

Nuclear comeback

The nuclear energy industry knows all about the vagaries of fashion. When the first nuclear reactors were built in the 1950s, they were lauded as heralding an age of cheap, abundant energy. But problems with safety and nuclear waste soon became apparent, tarnishing their image. The accidents at Three Mile Island in Pennsylvania, US, in 1979 and then at Chernobyl, Ukraine, in 1986 were the final straw, leading many countries, such as the US, to stop building new nuclear power stations.

But the threat of global warming is

now holding out the promise of a come-back for nuclear energy. It is becoming increasingly clear that nuclear energy is the only technology that can generate carbon-free electricity on a large scale. Nuclear reactors currently generate around 17% of the world's electricity, and renewable energy technologies, such as solar power and wind farms, are simply not yet ready to take their place.

The industry has worked hard to improve the safety of its nuclear reactors, introducing a number of 'passive'

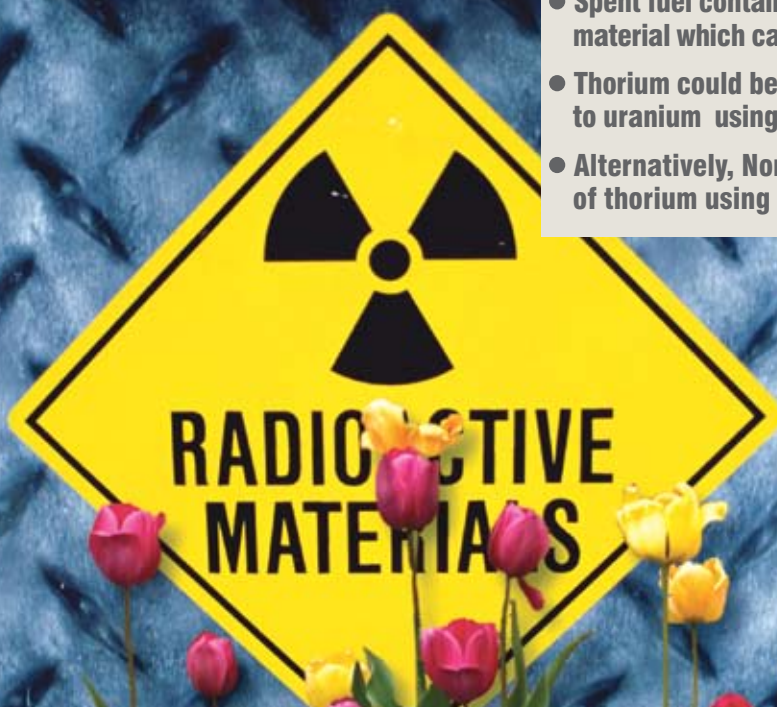
Jon Evans looks at the recent technological developments that could boost the future impact of nuclear energy

safety measures, such as automatically flooding the reactor core with water if it gets too hot. Unfortunately, the more intractable problem of how to deal with nuclear waste, particularly the highly radioactive spent fuel, remains. Recent experiences with North Korea and Iran have also highlighted the risk of nuclear fuel being used to produce nuclear weapons.

At the moment, most spent nuclear fuel is simply stored in water-filled ponds or concrete casks located at nuclear facilities. In the long-term, the

In brief

- Spent nuclear fuel (uranium) is currently stored in water-filled ponds or concrete casks
- Spent fuel contains 40% of the original fissile material which can be used for fresh fuel
- Thorium could be used as an alternative fuel to uranium using a 'seed blanket' approach
- Alternatively, Norway is looking at the use of thorium using ADS technology



plan is to store this waste in underground repositories, where it will have to be kept isolated for thousands of years. Finding appropriate repositories has proved difficult, however, and although some sites have been identified, such as Yucca Mountain in Nevada, US, none are yet storing any spent fuel. But, as with normal household waste, there is a more environmentally-friendly option: recycling.

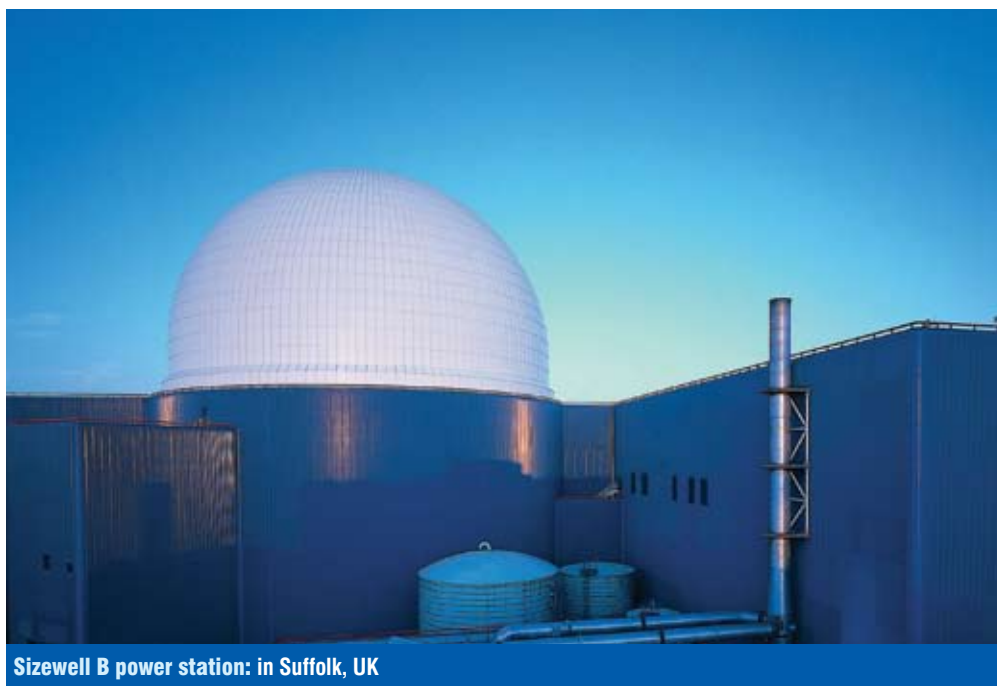
Most nuclear reactors use uranium oxide as their fuel and work by taking advantage of the chain reaction produced by the fission of a specific isotope of uranium (U-235). When hit by a neutron, a U-235 atom will split into atoms, such as barium and krypton, producing energy in the form of heat and more neutrons, which go on to initiate fission reactions in other U-235 atoms.

But the vast majority, about 95%, of the uranium oxide fuel is made up of a different isotope of uranium (U-238), which is non-fissile. U-238 is, however, fertile, which means that it can be transformed into a fissile material (plutonium-239) by absorbing neutrons. Indeed, 30% of the power generated by a nuclear reactor is produced by the fission of Pu-239.

Furthermore, as neutrons fly about inside the reactor, inducing fission or being absorbed, a range of other elements are produced. These include fission products, such as radioactive isotopes of iodine, caesium and strontium, and the heavy elements (actinides) produced by neutron absorption, such as plutonium, americium and curium. Eventually, the concentration of these elements becomes so high that they reduce the efficiency of the nuclear reaction and the fuel is replaced.

This all means that spent fuel contains unused U-235 atoms – up to 40% of the original fissile material can still be present in spent fuel: unused fertile U-238 atoms and new fissile material, mainly Pu-239, as well as the various fission products and higher actinides. If this remaining fissile and fertile material is extracted from the spent fuel, then it can be used to produce fresh fuel.

Such reprocessing of spent fuel does already take place and involves chopping the fuel up, dissolving it in nitric acid and then extracting the uranium and plutonium by dissolving them in an organic solvent, usually a mixture of tributyl phosphate and kerosene.



Sizewell B power station: in Suffolk, UK

Nuclear Industry Association

‘Nuclides generated in nuclear reactors could be used for medical applications, such as imaging, diagnosis and therapy’

But this process uses hazardous materials, generates chemical waste and runs the risk of a nuclear reaction starting up in the spent fuel. So researchers are looking for ways to improve the process.

One such way is to replace the organic solvent with an ionic liquid. ‘Ionic liquids can be designed to be intrinsically safe,’ explains James Wishart, a chemist at Brookhaven National Laboratory (BNL), New York, who is investigating the radiation chemistry of ionic liquids. ‘Most don’t evaporate and have very little vapour pressure, which means they can’t catch fire.’ Even more impressive, however, is that certain ionic liquids containing boron ions can hold up to 100 times more dissolved plutonium than organic solvents before reaching the ‘critical’ point at which a nuclear reaction will begin.

This work is still at an early stage, but eventually, rather than simply extracting uranium and plutonium from the rest of the spent fuel, Wishart envisages using ionic liquids to separate each element of the waste into differ-

ent streams. This could allow spent nuclear fuel to find a whole range of novel uses.

‘A few of the nuclides generated in nuclear reactors could be used for medical applications, such as imaging, diagnosis and therapy,’ suggests Wishart. ‘Right now, those sorts of elements are being specifically generated, but some could potentially be obtained by extracting them from spent fuel.’

By then, it is also hoped that there should be more outlets for the extracted uranium and plutonium. At the moment, they are mainly used to produce mixed oxide (MOX) fuel, a combination of uranium and plutonium oxides, which is currently only used in a small proportion of nuclear reactors. The vast majority of reactors still operate what is known as a once-through fuel-cycle, where fresh uranium fuel is used and then stored.

A number of research groups around the world are busy developing novel reactor technologies that could operate truly closed fuel-cycles, in which all the actinides in the spent fuel are recycled back into the reactor until almost all

Nuclear power

the radioactive material has been transformed into non-radioactive elements, in a process known as burning. Much of this work is being done under the aegis of the Generation IV Nuclear Energy Systems Initiative, whereby 10 countries, including the US, the UK and Japan, are combining their efforts to develop the next generation of nuclear reactors. This initiative has already identified six promising reactor technologies, five of which can operate closed fuel cycles.

But this work is once again at an early stage, with these novel reactors requiring the development of cooling systems that utilise novel materials, such as liquid lead, and novel fuel formulations, such as a liquid mixture of sodium, zirconium and uranium fluorides. 'This is high risk, high pay-off,' says Todd Allen, a nuclear engineer at the University of Wisconsin-Madison, US. 'If you can get these reactors to work it will be a great improvement, but there's a bunch of technical issues.'

Other scientists are investigating ways to adapt the current generation

of reactors to utilise spent fuel. One such scientist is Mujid Kazimi, who is the director of the US Massachusetts Institute of Technology's Center for Advanced Nuclear Energy Systems. Together with colleagues, he has developed the Combined Non-Fertile and Uranium (CONFU) fuel assembly. This involves replacing 20% of the uranium oxide fuel pins used in water-cooled reactors with fertile free fuel, which contains all the higher actinide elements, including plutonium, produced in nuclear reactors.

So far, Kazimi and his colleagues have only shown that the CONFU concept will work in theory. 'We are undertaking very early conceptual and feasibility assessments,' says Kazimi. 'Although there is a great deal of experience of burning plutonium in reactors, the higher actinides are something new and we have not been recycling them. So this requires careful assessment.'

Others are thinking about using a completely different kind of fuel. Like uranium, thorium is a naturally-occurring actinide element and its main

isotope (Th-232) is fertile, able to transform into a fissile isotope of uranium (U-233). Thorium is over three times more abundant in the Earth's crust than uranium and would produce much less waste if used as a nuclear fuel, but its major drawback is that U-233 doesn't produce enough neutrons to sustain a nuclear reaction. This means that neutrons continually need to be supplied to keep the reaction going.

One way to do this is to develop fuel assemblies in which a uranium-rich seed is surrounded by a thorium-rich blanket. The neutrons produced by the self-sustaining reaction in the uranium-rich seed would then power a nuclear reaction in the thorium blanket. The advantage of this design, which is being developed by a consortium that includes BNL and a US company called Thorium Power, is that it could be used in current water-cooled reactors. The consortium is now testing this design in a nuclear reactor based in Moscow.

An alternative approach involves using a particle accelerator to fire protons at a lead target surrounding the thorium fuel. This causes the lead to release neutrons, which then power the nuclear reaction within the thorium. Unlike the 'seed-blanket' approach, this Accelerator Driven System (ADS) only needs thorium as a fuel but would require a new reactor to be built from scratch.

One of the cheerleaders for the ADS is Egil Lillestol, professor of physics at the University of Bergen, Norway. 'There are no major problems with the principle of ADS,' he claims, 'there are just a few technological problems that should be solved as soon as effort is put into them.' As a result of his campaigning, the Norwegian government recently set up a committee to look into the feasibility of ADS, which will publish its findings by the end of the year.

Despite their promise, all of these novel nuclear energy technologies are at least 15–20 years away and so won't be available before many governments will need to make a decision on how to meet future energy demand. But even the possibility of more environmentally-friendly nuclear technologies may be enough for nuclear energy to become once again the height of fashion.

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Oldbury power station: in Gloucestershire, UK