physicsworld

# FOCUS ON NUCLEAR ENERGY

Building the future of fission and fusion

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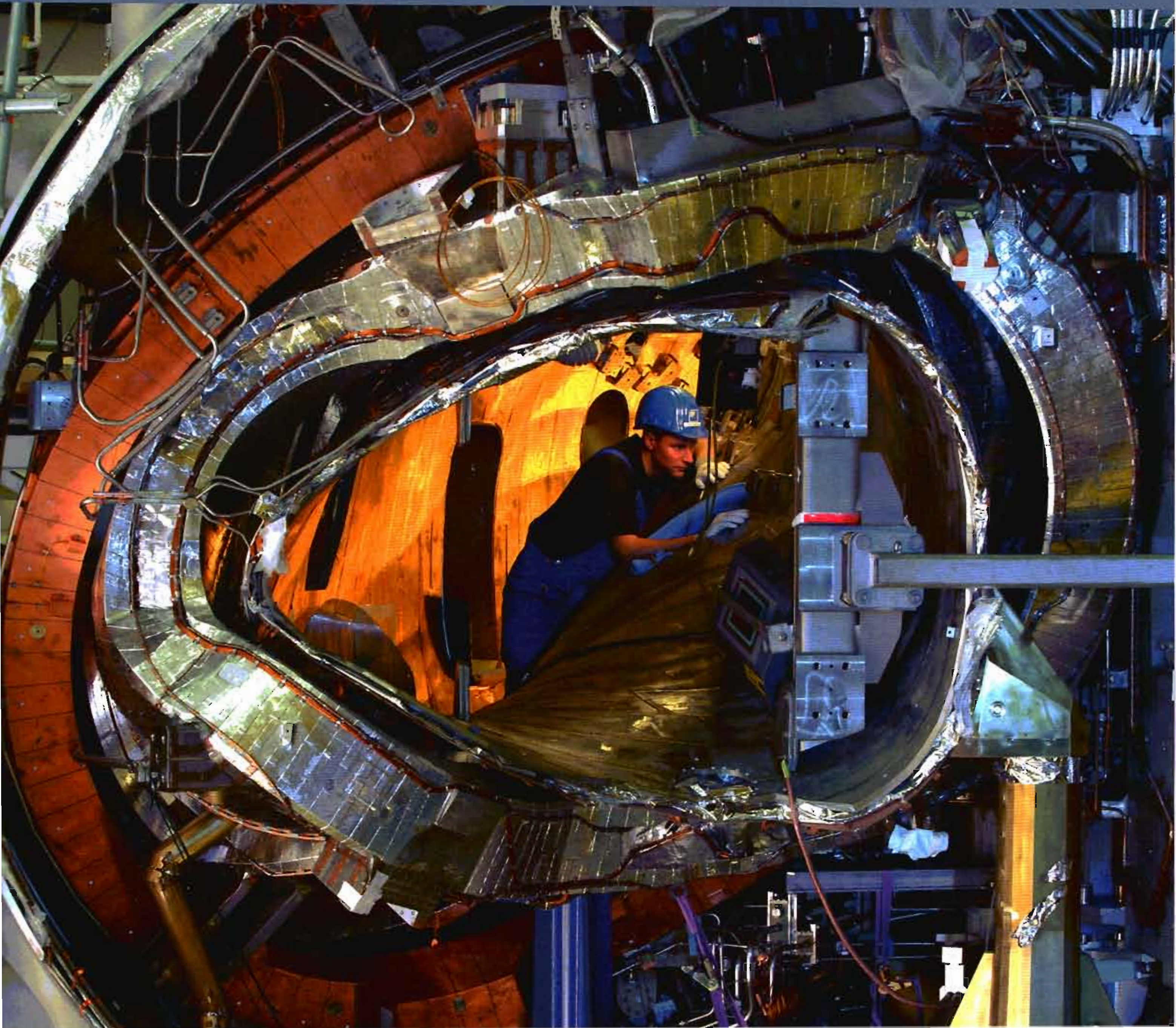

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## Focus on: Nuclear energy

Welcome to this focus issue of *Physics World*, which is devoted to nuclear energy – both fission and fusion. For decades physicists have dreamed of using fusion to generate electricity, and with construction under way on the ITER fusion tokamak in France, that vision is getting closer (p9). But is ITER the way forward? Several private firms are developing small-scale fusion technology (p15), while in Germany a novel stellarator device has started up (p23). Fission is a much more mature technology and while new, safer reactors are coming online (p7), there are other, more ambitious reactor designs in the pipeline that could vastly reduce the amount of nuclear waste (p13). Both fission and fusion face challenges but offer a carbon-free way of generating electricity that could help to tackle climate change (p19). I hope you find this focus issue stimulating and please do let us have your comments by e-mailing pwld@iop.org.

**Michael Banks**, Contributing Editor

## Features

**On the cover**
A stellar fusion device 23 (*IPP/Wolfgang Filser*)

# UK closes final Magnox reactor

The UK's oldest power station, and the last of its kind in the world, has shut, marking the end of an era in nuclear generation in the UK. The Wylfa Magnox nuclear power station, based on the island of Anglesey off the north-west coast of Wales, closed down on 31 December 2015 after 45 years of service. Built in 1971, in its heyday Wylfa generated 1000 MWe – enough for 40% of Wales' electricity needs.

Wylfa can trace its roots back to the 1950s, when the UK government, seeking plutonium for nuclear weapons, decided to build gas-cooled reactors that used natural, rather than enriched, uranium. The fuel cladding for such reactors was a magnesium non-oxidizing alloy, known as Magnox, and the first reactor, Calder Hall, was opened in 1956. Given its huge heat output, it was later converted to generate electricity and became the first reactor in the world connected to a national grid. At its peak, Calder Hall generated 190 MWe – enough to power 200 000 homes.


Magnox

**End of an era** The Wylfa plant based on the island of Anglesey, UK, was the last operating Magnox reactor in the world.

Another 11 Magnox plants that focused on electricity generation were built in the UK, with Wylfa being the last and largest of those. "The Magnox concept was relatively simple, but needed a fundamental understanding of the physics and the ability to calculate parameters without sophisticated computers," says Geoff Vaughan, chair of the nuclear-industry group of the Institute of Physics, which publishes *Physics World*. "That the early pioneers got it sufficiently right first time, and then developed the facilities so they became more efficient, is a tribute to them."

Indeed, the success of the Magnox programme led to two reactors being exported abroad. In 1963 Italy began operating a 160 MWe plant at Latino, while three years later Japan started up a 166 MWe reactor in Tokai, which was the country's first commercial nuclear power plant.

After the manufacture of Magnox fuel stopped in 2008, Wylfa was set to close in 2010, but its life was extended by regulators for another five years after engineers devised a way to transfer partly used fuel from other reactors that had closed down. "The closure of Wylfa marks the end of the first generation of nuclear power plants in the UK," adds Vaughan. "Nearly 60 years of Magnox operation without any accidents, while providing a base load of power, is a massive achievement by all involved and deserves to be celebrated."

The Magnox site will now be decommissioned, while Horizon Nuclear Power, which is owned by Hitachi, plans to build two 1380 MWe Japanese Advanced Boiling Water Reactors near the site.

**Michael Banks**

**South Korea**

# KSTAR achieves fusion milestone

Researchers working on the Korea Superconducting Tokamak Advanced Research (KSTAR) device have managed to create a high-confinement plasma – known as "H-mode" – for a record time of 55 s. This extends the tokamak's previous record of 45 s achieved in 2014 and puts the facility close to operating at ITER-like conditions.

KSTAR is located at the National Fusion Research Institute in Daejoen, which lies about 150 km south of Seoul. With a radius of 1.8 m, the tokamak achieved its first plasma in 2008, which lasted for a quarter of a second. KSTAR's main aim is to create a plasma of deuterium lasting around 300 s. It is also one of the few tokamaks in the world that employs superconducting magnets – made from niobium and tin – which are used to confine the plasma.

The H-mode of a plasma was discovered in the 1980s by physicist Fritz Wagner while he was working on the Axially Symmetric Divertor Experiment at the Max Planck Institute for Plasma Physics in Garching, Germany. He came across a "transition" in the plasma when heating it with a neutral beam of particles in which the time that the plasma was confined suddenly doubled. Later dubbed H-mode operation, all tokamaks today are designed to run in this mode. The ITER fusion reactor currently under construction in France, which aims to maintain a burning plasma for around 1000 s, would need to be twice as large – and costly – if the H-mode had not been discovered.

**Burning issue** The Korea Superconducting Tokamak Advanced Research has run a "high-confinement plasma" for a record time of 55 s.

Michael Banks

Fusion scientists at KSTAR created their H-mode in a plasma at 40 million K. "H-mode is known to be a very reliable, high-confinement mode in a tokamak," says Jong-Gu Kwak, head of KSTAR. "Until now, it was only tested in devices with conventional magnets, so to do it in KSTAR with its superconducting magnets is an achievement towards making fusion a feasible energy source." KSTAR will now put its achievement into action by studying ITER-related plasmas as well as trying to boost that time towards its target of 300 s.

**Michael Banks**

**Radioactive waste**

# US set for borehole field trial

A long-overlooked technique for disposing of high-level radioactive waste by drilling deep boreholes into the ground is expected to be tested later this year. Scientists and engineers will drill a 5 km-deep, 0.43 m-wide borehole in North Dakota, US, to assess whether reprocessing waste, spent fuel and other radioactive materials could be buried in such structures and safely stored for hundreds of thousands of years.

Most countries with stocks of high-level waste have plans that involve disposing of it in huge repositories mined some 500 m to 1 km underground. However, strong public and political opposition has meant that no such facility has yet been built. Proponents of boreholes, however, argue that the deep, narrow constructions would be safer and quicker to build than conventional repositories.

Boreholes, which are typically about 0.5 m in diameter, would contain waste canisters in their lowest 1–2 km and a mixture of sealant materials and backfill above that. According to geologist Fergus Gibb of Sheffield University in the UK, who is working with the US-based Sandia National Laboratory in New Mexico on the field test, burying waste at such depths means that any radioactive particles escaping could not be transported by groundwater back up to the surface. Gibb also claims boreholes would be relatively cheap, estimating that all of the UK's reprocessing waste could be housed in about six boreholes totaling £300m ($427m) to £400m – less than a 10th that of the equivalent mined repository.

Although boreholes were first proposed in the 1950s, it was not until the 1990s that the technology existed to drill holes suitably wide and deep. The UK and Sweden reviewed the concept in 2004 and 2010, respectively, but concluded that mined repositories were preferable. Among the concerns from Swedish experts was whether waste canisters being lowered into a hole might get stuck and break before reaching the bottom.

The renewed interest in boreholes in the US follows the decision by US President Barack Obama in 2011 to abandon the Yucca Mountain nuclear repository in Nevada. A presidential commission that he later set up noted that boreholes are a "potentially promising technology for geologic disposal".

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**Heading underground** Could high-level radioactive waste be held in 5 km-deep boreholes?

Scheduled to begin in September and produce its first results within about a year, the field test will be carried out by an industrial–academic consortium led by Battelle Memorial Institute on behalf of the US Department of Energy (DOE). Costing $35m, the test aims to prove that a borehole can be drilled smoothly and that suitably sized non-radioactive packages can be sent up and down it. Gibb says that if the run is successful, then another borehole could be drilled elsewhere and house highly radioactive waste, perhaps from the Hanford nuclear research centre in Washington state.

Yet some see boreholes as a distant prospect. In a submission to the DOE, the Nuclear Waste Technical Review Board – a US independent government agency – noted that it had not seen any "compelling evidence" that boreholes could be built more quickly than mined repositories, explaining that both approaches would need to undergo a lengthy process of site selection and licensing.

Gibb acknowledges that boreholes would also probably face opposition from the public and local authorities. Indeed, he points out that the field test has itself created resentment after the University of North Dakota – a consortium partner – failed to inform state and county authorities of their plans before bidding for the DOE contract. "There will be all sorts of posturing," he says. "The project could be delayed a bit but I can't see it being stopped."

**Edwin Cartlidge**

## News briefs

### Fourth Japanese reactor restarts

A fourth nuclear reactor has restarted in Japan following the decision to shut down the nation's nuclear capacity after the Fukushima accident in 2011. In late February, Kansai Electric Power turned on the unit 4 reactor at the Takahama nuclear power plant based in the Fukui prefecture. The move quickly followed the firm's decision to restart its unit 3 reactor at Takahama in January. Unit 1 of Kyushu Electric Power Company's Sendai plant in Kagoshima prefecture was the first of Japan's reactors to resume operation when it restarted in August 2015, while unit 2 came back online in October. Another 20 Japanese reactors are moving through the restart process, which has been prioritized to bring reactors online in regions that are more supportive of nuclear power.

### Korean physicist takes ITER helm

The Korean physicist Won Namkung has become the chair of the ITER council – the highest governing board of the fusion reactor currently being built in France. Namkung received his BSc in physics from Seoul National University in 1965, and did a PhD in tokamak radio-frequency heating systems at the University of Tennessee, US, graduating in 1977. After positions at various US institutions, he returned to South Korea in 1988 to the Pohang University of Science and Technology and became director of the Pohang Accelerator Laboratory from 1996 to 1998. From 2003 to 2012 he served as president of the Korea Accelerator and Plasma Research Association. Namkung succeeds Robert Iotti of the US, who reached the end of his two-year term last year. One of Namkung's first tests will come in June, when ITER publishes an update on construction progress.

### Go-ahead for Finnish repository

Following a three-decade search, Finland's government approved construction of a deep underground facility to permanently store spent nuclear fuel in December 2015. Based on Olkiluoto island off Finland's west coast and due to open in the early 2020s, the repository – the first of its kind in the world and costing €3bn ($3.2bn) – will dispose of up to 6500 tonnes of uranium in copper canisters that will be buried 400 m underground in a series of tunnels cut out of granite rock. Officials estimate that the repository will be sealed off in 2120, when it should be able to hold waste for tens, if not hundreds, of thousands of years.

# A nuclear revival

The first European pressurized water reactors are expected to be switched on next year, but they have been hit by redesigns, cost hikes and delays, as **Michael Banks** reports


EDF Energy

**Waiting game** Hinkley Point C – a European pressurized water reactor – would, if built, be the first nuclear new build in the UK for more than 20 years.

The headlines have not been kind to Hinkley Point C – a proposed nuclear reactor for south-west England. In the planning stages for almost a decade, the reactor has been hit by numerous delays as well as fights over funding and the price of the electricity it would generate. It was thought a breakthrough would come in early February when the French electricity giant EDF – the majority shareholder in the facility – would finally agree to start construction, but that had still to be announced as *Physics World* went to press.

The site at Hinkley is currently home to Hinkley Point A, a Magnox station that has been in the process of being decommissioned since 2000 after a 35-year life, as well as Hinkley Point B, which is an advanced gas-cooled reactor (AGR) station that opened in 1976 and still generates around 1250 MWe of electricity. Hinkley Point C is scheduled to begin operating in 2025 and will generate 1600 MWe – about 3.5% of the UK's electricity needs. It will also be one of the first new nuclear power stations to be built in the UK for more than 20 years.

Hinkley Point C represents the future of nuclear energy generation in the UK – a new type of design that promises higher output and greater efficiency with less waste. It is a European pressurized water reactor (EPR) – a "third generation" reactor that is based on the pressurized water reactor (PWR), a type of light-water reactor. There are around 300 PWRs currently operating around the world, with 75 alone in France. PWRs use water as the primary coolant, which is pumped under high pressure to the reactor core where it is heated by the energy from nuclear fission. The heated water then flows to a steam generator where it transfers its energy to a secondary system where steam is generated and flows to turbines that, in turn, spins an electric generator. The EPR is basically a "beefed up" PWR, according to Paul Norman, who runs a Master's course in the physics and technology of nuclear reactors at the University of Birmingham in the UK. "They are the next evolution, the next step up in PWR design," he adds.

Hinkley Point C is not the first of its type. Four other EPR units are being built around the world (see "Delays and costs overruns – the EPR story" on page 8). Two reactors in China are scheduled to come online in 2017, while ones in both Finland and France have been hit by costly delays and are expected to be online in 2018.

The common feature of PWRs is that they are simple to operate: they require less intervention, less fuel and are easier to maintain than previous designs. They also have advanced, and/or "passive" safety features that rely on physical forces such as gravity and convection, with little or no need for mechanical devices such as pumps. "Water reactors are cheaper and simpler, more economical, and don't have complex parts," says Norman. "The EPR has the highest power and highest thermal efficiency of any PWR, and a host of back-up safety systems."

Following the Fukushima nuclear accident in Japan in 2011, regulators in the four countries that were building EPR reactors demanded small tweaks to the design to take into account a possible Fukushima-style event happening with an EPR. They are now thought to be very safe and include several mechanisms to prevent accidents from occurring. They have four independent emergency cooling systems, each providing the required level of cooling for the decay heat that continues for one to three years after the reactor's initial shutdown.

EPRs also have a leak-tight containment around the reactor as well as an extra container and cooling area if a molten core does manage to escape the reactor. The two-layer concrete wall with a total thickness of 2.6 m is designed to withstand impact by aeroplanes and internal overpressure. "There are many positives for the EPR design," says Norman. "But there are also negatives where the designs following Fukushima could have been overtweaked with safety systems going too far, increasing the complexity and build times."

## Learning from the past

There are currently 14 AGRs operating in the UK and one PWR, which is located in Sizewell, Suffolk, and is the UK's newest reactor, having opened in 1995. While the UK's expertise is with gas-cooled reactors, Peter Haslam, head of policy at the Nuclear Industry Association (the trade association for the civil nuclear industry in the UK), does not see there being an issue with switching to water reactors. "There are clearly opportunities for the UK supply chain to be involved with a different reactor design, so that has a positive effect," he says.

Hinkley Point C received planning consent in early 2013, yet it has taken years to get the project off the ground with wrangling over finance as well as the price for the electricity it would generate. Last year, the UK government provided a £2bn ($2.8bn) sweetener to support the reactor and later in the year EDF and China Guangdong Nuclear Power Group (CGN) signed an investment agreement for £18bn to build it. Under the agreement, CGN will take a 33.5% stake in Hinkley Point C with EDF

## Delays and costs overruns – the EPR story

TVO

**Leading the way** The Olkiluoto 3 European pressurized water reactor currently being built on Olkiluoto Island in south-west Finland was, in 2005, the first to start construction.

As well as Hinkley Point C in the UK, four other European pressurized water reactor (EPRs) are currently being built around the world – two in Europe and two in China. Yet they have been plagued by delays and cost hikes.

### Olkiluoto 3

The first-of-a-kind EPR at the Olkiluoto Nuclear Power Plant on the Olkiluoto Island in south-west Finland has been under construction since 2005 and was initially scheduled to come online in 2009 at a cost of around €4bn ($4.4bn). With an output of 1600 MWe, the reactor is being built by Areva and Siemens for the Finnish electricity operator TVO. Yet it has seen several revisions to its start-up date and has been hit by quality-control issues as well as the supply of components. It is now expected to be online by 2018 with the project estimated to cost at least €8bn.

### Flamanville 3

Construction of the EPR at the Flamanville Nuclear Power Plant on the north-west coast of France began late in 2007. With an output of 1630 MWe, the plant was expected to be operational within four years. Yet by 2011, EDF, which is the operator of the plant, announced that the costs had increased 50% to €6bn and that the project would be delayed until 2016. When the Fukushima nuclear accident hit in March 2011, it led to French regulators demanding changes to the design. Last year, Areva, which is building the reactor, announced that "anomalies" had been detected in the reactor's vessel and by late last year EDF announced that costs has escalated to €10.5bn with the reactor set to open in 2018.

### Taishan 1 and 2

Taishan 1 and 2 are the first two reactors based on Areva's EPR design to be built in China, with the firm managing to win the bid to build them in 2007 at a cost of €8bn. Taishan 1 has been under construction since 2009 and is expected to start up in early 2017, while work on Taishan 2 began in 2010 and it is scheduled to begin operating later in 2017. The reactors – both generating around 1750 MWe – are located on China's south coast around 140 km west of Hong Kong and will be owned by the Guangdong Taishan Nuclear Power, a joint venture between EDF and China Guangdong Nuclear Power Group.

owning the rest. Meanwhile, the two firms would also build another EPR at Sizewell in Suffolk, as well as a reactor in Bradwell, Essex. The latter will be built using Chinese reactor technology with CGN being the majority stakeholder.

Pricing has been a major obstacle for the project, in particular the "strike price" – the minimum price for electricity that is paid for what the reactor produces over a 10-year span. If the price for electricity generated at Hinkley Point C is below the agreed strike price – £92.50 per megawatt hour – then the government will top up the rest with the money coming from the consumers of electricity rather than being state subsidized. Yet the agreement works both ways and if the price of electricity increases beyond the strike price, then EDF will pay back the difference.

In February, EDF was expected to finally announce that it was going ahead with building the reactor, but progress has since stalled as it seeks to get approval from the firm's board. "The economics of new nuclear builds are heavily weighted towards construction," adds Norman. "You need to get that capital upfront as most of the cost of a reactor is in building it and that is where the Chinese investment has been so important to get it off the ground."

Yet if construction does start soon, the reactor is expected to be roughly built on time and to budget, mostly because the firm has learned lessons from previous reactors riddled by delays, especially Olkiluoto 3 in Finland. "Olkiluoto 3 was the first of a kind so it is breaking fresh ground," says Norman. "The general thought is that when you have a handful of new reactors, the next one you build will be a smoother process." Some of those benefits have already been seen in the latest two EPR reactors that China is building, which are so far roughly on budget and have not been hit by major delays.

Norman's view is shared by Haslam. "Olkiluoto 3 hasn't been a huge success story, but the lessons from the previous reactors have been applied to Hinkley Point C to ensure it will be closer in terms of time and budget," he says. "The key point is that we have learned the lessons of previous reactor builds and the UK EPR has passed the regulatory process – it is a stable reactor."

# Taking the heat

The ITER fusion reactor will use 54 divertor cassettes, each weighing 10 tonnes, to funnel out waste particles and heat, as **Daniel Clery** explains

Fusion reactors are all about containment: keeping a superhot plasma of hydrogen isotopes entrapped by magnetic fields long enough for nuclei to collide and fuse, thus releasing energy. It is ironic, then, that one of the most technologically challenging components of a modern tokamak is the mechanism for removing particles and heat from the vacuum vessel, known as the divertor.

Normally, fusion scientists go to extreme lengths to prevent the plasma, which is at a temperature greater than 100 million degrees, from touching a solid surface like the wall of the vacuum vessel that contains it. Any contact will probably melt the wall or scour atoms from its surface into the plasma, poisoning it for any further fusion. But if you want to get particles or heat out of the plasma, contact is exactly what you need. Contact cools the plasma and neutralizes the ions so they can be pumped out. Hence, the divertor is the one place where reactor operators allow that to happen.

The divertor's primary function is as an exhaust pipe. In a working power reactor, the fusing isotopes – typically deuterium and tritium – combine to produce a helium nucleus (or alpha particle) and a neutron. The neutron carries 80% of the reaction energy and, as it is immune to the tokamak's magnetic fields, shoots straight out and embeds itself in the reactor wall where its energy, in theory, is used to boil water, which then drives a steam turbine to generate electricity. The alpha particles remain in the vessel, whirled around by the magnetic field, sharing their energy with the fuel plasma and helping to keep it hot. But once that is done, the alphas are simply "ash". "We need to pump away the helium ash because it dilutes the reacting plasma in the core," says Christopher Lowry of the Joint European Torus (JET) based at the Culham Centre for Fusion Energy in the UK. "If we concentrate it in the divertor, we can then pump it away."

## Dealing with fluxes

ITER Organization

**Carefully does it** Researchers at the VTT Technical Research Centre in Tampere, Finland, practise inserting a dummy cassette of the type that will be used in the ITER fusion reactor, which is currently being built in France.

The trick is to get the helium from the core of the plasma to the divertor. The cross-section of the plasma in a tokamak is D-shaped, with the flat side towards the middle – the hole of the doughnut – and the concentric magnetic-field lines mirror that shape. But in a tokamak with a divertor, the outermost layers of the magnetic field do not join up at the bottom but veer out and down into a sort of antechamber to the main plasma vessel. It is there that the field lines hit the wall. "You want to remove where the plasma touches the wall away from the main vessel," says Rajesh Maingi of the Princeton Plasma Physics Laboratory in the US. That way any atoms sputtered off the divertor wall do not infect the rest of the plasma.

In normal operation, the ions in the plasma follow the magnetic-field lines, looping round and round. But there is some drift across the field lines because of particle collisions and other effects, so some particles will slowly migrate outwards towards the vessel wall. Since such lateral motion is slow compared with movement along the field lines, any particles that end up following one of those outer unclosed field lines will get swept down into the divertor. In this way, the divertor continually extracts some of the plasma out of the vessel. Extracted fuel can be recycled back into the vessel and the helium ash disposed of.

But engineering that first point of contact is incredibly tough. The ITER reactor, currently under construction in France, is so large and contains so much plasma that its divertor will have to cope with huge heat fluxes, up to 10 $\mathrm{MW\,m^{-2}}$ in normal operation with peaks up to twice that amount. To lessen the load, the design incorporates tricks learned with earlier divertors, including positioning the target plate so that the field line hits it at a shallow angle, spreading the stream of hot plasma over a wider area. The divertor also squirts gas into the path of the incoming plasma to cool it down. This gas includes some atoms with a high atomic mass that radiate heat more effectively. Some of the plasma ions, which get neutralized on impact with the target, bounce off and aid cooling of the incoming plasma.

But the biggest decision for any reactor designer is the choice of divertor material. The material of choice is carbon, because it is a tough ceramic that will not melt at the temperatures in a fusion reactor. And if some carbon atoms get out into the plasma, their low atomic mass means they pollute the plasma less than a metal would. The original plan had been to use a carbon divertor in ITER at the beginning. Then while they were learning its characteristics, operators could push the reactor to its limits and not have to worry about blasting the divertor occasionally. But carbon has one big drawback: it chemically reacts with hydrogen and so soaks up fusion fuel like a sponge. In a research reactor, that is not a problem but ITER will be using tritium – a radioactive material that must be audited precisely for nuclear regulators, who would not accept the divertor soaking up unknown quantities of the isotope.

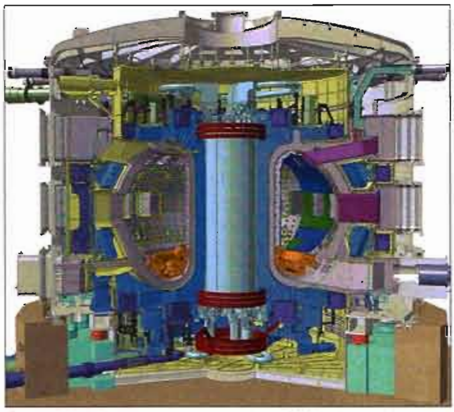
## Prototype testing

In 2013, in part to help stem the rapid growth of ITER's cost, a decision was made to take a risk and start ITER with a divertor made from tungsten rather than carbon. Although tungsten has an extremely high melting point, its high atomic number means that if some of it got back into the main plasma, then it would radiate heat efficiently, making fusion difficult.

To test the viability of a tungsten divertor, researchers had already tested it on smaller reactors before the 2013 decision. An upgrade to the Axially Symmetric Divertor Experiment in Germany was fitted with tungsten walls throughout, while JET was given a tungsten divertor and beryllium walls elsewhere – mirroring the design of ITER. These machines showed that replacing carbon with tungsten would reduce the retention of tritium by between 20 and 50 times, "which is an acceptable level for ITER" according to Maingi. It is also suggested that a tungsten divertor would be able to cope with the heat flux in ITER, but more specific tests still need to be done.

A task force was set up to organize the design and testing of the new tungsten divertor parts. The companies in Japan and the European Union that were responsible for the divertor targets began experimenting with ways to braze the blocks of tungsten that form the face of the target onto the copper-alloy cooling water pipes so that they have a good thermal connection. They produced small-scale mock-ups that they then shipped to the Efremov Institute in St Petersburg, Russia, home of the ITER Divertor Test Facility. This device bombards components with an 800 keV electron beam to simulate the heat flux they will face inside the reactor.

The mock-ups survived the ordeal and so the Japanese contractor went ahead and built a full-scale prototype of one divertor "cassette" (the divertor is made up of 54 removable cassettes so it can be easily repaired or its design or material changed). That prototype was also tested at St Petersburg in 2014 and 2015. More prototypes are now being built to perfect the production technique before scaling up. "We will learn a lot while making the prototypes, then we can launch full manufacturing," says Frederic Escourbiac, head of the divertor section at ITER headquarters at Cadarache, France.

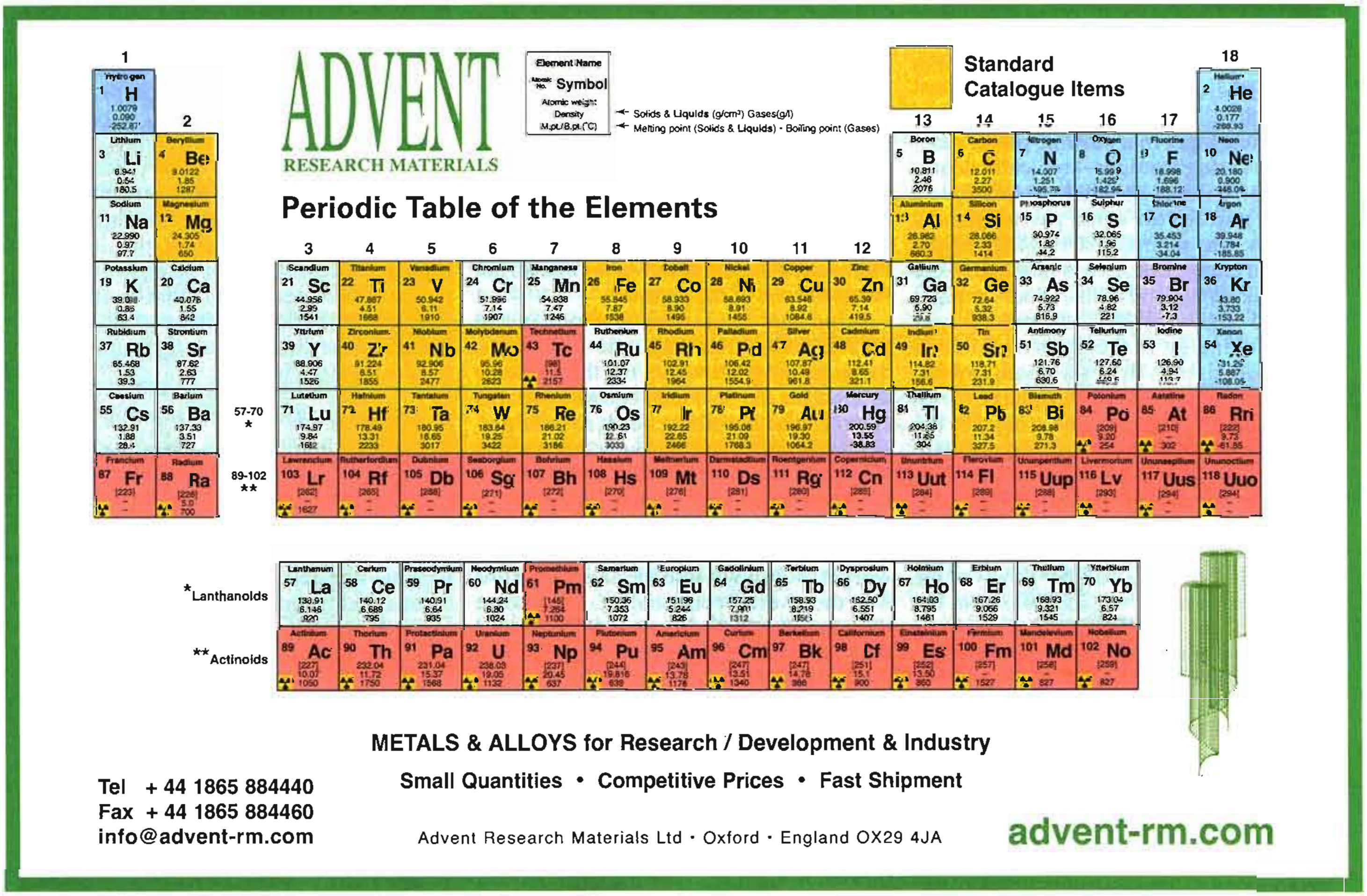

ITER Organization

**Grand designs** A cut-away of the ITER tokamak. The divertor is shown in orange.

Elsewhere, researchers have been testing the procedures for inserting and removing cassettes. The divertor was designed to be more easily replaceable because it will be taking the hardest pounding of any part of the vessel wall. "When you have issues, they tend to be in the divertor," says Maingi. The reactor design has a single port next to the divertor through which one cassette can be withdrawn by a remote-controlled mover. When a cassette has been removed, the next one then moves around on rails until it is lined up with the port and can be extracted in turn until all 54 are out.

But this process presents huge engineering challenges because space around the base of the tokamak will be tight and each cassette is 3.4 m long and weighs 10 tonnes. Researchers at the VTT Technical Research Centre in Tampere, Finland, have built a mock-up of the divertor port so that technicians can practise manoeuvring the huge cassettes in and out. Since they will likely be radioactive from exposure to fusion neutrons, everything has to be handled remotely. In a series of tests at Tampere in 2014, technicians managed to move model cassettes in and out with millimetre tolerances.

With the manufacture of ITER now in full swing, the emphasis will soon shift to qualifying components and assembling the tokamak. Only later next decade will the researchers see whether their divertor design can really stand the heat.



# Planning a new generation

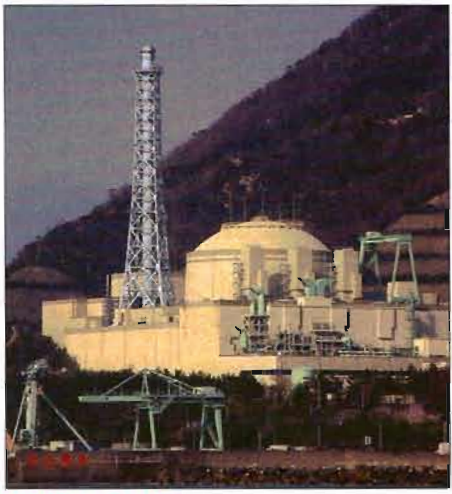
The 2011 Fukushima nuclear accident in Japan has slowed research on advanced nuclear reactors over the last five years. But proponents argue that "generation IV" designs will still play a vital role in the long term, as **Edwin Cartlidge** reports

The 14 m-high waves that crashed over the meagre defences of the Fukushima Daiichi nuclear plant in Japan in March 2011 – flooding the plant, crippling its back-up generators and causing a meltdown – had a widespread and, in some cases, dramatic impact on the nuclear industry. Germany shut down half of its reactors in response, while Japan itself took all of its reactors offline, and as of March has so far restarted just four of them.

Less apparent to the outside world was the effect that the disaster also had on the nuclear reactors of tomorrow. In 2002 a group of 10 countries – led by the US – known as the Generation IV International Forum (GIF) published a roadmap detailing the research and development that would be needed to commercialize six advanced-reactor concepts by 2030. The GIF chose the six "generation IV" designs from a list of nearly 100 candidates on the basis that each would be better than the existing light-water reactor (LWR) in four key respects: sustainability, economics, safety and reliability, as well as proliferation resistance.

But following the Fukushima meltdown, Japan slowed research on advanced reactors and placed more emphasis on improving the safety of existing ones. A similar switch also took place within the European Union (EU). Coupled to ongoing technical challenges with many of the designs and US ambivalence in the face of plentiful fossil fuels, progress on generation-IV technologies has slowed. An updated roadmap published by the now 13-member GIF in 2014 pushed back the R&D schedule for many of the designs by around 10 years, predicting that most would probably not be ready for commercial deployment before 2040.

Some experts question if it is worth spending the several billion dollars needed to commercialize each of these reactor types given the slow progress so far and the fact, they argue, that LWRs should serve our needs for decades to come. But those working on the GIF programme insist that generation-IV reactors' ability to maximize uranium resources, minimize high-level waste and boost generating efficiencies makes them essential in the long run.


CC BY-SA 3.0 Nife

**Suffering setbacks** Generation-IV designs include improved sodium-cooled fast reactors. Previous and existing sodium reactors – such as this one in Monju in Japan – have been hit by problems.

Henri Paillere of the Organisation for Economic Cooperation and Development's Nuclear Energy Agency in Paris, which supports GIF members, argues that the programme's financial shortfall – its annual budget being about half that originally envisaged – could in fact stimulate international cooperation. "Each individual country has more to gain from collaboration when it has less money itself," he says.

## Slow-going in the fast lane

A key characteristic of a number of the generation-IV designs is the ability to use "fast" neutrons. In a conventional LWR, neutrons from nuclear fission are deliberately slowed down, or "moderated", using hydrogen atoms in water. These "thermal" neutrons are very good at splitting the fissionable nuclei uranium-235 and plutonium-239, which maximizes reactors' power output. But fast (unmoderated) neutrons – while less likely to stimulate fission in the first place – produce more secondary neutrons when they do manage to split plutonium nuclei apart.

Fast reactors exploit this by exposing a uranium–plutonium mixture to unmoderated neutrons and using the many emitted neutrons to convert some of the unfissionable uranium-238 into plutonium-239. Such reactors therefore create lots of fissile material, as well as burning it. While thermal reactors only burn the 0.7% of naturally occurring uranium that comes in the form of uranium-235, fast reactors can, in principle, burn the whole lot, so allowing far more energy to be extracted from the Earth's uranium resources.

Fast reactors could also help solve the problem of nuclear waste. Since fast neutrons can fission many of the long-lived "transuranic" isotopes that build up within spent fuel – reducing half-lives from tens or hundreds of thousands of years to just a few hundred years – such reactors could cut the volume of waste destined for geological repositories while also easing pressure on the water-filled pools used for temporary storage.

The most developed of all the generation-IV designs is the sodium-cooled fast reactor. This takes advantage of sodium's high heat capacity and thermal conductivity to efficiently remove heat from the high-density core (fast neutrons requiring greater concentrations of fissile material than their thermal counterparts) as well as leaving the neutrons fast. Sodium's higher boiling point also means that the reactor can operate at higher temperatures than a LWR, so improving thermal efficiency, and at lower pressures, which improves safety.

Sodium-cooled reactors were first developed in the US and Russia back in the 1950s and have since been built by a number of other countries. However, they have some big drawbacks. In contrast to their thermal counterparts, fast reactors tend to experience enhanced fission reactions when they lose coolant. Sodium also reacts violently with water – meaning that the steam generators used to drive turbines are liable to catch fire. Another problem is that sodium burns in air, thus complicating refuelling and maintenance. In addition, since sodium becomes radioactive when exposed to neutrons, it must be separated from the steam generators by an additional cooling loop, which complicates plant design.

As a result, progress has been far slower than expected. The one commercial-sized fast reactor built to date, France's Superphénix, was out of action for more than half of its operating life, while the Monju reactor in Japan shut down for a decade and a half after a major fire in 1996.

The GIF aims to make sodium-cooled fast reactors cheaper, safer and less complex than they have been to date. One of the most advanced projects is the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID). Developed by the French Alternative Energies and Atomic Energy Commission, together with the firm Areva, this 600 MWe reactor would leak neutrons to slow down reactions if it lost coolant and might use nitrogen rather than steam to drive turbines. Assuming it gets the go-ahead, it should start operating by about the middle of the next decade.

## Beyond sodium

GIF members are also developing several fast-reactor designs that use coolants other than sodium. One of these uses helium as the coolant, while another uses lead. Neither of these substances reacts with air or water, so potentially simplifying plant design. Helium could also be used at higher temperatures (up to 850 °C) to improve thermodynamic efficiency. But both types of reactor face major technical hurdles. Helium cools nowhere near as well as sodium, while liquid lead would corrode almost any metal it touched.

Perhaps the most ambitious of the six designs, however, involves dissolving nuclear fuel in a circulating molten salt. Such a reactor would require no separate coolant, would automatically switch off if it lost molten salt and could be refuelled continuously. But here, too, there are challenges. Building a molten-salt reactor would require significant new chemistry and the development of special corrosion-resistant materials.

Indeed, many scientists are sceptical about the prospects for fast reactors altogether. Frank von Hippel, a physicist at Princeton University in the US and co-chair of arms-control advocates the International Panel on Fissile Materials, says that fast-reactor R&D has so far cost more than $100bn worldwide and yielded "pitiful results". He argues that sodium-cooled reactors will continue to be "more costly and less reliable" than LWRs, adding that in any case manmade climate change needs to be addressed within the next 10 to 15 years. "You can't build up fast reactors on that timescale," he says.

For Von Hippel, there is an additional factor that makes any kind of fast reactor unattractive: the proliferation of weapons-grade plutonium. For fast reactors to burn significant fractions of natural uranium, their fuel needs to be reprocessed. Fuel assemblies fail after a certain period, which means that the uranium-238 and plutonium-239 that remain in the reactor core have to be separated from the rest of the spent fuel and refashioned into fresh assemblies.

Supporters of fast reactors claim that the separated plutonium would be of no use to terrorists or others wanting to make a bomb if it is left bundled with the highly radioactive and therefore hard-to-handle transuranics. According to Bill Stacey, a nuclear engineer at the Georgia Institute of Technology in the US, "it is inconceivable that anybody outside the five or six nations which already reprocess" could extract plutonium from spent fuel. But Von Hippel counters that the radiation from the plutonium–transuranic mix would be far less intense than the International Atomic Energy Agency considers necessary to protect against theft.

PBMR

**Pressure point** The failed pebble-bed reactor in South Africa used helium as a coolant.

## Aiming (not quite as) high

Fast reactors are not the only game in town, however. GIF members are also working on a design known as the supercritical water-cooled reactor, which could use either fast or thermal neutrons. This would heat water above its critical point, making the reactor more efficient than a LWR and simplifying heat exchange. But it would need to withstand very high temperatures and pressures, and would also require a better understanding of water chemistry.

The one purely thermal generation-IV design is the very-high-temperature reactor. This would burn fuel consisting of submillimetre-sized particles of carbon-coated uranium contained within blocks or spheres of graphite moderator, around which helium-gas coolant would flow (a variant on this would use molten salt, rather than helium). Reaching temperatures potentially as high as 1000 °C, these reactors would be very efficient generators of electricity and might also produce hydrogen by splitting water molecules. In addition, they would be very safe, since any coolant they lose would tend to be replaced by air, which would also cool the reactor core.

However, technical problems in developing the fuel and a limited demand for hydrogen, given continued low fossil-fuel prices, has led this design to be scaled back in the latest roadmap – to a top temperature of 750–850 °C. China is building a high-temperature reactor using spherical "pebble bed" fuel technology that was explored and then abandoned by South Africa, but this device will not operate beyond about 750 °C.

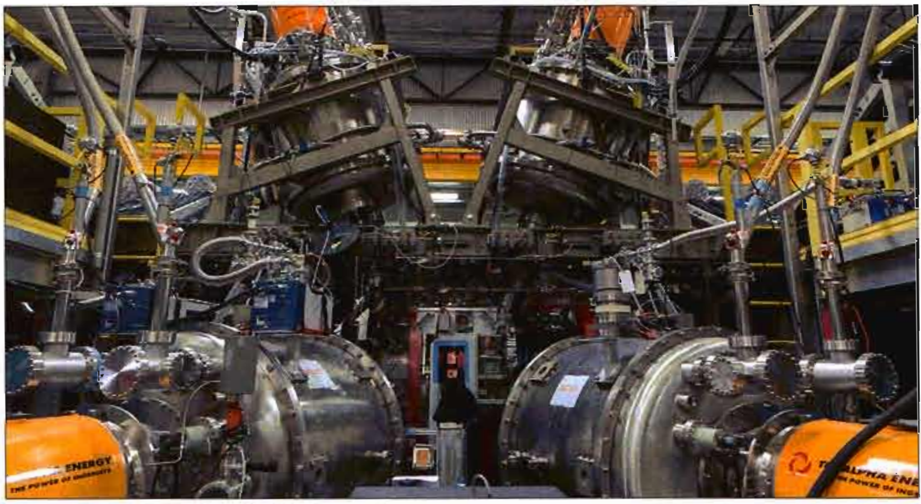
William Nuttall, an energy-policy expert at the Open University in the UK, believes that "the wind has been taken out of the sails" of generation-IV R&D. He says that, with the possible exception of ASTRID, "the bold ambitions of generation IV may have largely evaporated". He argues that the future of nuclear power may instead lie with a less-revolutionary idea: a prefabricated version of existing LWRs known as the "small modular reactor". This, too, he says, "offers the prospect of improved safety and economics".

Paillere, however, remains confident. Despite the setbacks, he thinks that generation-IV reactors will eventually be commercialized. Aside from the continued need to deal with radioactive waste, he believes that increased demand for uranium as well as hydrogen will act as a spur in the long run. Although uranium is currently plentiful, and therefore cheap, he believes the situation could change within the next 50 years, particularly, he says, "if China expands its reactor fleet".

Harold McFarlane, a physicist at the Idaho National Laboratory in the US who used to be GIF technical director, is also sanguine. He says that the generation-IV roadmap has slipped less than he expected, with Russian expertise in lead-cooled fast reactors and Chinese development of high-temperature and molten-salt reactors having, he feels, "in some senses accelerated" the GIF programme. While the US and other Western nations are, as he puts it, "less keen on breeding" plutonium from uranium-238 than are China and India, he believes that all countries remain concerned about long-term supplies of uranium. "That continues to be a motivation," he says.

# An independent endeavour

Fusion doesn't need billions of euros – at least that is what venture capitalists claim. **Jon Cartwright** takes a look


Tri Alpha Energy

**Downsizing** Fusion start-up Tri Alpha Energy based in Orange County, US, has reportedly made a "breakthrough" in its colliding-beam fusion reactor.

Fusion is just 20 years away, and always will be. Those who work on publicly funded fusion must be tired of hearing this well-worn joke, but it is not without an element of truth. After all, 2016 is the year in which ITER – the world's first "more energy out than in" fusion reactor that is currently being built in France – was originally scheduled to begin operations, by confining its first plasma. ITER's current schedule predicts that operations will actually begin in the mid-2020s – nearly 20 years after the facility was officially given the go-ahead – but that could yet be further delayed. The estimated cost, too, has tripled from around €5bn ($5.5bn) to €15bn.

ITER will be big because physics says it must be big: as a reactor grows, you get more output power from a given input power. At least, that is the conventional view. In January last year, however, physicist Alan Costly and others at the company Tokamak Energy in Abingdon, UK, published a paper claiming that the fusion-power gain depends only weakly on reactor size (*Nucl. Fusion* **55** 033001). The paper, which has been downloaded more than 12000 times, implies that gargantuan projects such as ITER are not the only route to fusion power. "The basic message is that smaller, lower-cost pilot plants and reactors may be feasible," says Tokamak Energy's chief executive, David Kingham.

Indeed, smaller and cheaper fusion plants are on the rise, but not in the public sphere. Tokamak Energy is one of several privately funded companies that have sprung up in recent years, each hoping to demonstrate that fusion does not need billions of euros and thousands of tonnes of metal. It was formed in 2009 by Mikhail Gryaznevich and Alan Sykes, who previously worked down the road from Abingdon at the Culham Centre for Fusion Energy (CCFE) – home to the Joint European Torus (JET), which is currently the world's largest and most powerful fusion tokamak.

The principal workhorse of fusion research since its invention in the 1950s, the tokamak is a doughnut-shaped enclosure that confines a plasma – that is, the fusion reactants – in a magnetic field. As its name implies, Tokamak Energy is also developing tokamaks, but is focusing on those small enough to fit in rooms rather than aircraft hangers, and using more of a spherical ("cored apple") shape rather than a doughnut design, like ITER.

A smaller footprint means the magnetic confinement is more important than ever, and for this reason Tokamak Energy is employing the latest high-temperature superconductors for its magnets. ITER, in contrast, is destined to rely on conventional superconducting magnets. Tokamak Energy's current model, the 50 cm-wide ST25 HTC, ran its high-temperature superconducting magnets for 29 hours non-stop in July last year – a world first, according to Kingham.

The company has 14 permanent members of staff and, to date, $14m of private investment from sponsors including the manufacturers Oxford Instruments (also based in Abingdon) and the UK's Institution of Mechanical Engineers. With such modest support, competing with the likes of ITER seems a challenge, yet Kingham says that the firm is not competing at all: where ITER and other publicly funded fusion hopes to proceed via rigorous scientific methodology, Tokamak Energy is proceeding by trial-and-error engineering.

"Build a device, see how it works, measure what you can, build the next device," Kingham explains. "The outputs are proof-of-principle patents in some cases, rather than primarily scientific papers. We may sacrifice a depth of understanding about the science, but we hope to gain a whole lot of knowledge about how to engineer tokamaks and high-temperature superconducting magnets."

## Different approaches

Tokamak Energy is relatively conventional in opting for tokamak reactors, but this is not true of other private ventures. General Fusion in Burnaby, Canada, was founded in 2002 by plasma physicist and former laser-printer engineer Michel Laberge, and is based on the concept of an enclosed, liquid-metal vortex. Plasma is injected into the centre of the vortex before numerous pistons hammer on the outside of the enclosure, compressing the plasma and – theoretically, at least – sparking a fusion reaction.

It is a bold idea, but one that dates back to the 1970s with a programme called Linus at the US Naval Research Laboratory in Washington, DC. The main problem with Linus, says Laberge, is that the pistons could never strike the enclosure at exactly the same time. With some $100m of private investment, however, he and more than 60 colleagues are trying to solve this timing problem with modern computing systems – as well as demonstrate the various other complex sub-systems required to make this kind of "inertial confinement" fusion work.

Like Kingham, Laberge does not feel in competition with ITER – and, in fact, he believes the scientific approach provides a crucial resource. "All the physics those guys are learning – we want it, we need it," he says. "Where we don't quite agree with [ITER], is we don't believe the standard superconducting tokamak will make a good power plant. In the future, it's difficult to conceive that this machine will make electricity in a cost-effective way. It's a fantastic experiment to learn the plasma physics, but as a power plant we think it's not the way to go." One of the main problems with ITER, Laberge says, is that the heat and emitted neutrons will melt and deteriorate the tokamak's walls over time, forcing them to be replaced. "We have a wall that is already liquid," he points out.

> There are many approaches to developing fusion-based technology and we can learn from all of them

The apparent camaraderie among fusion start-ups even extends to what is considered to be the best-funded private venture: Tri Alpha Energy, based in Orange County, US. With backers including the Microsoft co-founder Paul Allen and Rusnano, a Russian government-owned private-equity company, it is attempting to develop a technology known as a colliding-beam fusion reactor, in which plasma vortices are fired into a cylindrical chamber containing the magnetic field. The geometry is simpler than a tokamak, yet still, in theory, generates closed magnetic-field lines, which are thought to be most effective at confining plasmas and promoting fusion.

"There are many approaches to developing fusion-based technology and we can learn from all of them," says Michl Binderbauer, Tri Alpha's chief technology officer. "For example, we are benefitting tremendously from the pioneering technology work done by ITER, especially related to the design and fabrication of superconducting magnet systems and its components. There are some advantages to a private company, including speed and flexibility, but we can learn from all approaches."

In May last year, after 16 years in the business, Tri Alpha reported what it considers a "breakthrough": a plasma heated to a temperature of 10 million degrees and confined for five milliseconds (*Phys. Plasmas* **22** 056110). But CCFE director Steve Cowley, who is also chief executive officer of the UK Atomic Energy Authority, points out that JET can already reach 250 million degrees for half a second. Moreover, Tri Alpha is aiming to achieve proton–boron fusion – a reaction that is desirable for not generating any damaging neutrons but one that requires temperatures of more than four billion degrees. "I don't want to pick holes in all of [these private ventures]; you could pick holes in what we're doing," says Cowley. "As a scientist, I'm looking for people who have new ideas – ideas we might adopt, or that change the field. And I don't see any new ideas from these start-ups – yet."

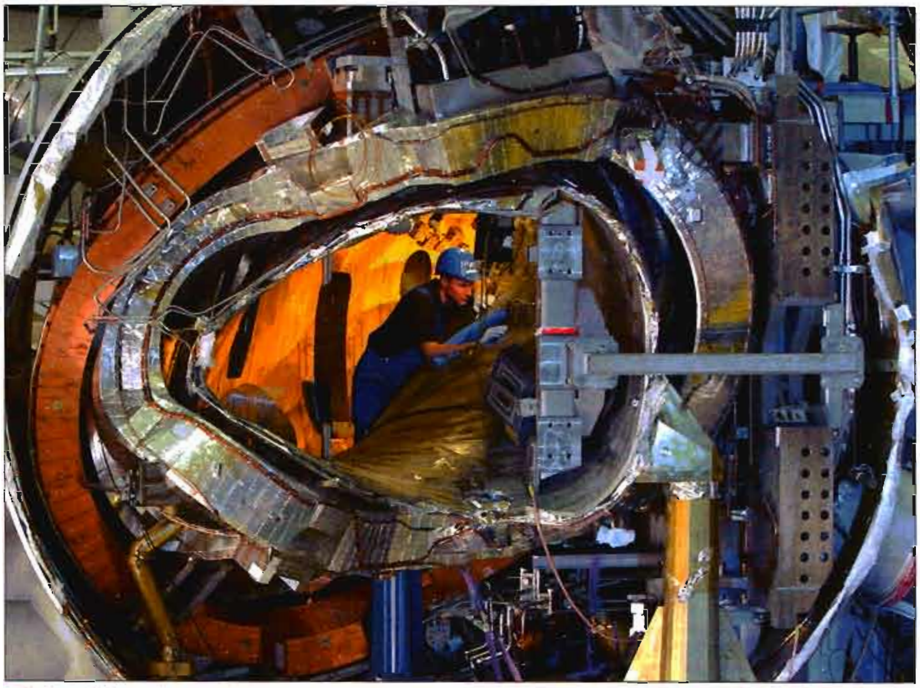
Cowley repudiates the paper by Costly and colleagues that claims smaller fusion reactors are viable, saying it relies on an empirically derived "confinement enhancement factor", *H*. "The broad consensus is that it is difficult to achieve an *H* above 1," says Cowley, yet the Tokamak Energy researchers take *H* to be over 1.5. Cowley is also sceptical of the engineering approach. "The idea that you can do this as Thomas Edison invented the lightbulb is attractive, but not all inventions work that way – especially where every step costs a lot of money," he says. "Edison would make 50 bulbs, see which worked best, then try again. But if [a prototype] is going to cost millions, or billions, you need science so that you don't have to build 50, you only need to build a few."

# A stellar fusion device

**Michael Allen** looks at a novel fusion experiment that promises a "steady state" plasma

In February, German chancellor Angela Merkel made a special trip to Greifswald – a small city in the north-east of the country next to the Baltic Sea. Merkel, who has a PhD in physics, was personally on hand to usher in a new era of plasma physics as she switched on the €1bn ($1.1bn) Wendelstein 7-X fusion device. Built on the outskirts of the city at the Max Planck Institute for Plasma Physics (IPP), Merkel's visit marked the start of the reactor's scientific run as the device burned its first hydrogen plasma at a temperature of 80 million degrees for about a quarter of a second.

Following the successful start of operations, Merkel declared that Wendelstein 7-X is "a unique experiment" that could "take us one step closer to the energy source of the future". "[It] is the world's most important fusion device of the stellarator type," Merkel noted, adding that experiments could provide "important insights into whether stellarators can one day be used for the commercial production of energy".


IPP/Wolfgang Filser

**Twists and turns** Germany's Wendelstein 7-X stellarator will use a complex magnetic-field design to sustain a hydrogen plasma for about 30 min.

While experimental fusion devices have been around for decades, most of them – such as the ITER reactor currently under construction in France – are tokamaks. Stellarators and tokamaks both use magnetic fields to confine a plasma, but how they do this is different. To hold the plasma in place, the particles in the plasma need to be driven through a helical pattern. A tokamak uses toroidal magnets to generate a magnetic field that travels around the tokamak. This is combined with a vertical looping magnetic field generated by an electrical current induced in the plasma by a transformer. But as transformers only work in pulses, it makes it very difficult to generate a steady-state plasma – the plasma can collapse in between the pulses.

Stellarators, however, only use magnetic fields generated outside the plasma. This means that the magnetic fields can be continuous, in theory making it easier to generate a steady-state plasma. Yet stellarators are fiendishly difficult to build as the use of external magnetic fields means that, compared with tokamaks, a different plasma shape is needed. The optimal plasma for the latest generation of stellarators resembles (when viewed from above) a pentagon, varies in cross-section and moves through a more-pronounced twisting pattern than in a tokamak. Generating a magnetic field that can create these patterns requires magnets with a complex 3D geometry that need to be as close as possible to the plasma. Because of this, the inside of the reactor is far from a smooth torus like a tokamak – it is an incredibly complex 3D shape. Indeed, building Wendelstein 7-X has proved challenging, with the project costs doubling from the original €500m estimate.

## The next generation

The first stellarator was developed at Princeton University in the US by physicist Lyman Spitzer in the 1950s. It created the helical pattern by confining the plasma in a figure-of-eight-shaped tube. Later designs used superconducting coils – in combination with toroidal coils – that spiralled around a doughnut-like tube to generate the required magnetic field. Before Wendelstein 7-X came online earlier this year, the world's largest and most successful stellarator was the Large Helical Device in Toki, Japan, which had a performance approaching that of a similarly sized tokamak. It began operating in 1998 and uses two superconducting helical coils to twist the plasma.

The first "advanced" stellarator was Wendelstein 7-AS, which operated at the IPP's institute in Garching, Germany, from 1988 to 2002. In the US, the helically symmetric experiment (HSX) was built at the University of Wisconsin-Madison, and started operating in 1999, while in 2004 researchers at the Princeton Plasma Physics Laboratory started building their own larger device – the National Compact Stellarator Experiment (NCSX). However, because of spiralling budgets it was cancelled four years later with the project struggling to assemble the various 3D sections and magnets with the required precision.

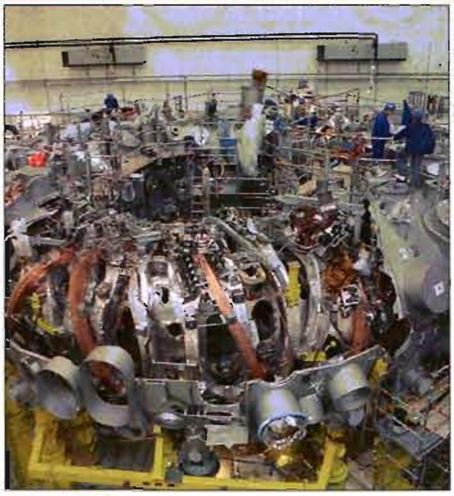
Wendelstein 7-X is part of a new generation, and rather than relying on helical and toroidal magnets, it uses complex 3D superconducting magnets to confine and twist the plasma.

Indeed, theoretical physicists calculated the best shape for the plasma and so derived the basic shape of the coil that can produce the desired magnetic field. The computing power required to calculate the optimal shape of the magnetic field and magnets needed to generate it was not available until the 1980s.

### Complex design

During the construction of Wendelstein 7-X, it took about 12 years to perfect the design of the magnets and build a suitable prototype. Physicists and engineers went back and forth until they reached a compromise between coil shapes that could be manufactured and the optimal plasma shape. The main sticking point was the minimum radius through which the superconducting coils could be bent. Engineers also had to work out how to construct magnets with these complex 3D coils at the centre.

The construction of the magnets is similar to those on tokamak reactors. A niobium–tin superconductor is embedded inside a cable of copper wires – during operation this is cooled with liquid helium to a temperature of 4 K. Most superconductors enclose this cable in a stainless-steel jacket, but Wendelstein 7-X uses aluminium jackets to provide the flexibility needed for the complex 3D shapes. The conductor is then wound through 108 turns to create the magnetic coil and enclosed in a steel case filled with hardened sand and resin. The final 3.5 m-high magnets weigh six tonnes.


IPP/Anja Ullmann

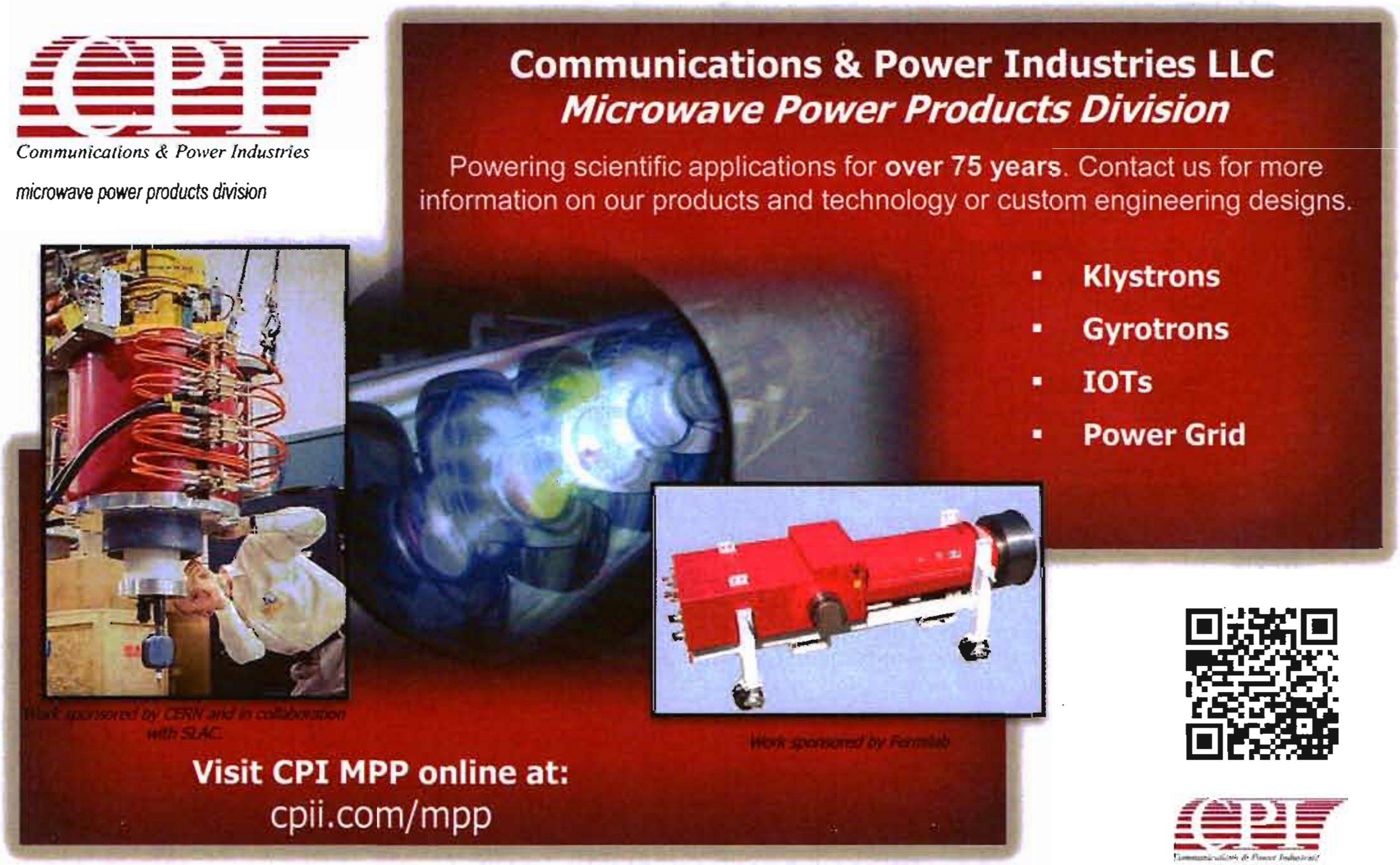
**Unique design** It took 12 years to perfect the design of the magnets for Wendelstein 7-X and build a suitable prototype.

While a similar-sized tokamak device would need around 18 magnets, Wendelstein 7-X has 50 primary "bean-shaped" magnets. A stellarator is normally much lower and wider than a tokamak, which, assuming the same plasma volume, gives it a much larger circumference. According to Thomas Rummel, who managed the magnet production, this requires more magnets to avoid gaps between coils that could be detrimental to the magnetic-field stability.

The final design for Wendelstein 7-X uses five sets of 10 magnets. Each set has a different geometry and is on a different electrical circuit so the magnetic fields can be adjusted separately. This is necessary because the plasma does not travel around a perfect circle. Wendelstein 7-X also has 20 flat secondary superconducting magnets on two electrical circuits. These are not absolutely necessary for operating the stellarator, but provide "flexibility to allow a broader range of plasma parameters", notes Rummel. This will allow researchers to investigate the physics of the plasma in more detail.

### One big step

While stellarator research is set to be hugely improved by Wendelstein 7-X, which hopes to maintain a plasma for around 30 min, it is still behind that of conventional tokamaks such as ITER, and it may never reach parity. "Unfortunately, stellarators are one big step behind tokamaks and are not yet in a position to think about power generation," says Rummel. "Our research over the next year will concentrate on finding the best plasma shape, holding the plasma stable and trying to find clever ways to bring the energy out."



# Plotting a carbon-free future

Michael Banks talks to **Gene Grecheck**, president of the American Nuclear Society, about how nuclear can help to reduce carbon emissions

### What is the role of the American Nuclear Society (ANS)?

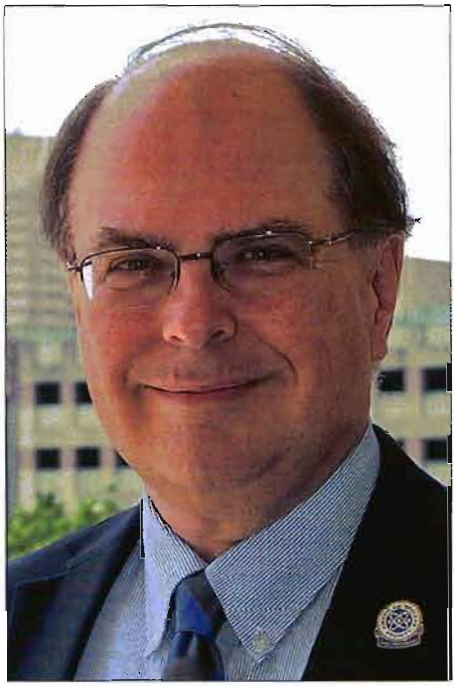
ANS was founded in 1954 and represents nuclear professionals in every area of nuclear technology, including academia, research and industry. We have about 11 000 members, with around 10% based outside the US. In addition to publishing a news magazine and several technical journals, and organizing meetings, ANS spends a substantial amount of time on policy issues, engaging with government officials and policy makers to ensure that the voice of nuclear professionals is heard.

### How does the ANS operate as an organization?

ANS has a board of directors, with each member elected for a three-year term. There is also an executive committee that is comprised of the president, president-elect, past president and the treasurer. The president's term is one year and in that year each president seeks to increase awareness of nuclear science and technology using his or her own message. The message during my presidency, which began in June 2015, has been that the world needs nuclear and nuclear needs ANS.

### What does your role as ANS president involve?

In addition to chairing our board and executive committee, I travel to Washington, DC frequently to meet officials, and I also represent ANS at a variety of conferences. For example, late last year I attended the United Nations Climate Change Conference in Paris to deliver our message that nuclear is necessary for a low-carbon world. I also visit as many of our local and student sections as I can to help keep our membership informed and engaged.


ANS

**Looking forward** Gene Grecheck.

> If policy makers determine that a reduction in carbon-dioxide emissions is necessary, then the amount of electricity generated from nuclear has to increase

### What is the state of nuclear power in the US?

With 99 nuclear power plants in operation today in the US, nuclear represents about 20% of all electricity generated in the country and produces about two-thirds of all electricity that is carbon-free. Nuclear power plants are doing very well, with capacity factors at around 90%, which has been consistent for a decade now. On the negative side, the extraction of large amounts of shale gas has driven the price of natural gas in the US down substantially, which makes it difficult for electricity generated from nuclear to be cost-competitive in many parts of the country. This creates a real dilemma: since current market structures largely do not credit nuclear for the environmental and fuel-diversity benefits it provides, short-term economic decisions are leading to the premature shutdown of some nuclear units.

### Has this hit the prospects for new nuclear builds?

Despite such price pressure, there are currently five new-build reactors in the US. One is scheduled to open this year, marking the first time in 20 years that a new nuclear power unit will open in the US. The remaining four are AP1000s that are designed and sold by Westinghouse Electric. There are also a number of other proposed reactors or designs that are in the licensing stage for approval. Market conditions and carbon-reduction policy decisions will dictate when construction can start on these additional projects.

### How has the Fukushima nuclear accident in Japan in 2011 affected public opinion of nuclear?

Public opinion has not been significantly affected by what happened in Japan. There was, of course, some concern immediately after the incident, but people have realized that US plants are designed and operating safely. Where it has had an impact, however, is that plant operators have needed to make changes – mandated by the US Nuclear Regulatory Commission (NRC) – to their plants and implement additional safety plans to deal with "beyond-design-basis" events. On average, this has cost each plant around $100m in the US. Plants have dealt with this while struggling with the effects of the low price of natural gas.

### Have you been surprised by countries such as Germany that have scaled back nuclear post-Fukushima?

What has surprised and disappointed me is that the German government has embraced an illusion that shutting down supposedly dangerous nuclear plants and replacing them with wind and solar can reduce carbon emissions. But when wind and solar are not available, Germany is largely using coal, meaning that its carbon-dioxide emissions are even greater than before. I find it unfortunate and disappointing that nuclear – a proven, safe, large-scale way of carbon-free generation – is being shut down in that country. The world cannot meet its goals to reduce carbon dioxide if the most available, scalable and reliable source of clean electricity is not used and expanded.

# Interview: Gene Grecheck

### What is your view of how to best store nuclear waste in the long term?

Every nation has to make a decision on how to deal with used fuel, and the US is no different. In the 1980s some thought that nuclear would be a temporary aberration – a finite number of plants would be built before another, better, way of generating electricity would appear. Given the need for additional utilization of nuclear to meet climate goals, it is probably time we re-evaluate that and come to terms with how best to deal with used fuel; for example, can we develop and implement reactor technologies, such as fast reactors, that would end up burning a greater fraction of it? We need to pursue such technical innovations.

### Do you think the Yucca Mountain nuclear-waste repository is viable?

The ANS position on Yucca Mountain is that the licensing process can demonstrate whether or not it can be safely operated. The NRC made significant progress in its licence review before funding was cut off. We encourage the US government to implement the provisions of the Nuclear Waste Policy Act and continue with the licensing process. At the same time, we support the development of an energy policy and legal framework that addresses a comprehensive and sustainable programme for the US nuclear-fuel cycle, which includes used-fuel recycling and geologic disposal.

### What challenges face the US nuclear industry in terms of skills?

The US has a very vibrant, technical economy. Around 15 years ago, the number of people seeking to study nuclear specialties dropped, but since then it has risen thanks to the fact that many young people are now excited about the prospects of nuclear and its potential to expand access to electricity in an environmentally responsible way. I am not worried about nuclear-engineering talent, although there is a skills shortage in some areas needed to build new plants, especially in construction, inspection and welding technology. Given that plants take a long time to plan and build, however, I imagine that there would be a response to the demand.

### How will nuclear feature in a future energy mix?

If policy makers determine that a reduction in carbon-dioxide emissions is necessary, then the amount of electricity generated from nuclear has to increase. There is no way to substantially reduce or eliminate carbon-dioxide emissions without nuclear, and it is simply wishful thinking that "renewables" alone will be able to supply the world's growing need for energy. Increasing numbers of energy and climate experts are finding that this conclusion is inescapable.

### What excites you most about the nuclear industry?

There is a lot of exciting technology in terms of new concepts and designs, as well as many important questions that still need to be answered, such as how best to deal with high-level waste. The same kinds of technological innovation that we have seen transform our everyday lives in recent years can also facilitate the use of nuclear technology as the world strives to meet the energy needs of growing economies in a way that does not further threaten the atmosphere. This presents a great opportunity for government, academia and private industry to work together to address these challenges for the benefit of everyone.