's Lake district, since the 1940s. (Part of the Windscale site was later renamed Sellafield.) In 1954 the UK Atomic Energy Authority (UKAEA) was set up to oversee the development of nuclear technology. Two years later a power station at Calder Hall, Cumbria, was connected to the national grid. The two reactors at Calder Hall were a prototype of the Magnox gas-cooled reactor, a design which was to be used at 11 power stations in the UK, one in Japan and one in Italy. Magnox, which is short for "magnesium non-oxidising", is a magnesium alloy used in cladding unenriched uranium metal fuel with a non-oxidising covering to contain fission products. Magnox reactors have a graphite moderator and use pressurised CO_2 as the coolant. In 1964 the Magnox design was superseded in the UK by the Advanced Gas-Cooled Reactor (AGR). In the AGR, stainless steel replaced magnox as the material used for the fuel cladding, with the result that higher temperatures and greater thermal efficiency became possible. In the UK seven power stations each using two AGR reactors were built.

The USA set up the Atomic Energy Commission in 1946 with the purpose of both promoting and regulating nuclear power. (The AEC was replaced in 1974 by two bodies, the Nuclear Regulatory Commission and the Energy Research and Development Administration.) The AEC initiated a five-year programme to try out various different reactor designs and from 1954 was allowed to license private companies to build and operate nuclear power plants. In 1957 the Duquesne Light Company began operating the USA's first large-scale nuclear power plant, a PWR, in Shippingport, Pennsylvania.

In both military and power-generation matters, France from 1945 adopted a resolutely independent approach, pursuing its own *force de frappe* outside NATO and developing its own gas-graphite reactor, the UNGC, of which nine units were built. The design was similar to the UK's Magnox, with the difference that the fuel cladding was magnesium-zirconium alloy, not magnox. The first such reactor of this type to go on-line was G-2 (Marcoule), in 1959.

Canada was brought into the nuclear race because of the country's abundant supply of uranium, conveniently located next to the USA. From the

Kashiwazaki Nuclear Power Station, Japan, the largest nuclear power plant in operation today.



Cutaway of the ITER reactor

start, the Canadian nuclear industry was characterised by the use of heavy water, a combination of deuterium and oxygene (D_2O), the first batch of which had been smuggled out of Norway to elude Nazi control. During the war British and Canadian scientists carried out research at the University of Montreal, and as a result various reactors were built using heavy water, notably the NRX reactor at Chalk River, Ontario. In 1952 the Atomic Energy of Canada Limited (AECL) was set up to take over the Chalk River complex and develop the peaceful applications of nuclear energy.

Nuclear fusion

Weaponry, energy and medicine are just three of the ways nuclear energy has affected life in advanced industries. Other applications include smoke detectors, detection of leaks and flaws in welds, prospecting by mining and petroleum companies, food irradiation and long-haul vehicles such as submarines, aircraft carriers, ice-breakers and spacecraft.
One application that could be important for future power generation is nuclear fusion. Although all the electricity currently derived from nuclear power is currently generated by fission, theoretically it should be possible to fuse isotopes of hydrogen to produce helium and energy that could be used for power generation.
Nuclear fusion can be either “hot” or “cold”. Cold fusion was attempted in 1989 two chemists, Stanley Pons of the University of Utah and Martin Fleischmann of the University of Southampton, but attempts to replicate the experiment produced haphazard results, leading many to dismiss the original experiment as flawed. Work on cold fusion continues, however, and has been endorsed by none other than scientist and sci-fi writer Sir Arthur C. Clarke.
A more likely contender is “hot” nuclear fusion, which takes place at very high temperatures inside a ring-shaped chamber called a tokomak, invented in the 1950s by Igor Tamm and Andrei Sakharov as an offshoot of their work on the Soviet hydrogen bomb. Soviet/Russian and western scientists have been collaborating for decades on nuclear fusion. Currently an international team is being assembled at Caradache, France, to build ITER (International Thermonuclear Experimental Reactor). If a self-sustaining reaction can ever be produced economically, fusion promises to be a source of almost unlimited clean, secure energy. However, according to ITER, a commercially viable plant will not be available before the middle of this century.

Expansion of nuclear power

In the 1960s it was fission, not fusion, that pointed the way ahead. Post-war economic growth required abundant and reliable sources of energy, and so the USA, Europe and Russia stepped up the construction of more and ever larger nuclear power stations. In the USA the steady development of nuclear plants in the early 1960s intensified: before 1966, less than ten reactors had been ordered, but in 1966-67 that number quadrupled, as General Electric and Westinghouse Electric Corporation vied with each other for turn-key contracts. US orders for nuclear power plants peaked in 1972-73.
By the start of the 1960s reactor technology had crystallised along national lines: the light-water reactor in the USA; Magnox in the UK, superseded in 1964 by AGR; CANDU in >>

Qinshan reactor at Qinshan, China

Canada; and RMBK in the Soviet Union. Of these, only the LWR and the CANDU have proved commercially viable over the long term.

Light-water reactors include the boiling water reactor (BWR) and the pressurised water reactor (PWR). The BWR uses "light" (i.e. normal) water in one continuous loop, whereas the PWR uses both a primary loop containing pressurised water that does not boil and a secondary coolant to produce the steam that drives the turbines. The BWR had a simpler configuration and greater thermal efficiency than the PWR, but the latter proved cheaper to build. The PWR's commercial success was confirmed by events in France and the UK. In France under President De Gaulle, nationalist sentiment meant the adoption of a US reactor design in France was unthinkable, but in 1969 De Gaulle's successor Georges Pompidou reversed this policy by authorising EDF, the national utility company, to buy PWRs from Westinghouse.

Subsequent reactors in France have all been PWRs. In the UK, the AGR had proved less successful commercially than originally hoped. Therefore in 1978 the UK government decided to build no more AGRs and ordered its first PWR, Sizewell B in Suffolk, from Westinghouse. After a long public enquiry, construction started in 1987 and finished in 1994. To date, it is the last nuclear reactor to have been built or ordered in the UK.

Another successful design was developed in Canada. Between 1954 and 1973 the AECL built four heavy-water reactors, to which the name CANDU (CANada Deuterium Uranium) was attached from 1958. Among CANDU's features are a more efficient use of uranium (the use of natural rather than enriched uranium as a fuel thanks to the use of heavy water) and the successful implementation of on-power refuelling. AECL has not only supplied reactors to Canada, it has exported them to several parts of the world, notably India, China, South Korea and Pakistan.

Oil shock

The oil embargo of 1973 and the subsequent quadrupling of oil prices prompted the USA, Europe and Japan to search for alternatives to petroleum. As a result petroleum as a source of power generation was phased out in favour of an increased reliance on nuclear power. Between 1973 and the early 1990s, nuclear energy's share of US electricity increased from 4 per cent to 20 per cent, while oil's share dropped from 17 per cent to 4 per cent.

Nowhere was the growth of nuclear power in the 1970s more dramatic than in France, where EDF embarked on an intensive programme of nuclear plant construction using Framatome's N4, the first 100 per cent French design of PWR. The first of 34 900MW reactor units started up operations at Fessenheim in 1977. In France nuclear

Areve's nuclear reprocessing plant, Cogema-La Hague, in Normandy, France

contribution to electricity production has risen from 8% in 1974 to 78% today. France exports electricity to England and Italy and has exported its PWR technology to Belgium, South Africa, South Korea and China.
Where France led, other European countries followed. In West Germany, 17 reactors (17 PWRs and 11 BWRs) came on-line between 1975 and 1989. All were constructed by Siemens-KWU, and they now provide one third of the electricity of united Germany. By the end of the seventies, Italy, Spain, the Netherlands and Switzerland had built reactors, as had Czechoslovakia, Bulgaria, Japan, Argentina and North Korea.

Reprocessing

In addition France and England developed a reprocessing industry. (Reprocessing is also carried out by to a lesser extent in Russia, India and Japan; China also plans to develop it.) Nuclear fuel reprocessing started in the 1950s to extract plutonium for nuclear warheads. In civil nuclear power, uranium and plutonium are separated from fission (or waste) products and reprocessed into mixed oxide fuel (MOX) for reuse. The waste material is stored on-site, awaiting more permanent disposal. The UK and France reprocess spent fuel for customers all over the world. In 1967 the French Atomic Energy Commission (AEC) opened a reprocessing plant at La Hague, Normandy. The site is now managed by Cogema, which was set up in 1976 and is now part of the Areva group. In the UK there are two commercial reprocessing plants, both at Sellafield: the Magnox Reprocessing Plant, which began operations in 1965 and is scheduled to close around 2012, and the Thermal Oxide Reprocessing Plant (THORP), which started up in 1994 and will close around 2010. Both are run by the BNFL (British Nuclear Fuels Ltd), which was set up in 1971 to manage the fuel cycle.

Setbacks

Beginning in the 1970s, a number of factors conspired to check the growth of nuclear power. The turn-key contracts of the late sixties and early seventies had lost their manufacturers money. Also, the hope that nuclear power would be “too cheap to meter” (Lewis Strauss, Chairman, US Atomic Energy Commission, 1954) had proved over-optimistic. Huge quantities of natural gas were discovered in the North Sea from the 1950s to the 1970s, providing large parts of Europe with a cheap and attractive alternative to nuclear power. A spate of accidents at nuclear plants was causing mounting concern about possible damage to human health and the environment. In 1974, India detonated a nuclear bomb in an underground nuclear test, leading to fears of nuclear proliferation. The 1970s also saw the birth of the environmental movement, which has mostly been opposed to nuclear power. In the USA, a tougher regulatory regime came into force with the setting up of the Environmental Protection Agency (1970), making nuclear plants more expensive to build.

Accidents

The slowdown was already well under way when a serious but non-fatal accident occurred at the power plant at Three Miles Island, Harrisburg, Pennsylvania, in 1979. By coincidence, the film “The China Syndrome”, which describes a near meltdown at a nuclear plant, had been released just 12 days before the accident, and the similarities between the film’s plot and real events proved damaging to the nuclear industry’s image. After 1979, no US nuclear plants were

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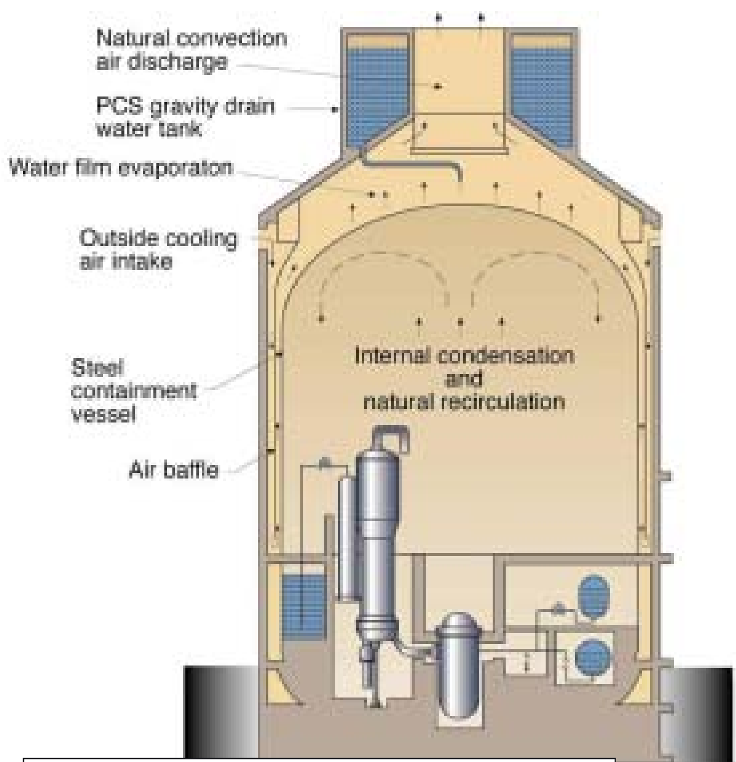
Nuclear power and popular culture

Inevitably, public perceptions about nuclear power have been affected by its treatment in novels and feature films. Film makers like to play on people’s fears, but perfect fiction and perfect science do not often make easy bedfellows. The effects of radiation should not be underestimated, but they do not include those portrayed in some sci-fi films, such as shrinking (“The Incredible Shrinking Man”, 1957), getting bigger (“The Amazing Colossal Man”, also 1957), giant ants (“Them”, 1954), mutant monsters (the Godzilla series, ad nauseam) or turning into a worm (“The X-Files”, 1994 season). Few films have anything serious to say about nuclear power as such. Four years after the above-mentioned “The China Syndrome” came “Silkwood” (1983), a semi-fictionalised version of the true story of Karen Silkwood, who died under unexplained circumstances shortly after gathering evidence of alleged dangerous practices at an Oklahoma nuclear plant (1974). Silkwood’s allegations centred on the quality of the welds in the stainless steel tubes containing the uranium-plutonium fuel pellets. The plutonium radiation from which Silkwood suffered was the subject of a protracted court battle. However, her allegations about the fuel pellets were never proven; on the contrary, the tubes in question were later found to perform satisfactorily after all (www.astonisher.com/archives/silkwood.html). Lighter in tone – but probably just as damaging to the nuclear industry’s image – was Matt Groening’s TV cartoon series “The Simpsons”, which started to be broadcast in 1989, just three years after the Chernobyl accident. Its hero is the beer-swilling, donut-quaffing Homer, an employee at a nuclear power plant, where he spends most of his time asleep on the job until, one day in 1991 (“Homer Defined”), a meltdown is averted when he happens to hit the right button on the control panel.

ordered, dozens of projects were cancelled and investment money dried up. The downturn also affected Europe: in referenda in Austria and Sweden, voters rejected nuclear power, and several reactors were cancelled.
The nuclear industry's woes were compounded by the reactor explosion at Chernobyl in 1986, which caused a number of deaths and contaminated large parts of Ukraine and Belarus. The Soviet Union's nuclear programme was stalled and, a year later, Italy decided to shut down its four power plants. Germany, too, decided to phase out its nuclear power stations.
Another factor in the post-Chernobyl slow-down in nuclear power was deregulation. Gradually, from 1978, the USA was required to open up the energy market; the same process started in Europe in about 1989. This led to increased competition and lower energy prices. Although nuclear power stations were relatively cheap to run, their high front-load costs placed them at a disadvantage compared to other energy industries. The pressure to reduce construction costs and enhance efficiency led nuclear industry designers back to the drawing board.

Third generation

Despite the setbacks of the 1980s and 1990s, nuclear power never completely went away. On the contrary, during the 1990s a third generation of new reactor designs was developed. (The US Department of Energy categorises nuclear reactor designs according to generations: see http://www.nei.org/index.asp?catnum=4&catid=339.) General Electric's Advanced Boiling Water Reactor (ABWR), Westinghouse's System 80+ Advanced Pressurised Water reactor (APWR) and Westinghouse's AP600 reactor were all certified by the NRC in the 1990s. Two General Electric ABW plants are operating at a Tokyo Electric Power Co. site in Japan, and 20 more are likely to be built. South Korea has opted for the Westinghouse 80+, while China has announced tentative plans for 30 advanced light-water reactors over the next three decades.
In Canada, the AECL has developed the Advanced CANDU Reactor (ACR), of which three units have been sold to South Korea (1997-99) and two to China (Qinshan Phase III, 2002-2003, with more sales planned). An important feature of the ACR is that the heavy water moderator is located within the calandria, with the aim of eliminating leaks.
Meanwhile, in Europe, Framatome (part of the French Areva group) and Siemens collaborated to develop the European Pressurised Water Reactor (EPR). In 2004 EDF announced it would build at Flamanville the first demonstration unit of an expected series of 1600MW Framatome EPRs. Even before that, Finland in 2002 had ordered an EPR unit to be built at Olkiluoto, the first nuclear new-build in Europe since the Chernobyl accident. France remains deeply committed to nuclear power and plans to replace those built in the 1970s with new ones from about 2015.



Design of Westinghouse's AP600, illustrating "passive containment"

Nuclear to the rescue?

At the beginning of the new millennium, two developments occurred that had strong implications for a possible revival of the nuclear industry. First, power blackouts in California and elsewhere in the summer of 2001 drew attention to the need to provide new energy infrastructure in the USA. Elsewhere, too, rapid economic growth in countries like China, India and Brazil has brought about a seemingly insatiable thirst for energy. The second factor was the growing awareness of the link between carbon emissions and global warming. Earlier this year the Kyoto Protocol, signed by several nations in 1997, came into force, obliging the signatories to reduce their collective emissions of greenhouse gases by 5.2% compared to the year 1990. Industrial nations are thus faced with the problem of how to meet their growing energy needs while at the same time reducing their greenhouse emissions. This dilemma, together with the impending need to replace the numerous second-generation reactors built in the 1970s, has led many countries to reconsider nuclear power. This in turn has encouraged the industry to position itself as the provider of solutions to the world's energy problems. For instance, Cogema claims that "kilowatt-hour cost [of nuclear power] is stable and competitive, it contributes to energy self-reliance and it doesn't pollute the environment with harmful gases or add to the greenhouse effect." (www.cogema.com). While it is true that nuclear power generation itself is free of greenhouse gases, it has to be admitted that the nuclear fuel cycle as a whole creates a lot of CO_2 emissions, though not nearly as much as coal-fired stations. Research into this problem is currently being conducted at the Öko Institut, Freiburg, Germany, and at the University of Groningen, The Netherlands.

Westinghouse's AP1000 reactor

Nuclear renaissance?

Signs of a nuclear resurgence are especially strong in the USA. The US nuclear industry saw the 2000 election of President George W. Bush, a declared supporter of nuclear power, as an opportunity to push for the kinds of construction programmes that were already taking place in countries like Taiwan, China and South Korea. The new energy policy was confirmed when on 8 August 2005 President Bush signed the USA's first energy bill for more than a decade. Its provisions include funds for research, for a hydrogen reactor, for decommissioning and even for nuclear-powered hydrogen cars; also tax credits, loan guarantees and a liability cap.

A significant new development is the emergence of various groups in the USA seeking combined construction permits and operating licenses, or COLs. A consortium led by Dominion that includes Bechtel Power Corp. and GE Energy is planning to use GE's Economic Simplified Boiling Water Reactor (ESBWR), a new version of the ABWR. The NuStart Consortium, consisting of the Constellation Generation Group, Duke Energy, EDF International North America, Entergy Nuclear, Exelon Generation, Southern Co., Florida Power & Light Co., GE Energy, Progress Energy, Tennessee Valley Authority and Westinghouse Electric, hopes to build the ESBWR and the Westinghouse AP1000. The consortium led by Tennessee Valley Authority, which includes GE Energy, Toshiba, USEC Inc., Global Fuel-Americas and Bechtel, plans to use the ABWR. Finally, Areva, together with Constellation Energy and supported by the Bechtel Energy Corporation, has formed UniStar Nuclear to market the U.S. Evolutionary Power Reactor (U.S. EPR), a design based on Framatome's EPR.

The USA has also made progress on the prickly issue of long-term storage of waste and spent fuels: in 2002, 24 years after the idea was first studied, President Bush signed a resolution allowing the DOE to take the next step in establishing a repository at Yucca Mountain, Nevada.

In the UK, Prime Minister Tony Blair has also expressed support for the construction of nuclear power stations, most recently at the Labour Party Conference in October 2005. At the time of writing, however, no specific plans for nuclear power expansion in the UK have been announced.

Safer designs

It is no exaggeration to say that the safety and efficiency of nuclear power is hotly disputed; also that both advocates and opponents have at times tended to overstate their case. What cannot be disputed is that all forms of power generation are inherently dangerous (especially coal); all technologies are particularly accident-prone and carry huge financial

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risks during the pioneer stage of their development (consider railways and aviation). Given these two factors, we should not be surprised at the number of accidents and technical failures at nuclear facilities in the late 20th century. However, useful lessons have been learnt from the Three Mile Island accident, and in the USA several measures to improve safety have been taken: retrofitting of improved safety devices, emergency reaction training, a more rigorous inspection and regulatory regime, and so on. Further grounds for optimism lie in the improvements in safety and efficiency promised by the third- and fourth-generation reactor designs. For example, Westinghouse's AP600 and its AP1000 reactor (approved in September 2004) are based on "passive" rather than "active" or "engineered" systems, using natural forces such as gravity, convection, evaporation and condensation and relying less on moving parts and fault-prone instruments. In the AP600 and AP1000, the emergency cooling water is above the reactor core, so that, in an emergency, the water can fall onto the core. Designs have been made simpler and cheaper, and construction times of plants are being reduced.

Pebble-bed reactors

Another third-generation reactor type is the pebble-bed modular reactor (PBMR). In PBMRs the fuel is contained not in rods but in graphite pebbles the size of tennis balls. PBMRs use graphite rather than water as the moderator, and are gas-cooled. In 2003 the South African government approved a prototype pebble-bed modular reactor for Eskom at Koeberg, South Africa, though a report published earlier this year declared the project to be economically unfeasible. In China, the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University in Beijing is collaborating with Chinergy to develop the HTR-10 (high-temperature reactor, 10MW). It will be a small-scale PBMR with a modular design, and it may provide an efficient way to make hydrogen. The first production plant is scheduled for 2007, and 30 more such plants are planned. Westinghouse has formed a co-operative relationship with INET with a view to bid for PBMR construction in the USA.

Generation IV

Waiting in the wings are fourth-generation reactors. In 2002 the US Department of Energy and the Generation IV International Forum, supported by Idaho National Laboratory, issued a "technology roadmap" which envisages the development of six generation IV systems. These systems, which could be ready by 2030, are said to "offer significant advances in sustainability, safety and reliability, economics, proliferation resistance and physical protection" (http://nuclear.inl.gov/gen4/).

Current situation

Nuclear power plants provided about 16 per cent of the world's energy production in 2003. As of 5 September 2005, 24 new reactors are under construction world-wide. Countries generating over half their electricity from nuclear energy in 2004 are: France, 78.1 per cent; Lithuania, 72.1 per cent; Slovakia, 55.2 per cent; Belgium 55.1 per cent; Sweden, 51.8 per cent; and Ukraine, 51.1 per cent. The UK share, at 19.4 per cent (other sources place this as high as 23 per cent), and that of the USA, 19.8 per cent, are modest by comparison, but the USA generates more electricity from nuclear power than any other country. China's share (2.2) and India's (2.8) are tiny, but are expected to grow rapidly (http://www.iaea.org/programmes/a2/index.html). According to a recent report, China plans to build 40 new nuclear reactors within the next 15 years, a big increase on earlier plans (BBC News, 7 April 2005).

What of the future?

How will historians in 50 years' time look back at the development of nuclear power? My guess is that their view will fall into three parts: first, a pioneering period up to about 1980 in which there was rapid growth and much was accomplished, but where mistakes were also made; secondly, a relatively quiet period up to 2000, when new-builds in the USA and Europe stopped (though they continued in Asia); thirdly, a resurgence of the industry worldwide, characterised by better designs and incorporating the lessons learnt during the first period. Governments do not like to put too many energy eggs into one basket. Most countries are therefore likely to opt for a mixture of different kind of power generation sources: renewables, gas, clean coal, biofuels, nuclear fission and, eventually, fusion, plus no doubt a dose of good old conservation. While prospects in the UK and most of Europe look uncertain, it is looking increasingly probable that the USA will build more nuclear power stations. Developing countries, especially in Asia, will increasingly turn to nuclear power to meet their energy needs and harness the technologies of hydrogen and desalination, essential for transport and water respectively. If the price of oil and gas stays high, nuclear power may become viable even without large government subsidies. Overall, the future prospects for the nuclear industry look reasonably bright. ■