physicsworld

physicsworld.com

Volume 23 No 10 October 2010

Nuclear power

The road ahead

Nuclear power

physicsworld

Physics World
Dirac House, Temple Back, Bristol BS1 6BE, UK
Tel: +44 (0)117 929 7481
Fax: +44 (0)117 925 1942
E-mail: pwld@iop.org
Web: physicsworld.com

Editor Matin Durrani
Associate Editor Dens Milne
News Editor Michael Banks
Reviews and Careers Editor Margaret Harris
Features Editor Louise Mayor
Web Editor Hamish Johnston
Web Reporter James Dacey

Advisory Panel John Ellis *CERN,* Peter Knight *Imperial College London,* Martin Rees *University of Cambridge*

Publisher Susan Curtis
Marketing and circulation Gemma Bailey
Display Advertisement Sales Edward Jost
Recruitment Advertisement Sales Chris Thomas
Advertisement Production Mark Trimnell
Diagram Artist Alison Tovey

Head of B2B and Marketing Jo Allen
Art Director Andrew Giaquinto

Subscription information 2010 volume
The subscription rates for institutions are £310/€460/$585 per annum. Single issues are £25.00/€36.00/$47.00.
Orders to: IOP Circulation Centre, CDS Global, Tower House, Lathkill Street, Sovereign Park, Market Harborough, Leicestershire LE16 9EF, UK (tel: +44 (0)845 4561511; fax: +44 (0)870 4420055; e-mail: iop@subscription.co.uk). *Physics World* is available on an individual basis, worldwide, through membership of the Institute of Physics

Bibliographic codes ISSN: 0953-8585
CODEN: PHWOEW
Printed in the UK by Warners (Midlands) plc, The Maltings, West Street, Bourne, Lincolnshire PE10 9PH

IOP Publishing

The Institute of Physics
76 Portland Place, London W1B 1NT, UK
Tel: +44 (0)20 7470 4800
Fax: +44 (0)20 7470 4848
E-mail: physics@iop.org
Web: iop.org

Photolibrary

The road ahead

This special issue of *Physics World* examines the challenges in store for nuclear power

From breathless early excitement at an energy source that could be "too cheap to meter" to the fear and suspicion following the accidents at Three Mile Island and Chernobyl, nuclear power has always aroused strong feelings. Some see it as the ideal carbon-free energy source – a proven technology that will play a key role in our future energy supply. Others, however, regard nuclear power as dirty, dangerous, costly and uneconomic, as our special debate makes clear (p24). And, of course, it has always had to live – fairly or unfairly – in the shadow of the nuclear bomb (p28).

But there are signs that nuclear power could make a dramatic comeback. Countries such as Germany, Italy, Sweden and the UK (p26) are dusting off nuclear plans, extending the lifetime of existing plants, or reversing previous decisions to halt any new stations, which could be good news for physicists looking for a job (p60). In the short term, any new plants are most likely to be pressurized-water reactors – the most common current variety of light-water reactor (p38). But longer term, the nuclear industry is eyeing up a range of six alternative reactor designs, going under the banner generation-IV (p30). Technically fascinating, the reactors promise much, although hurdles remain before any are ever built.

This special issue of *Physics World* also examines the prospects for energy from fusion, focusing on the ITER facility being built in southern France (p46). We weigh up India's ambitious "three-stage" nuclear vision, which seeks to exploit the country's vast reserves of thorium as an alternative to uranium (p40). And online, check out *physicsworld.com* for upcoming video interviews with Christopher Llewellyn Smith – former chair of ITER's council – and with Melanie Windridge, who is spreading the message of fusion via this year's Institute of Physics' Schools Lecture. Our view is that, despite the challenges, particularly of waste (p15, p16 and p55), nuclear power deserves a significant place in the energy mix.

Matin Durrani, Editor of *Physics World*

The contents of this magazine, including the views expressed above, are the responsibility of the Editor. They do not represent the views or policies of the Institute of Physics, except where explicitly stated.

Nuclear power: yes or no?

There are no universal truths in a complex question such as the future role of nuclear power. Each country has a unique energy supply and demand pattern. At one extreme, France gets over 80% of its electricity from fission reactors, so the country would find it almost impossible to do without nuclear power on any realistic timescale. At the other extreme, countries such as Australia, Portugal and Norway have no commercial reactors and limited capacity to develop the technology quickly, so it would take decades for them to develop a nuclear-power industry. Most countries belonging to the Organisation for Economic Co-operation and Development, such as the UK, are somewhere between those two extremes.

The only reason anyone would even consider building nuclear power stations in a nation that does not already have any is the recognition that climate change is a serious threat to our future. A decade ago, nuclear power was widely seen as a failed technology. Originally hailed as cheap, clean and safe, after the Chernobyl accident it was seen as expensive, dirty and dangerous. The peak of nuclear-power installation happened more than 20 years ago. Since then, cancellations and deferments have outnumbered new constructions.

If nuclear power were the only effective way of slowing climate change, then I would support it. However, we would have to put a huge effort into managing nuclear waste. That problem is, in principle, one that we could eventually solve. Storing the current waste is a technical problem, while it is possible in principle to design reactors that could burn materials that are now seen as waste. But even if it were solved, I would remain desperately worried about the proliferation of nuclear weapons, as this is a social and political problem with no apparent prospect of a solution. Fortunately, we may not have to face that terrible dilemma as there are other, much better, ways of moving to a low-carbon future.

Nuclear-waste risks

Nuclear power is certainly not a fast enough response to climate change. In Australia, for example, a strongly pro-nuclear government committee concluded that it would take 10–15 years to build one nuclear reactor from scratch. It proposed a crash programme of 25 reactors by 2050 but then calculated that this would not actually reduce Australia's carbon-dioxide emissions; it would only slow the growth rate.

Nuclear power is also expensive. In most countries, there have to be direct or indirect

Photolibrary

Decision time Is nuclear power the best idea?

There is no risk from terrorists stealing solar panels or wind-turbine blades

public subsidies to make the nuclear option look competitive. Applying a carbon price of about £30 per tonne of carbon dioxide emitted by fossil-fuel power stations would make fossil-fuel electricity more expensive and make nuclear look more attractive, but it would also improve the relative economics of a wide range of renewable supply options. It might be true, as optimists assure us, that a promised new generation of reactors could deliver cheaper electricity, but we cannot afford to delay tackling climate change for decades.

While modern nuclear power stations do not have the technical limitations of the Chernobyl reactor, there will always remain some risk of accidents. There is community anxiety about nuclear energy because an accident at a nuclear power station poses a much more serious risk than an accident at any form of renewable-energy plant. Since nobody has yet demonstrated the safe and permanent management of radioactive waste from nuclear power stations, we can only give the public assurances that the problem will be solved in the future.

There also does not seem to be any real prospect of stopping the proliferation of nuclear weapons. Only five nations had nuclear weapons when the Non-Proliferation Treaty was drafted in 1970. Today, however, there are nearly twice as many, while a further group of countries has the capacity to develop weapons. The more countries that use nuclear technology, the greater is the risk of fissile material being diverted for weapons. Indeed, Mohammed El Baradei, the former head of the International Atomic Energy Agency, told the United Nations that he faced the impossible task of regulating hundreds of nuclear installations with the budget of a city police force. His agency documented countless examples of attempts to divert fissile material for improper purposes. There is a real risk of unaccountable military regimes, rogue dictators or even terrorists having either full-scale nuclear weapons or the capacity to detonate a "dirty bomb" that could make an entire city uninhabitable.

The fundamental point is that there are better alternatives. Australian, European and global studies have concluded that we could reduce demand dramatically – not by turning out the lights, but simply by improving the efficiency of turning energy into services such as lighting – and get all our electricity from a mix of renewables by 2030. That is a more responsible approach to tackling climate change. The clean-energy strategy is quicker, less expensive and less dangerous and there is no risk from terrorists stealing solar panels or wind-turbine blades! A mix of renewable supply systems would decentralize energy production, thus making societies more resilient and better insulated against natural disasters or terrorist action. We also know how to decommission wind turbines and solar panels at the end of their life, at little cost and with no risk to the community. So the question for pro-nuclear advocates is, as Australian political analyst Bernard Keane put it, "Why should taxpayers fund the most expensive and slowest energy option when so many alternatives are significantly cheaper and pose less financial risk?"

Ian Lowe is president of the Australian Conservation Foundation and a climate scientist at Griffith University, e-mail i.lowe@griffith.edu.au

• Both authors contributed to a new book *Why vs Why: Nuclear Power* outlining the case for and against nuclear energy (2010, Pantera Press)

The world is caught between providing enough energy for its citizens and fighting climate change by burning less fossil fuel. **Ian Lowe** says that climate change can only be tackled by using renewable energy sources, while **Barry Brook** argues that nuclear power offers the only alternative to fill this impending energy gap

As China, India and other populous developing nations expand their economies, with the very human aim of improving the prosperity and quality of life enjoyed by their citizens, the global demand for cheap, convenient energy is growing rapidly. If this demand is met by fossil fuels, then we are heading for both an energy-supply bottleneck and, because of the associated massive carbon emissions, a climate disaster.

Ironically, if climate change is the "inconvenient truth" facing high-energy-use, fossil-fuel-dependent societies such as the US, Canada, Australia and many countries in the European Union, then the inconvenient solution staring back is advanced nuclear power. The answer does not principally lie with renewable energy sources such as solar and wind, as many claim. However, these technologies will likely play some role.

There is a shopping list of "standard objections" used to challenge the viability or desirability of nuclear fission as a clean and sustainable energy source. None of these arguments stands up to scrutiny. Opponents claim that if the world ran on nuclear energy, then uranium supplies would run out in the coming decades and nuclear power plants would then have to shut down. This is false. Uranium and thorium are both more abundant than tin; and with the new generation of fast-breeder and thorium reactors, we would have abundant nuclear energy for millions of years. Yet even if the resources lasted a mere 1000 years, we would have ample time to develop exotic new future energy sources.

There is no silver bullet for solving the energy and climate crises, but there are bullets, and they are made of uranium and thorium

Going nuclear

Critics argue that past nuclear accidents such as Chernobyl mean that the technology is inherently dangerous. However, this simply ignores the fact that nuclear power is already hundreds of times safer than the coal, gas and oil we currently rely on. A study of 4290 energy-related accidents by the European Commission's ExternE research project, for example, found that oil kills 36 workers per terawatt-hour, coal kills 25 and that hydro, wind, solar and, yes, nuclear, all kill fewer than 0.2 per terawatt-hour. Moreover, in nuclear reactors the passive safety features do not rely on engineered intervention and so remove the chance of human error, making it impossible to have a repeat of serious accidents. For example, in an emergency in the core cooling tank of a Westinghouse AP-1000 third-generation nuclear power plant, water is channelled into the reactor core by gravity, rather than by electric pumps.

Some contend that expanding commercial nuclear power would increase the risk of spreading nuclear weapons. First, this has not been true historically. Furthermore, the metal–fuel products of modern "dry" fuel recycling using electrorefining, which are designed for subsequent consumption in fast reactors, cannot be used for bombs because it is not possible to separate pure plutonium from the mix of uranium and minor actinides. Potential bomb-makers would get only a useless, dirty, contaminated product in a mix of heavy metals. Indeed, burning plutonium in fast reactors to generate large amounts of electricity would take this material permanently out of circulation, making it the most practical and cost-effective disposal mechanism imaginable. Those opposed to nuclear energy also claim that it leaves a legacy of nuclear waste that would have to be managed for tens of thousands of years. This is true only if we do not recycle the uranium and other heavy "transuranics" metals in the waste to extract all their useful energy.

At present, mined uranium is cheap. For light-water reactor technology, the total fuel costs – including mining, milling, enrichment and fuel-rod fabrication – is £13m a gigawatt per year. In unit-cost terms, that works out at 0.13p a kilowatt-hour for uranium oxide at a price of £45 per kilogram. However, in the longer term a once-through-and-throw-away use of nuclear fuel makes no economic sense. This is because such "open" fuel cycles not only leave a legacy of having to manage long-lived actinide waste, but they also inefficiently extract less than 1% of the energy in the uranium. Feeding nuclear waste into fast reactors will use all of the energy in uranium, and liquid-fluoride thorium reactors will access the energy stored in thorium, which works out as an 160-fold gain!

After repeated recycling, the tiny quantity of fission products that would remain would become less radioactive than natural granites and monazite sands within 300 years. To claim that large amounts of energy (thus generating greenhouse gases) would be required to mine, process and enrich uranium, and to construct and later decommission nuclear power stations simply ignores a wealth of real-world data. Authoritative and independently verified whole-of-life-cycle analyses in peer-reviewed journals have repeatedly shown that energy inputs to nuclear power are as low as, or lower than, wind, hydro and solar thermal, and less than half those of solar photovoltaic panels. That is today's reality. In a future all-electric society – which includes electric or synthetic-fuelled vehicles supplied by nuclear power plants – greenhouse-gas emissions from the nuclear cycle would be zero.

Embracing nuclear energy

Finally, when all other arguments have been refuted, critics fall back on the claim that nuclear power takes too long to build or is too expensive compared with renewable energy. These arguments are perhaps the most regularly and transparently false arguments thrown up by those trying to block nuclear power from competing on a fair and level playing field with other energy sources. Many environmentalists believe that the best low-carbon solution is for governments to guide us back to simpler, less energy-consuming lives. Notions like that are unrealistic. The world will continue to need energy, and lots of it. But fossil fuels are not a viable future option. Nor are renewables the main answer. There is no single solution, or silver bullet, for solving the energy and climate crises, but there are bullets, and they are made of uranium and thorium – the fuels needed for nuclear plants.

It is time that we embraced nuclear energy as a cornerstone of the carbon-free revolution we need in order to address climate change and long-term energy security in a world beyond fossil fuels. Advanced nuclear power provides the technological key to unlocking the awesome potential of these energy metals for the benefit of humankind and for the ultimate sustainability of our society.

Barry Brook holds the Sir Hubert Wilkins chair of climate change at the University of Adelaide's Environment Institute in Australia. He also runs the popular climate-change blog *BraveNewClimate.com*, e-mail barry.brook@ adelaide.edu.au

The lost leader

With the UK having let its once-proud lead in nuclear technology fritter away, **Geoff Allen** looks at how the country can make the most of a bad situation

The UK has long been a pioneer in nuclear energy. It became the first nation to adopt – and then implement – a plan to supplant coal with atomic energy. It opened the world's first full-size nuclear power station in 1956 at Calder Hall in Cumberland, which was a gas-cooled, graphite-moderated "Magnox" reactor using fuel rods of natural uranium metal encased in finned, magnesium-alloy cans. Flushed by that early success, nine other Magnox plants were ordered by the then generating boards for various sites, which came online in the early 1960s. Producing some 10% of the country's electricity, these reactors promised much for the future.

The natural successor to the Magnox stations was the advanced gas-cooled reactor (AGR) designed by the UK Atomic Energy Authority (AEA). But by the late 1960s, the UK seemed to have lost the political will and organizational ability to tackle large projects successfully. The AEA's design team was broken up and replaced by five private engineering consortia, which proved a disaster. The lead AGR station – Dungeness B – was ordered in 1965 but only began operating in 1983, some 13 years later than planned. Meanwhile, further restructuring in the mid-1970s left the UK back where it began, with just one design team (British Nuclear Design and Construction) as the main contractor. The lack of progress was not the fault of the AGR technology, but simply one of administration.

By the time that a second power programme involving seven AGRs was completed in 1988, the nuclear industry was supplying more than 20% of the UK's electricity. But by then, pressurized-water reactors (PWRs) were the technology of choice around in the world, with France, for example, having long moved away from AGR technology and begun a massive programme to build 58 PWRs. In many ways PWRs are superior to AGRs, being largely factory-built, which means they are up to 30% cheaper to construct than an AGR of the same capacity because major components can simply be transported ready-made to where they are needed.

Eventually, the Central Electricity Generating Board (CEGB) – the UK's state-owned power-generating company – decided to follow suit and go down the PWR route. But in the absence of a UK-designed PWR, it opted instead for a US-designed version, drawing up plans to build 23 such reactors on UK soil. However, the oil crisis and economic downturn of the early 1970s tempered this enthusiasm, the anticipated demand for electricity was not realized, and such a large expansion of the nuclear programme was deemed unnecessary.


British Energy

What next? The Sizewell B pressurized-water reactor is the only UK nuclear power station to have opened in the last 20 years.

In the end, the UK only built one PWR – the Sizewell B station in Suffolk, which eventually opened in 1995 after a lengthy public enquiry. The point of this inglorious story is that, rather than choosing – and sticking with – one design, as France and many other countries have done, the UK dabbled in too many different options. The CEGB even toyed with the idea of building a fleet of fast-breeder reactors or steam-generating heavy-water reactors, all of which came to naught.

Filling the gap

The question facing the UK today is how to fill the massive gap in our electricity supplies that is looming large as the last of the ageing Magnox stations are forced to close – Oldbury-on-Severn in 2012 and Wylfa (in north Wales) in 2014. That these plants continue to be pressed into service more than 40 years after they were built is itself testimony to the superb – and sadly largely unrecognized – engineering that went into their construction and design.

The UK's energy needs are rising yearly as purchases of electrically powered equipment (electric cars, domestic appliances, etc) continue to increase and as the government seeks to build an additional 200 000 new homes per year. Yet the country continues to rely on imported coal for almost 40% of its energy supply, while its various domestic coal-fired power stations are scheduled to close at the end of 2015. Of course, there is wind power, but its supply is intermittent and the amount of electricity generated by the UK's 3000 existing wind turbines account for a mere 2% of the country's energy requirement.

Thankfully, nuclear power is back on the agenda, and the UK energy minister Charles Hendry has revealed that a National Policy Statement to pave the way for a new generation of nuclear reactors will be presented to parliament next spring. Hinkley Point in Somerset has been earmarked to be the first in the new wave of reactors, with energy giant EDF having submitted a planning application to build two massive plants at Hinkley C. However, these are unlikely to be in operation until well after 2018 – even assuming that planning permission is granted. Similarly, there is very little optimism that the Horizon plan – a joint venture between energy companies E.ON UK and RWE npower to construct a nuclear plant at Oldbury – could generate energy before 2025. Moreover, it is inconceivable that the UK will revert to the plethora of nuclear reactors that it had in the 1970s. Instead, these will probably be of one type – the PWR – built by different firms.

The problem for the UK nuclear industry is that, with the CEGB having been dissolved in 1990, only two of the six firms currently supplying electricity to homes – Centrica plus Scottish and Southern Energy – are UK owned. British Energy belongs to France's EDF, which also controls International Power, while Scottish Power has gone to Spain's Iberdrola and npower has fallen to Germany's RWE. While the nationality of the owners does not, in principle, matter, the problem is that these firms will, where possible, use their own staff and reactor designs, leaving the UK's nuclear expertise trailing and without the infrastructure to build its own indigenous nuclear plants.

Still, the French seem to be extremely good at nuclear power; the question is, can they do it in the UK?

Geoff Allen is an AWE William Penney Fellow at the Interface Analysis Centre, University of Bristol, UK, and has worked in the nuclear industry since 1970, e-mail g.c.allen@bristol.ac.uk

Nuclear fear revisited

With a revised edition of a landmark book about the public image of nuclear power due out soon, Robert P Crease explains why its central message is still relevant more than 20 years on

In 1988 the science historian Spencer Weart published a groundbreaking book called *Nuclear Fear: A History of Images*, which examined visions of radiation damage and nuclear disaster in newspapers, television, film, literature, advertisements and popular culture. In his analysis, Weart noticed something odd about nuclear-disaster scenarios: we have seen them all before. He found that their imagery and plots eerily resemble those of pre-nuclear and even pre-technological disaster scenarios.

In involving arrogant scientists who play God by probing nature's secrets with special machines before unleashing powers that they cannot control to destroy the world, these plots are suspiciously similar to earlier stories involving magicians or alchemists who play God by probing nature's secrets with special devices or processes before eventually unleashing world-destroying powers that *they* cannot control.

Tales of witches unleashing magical powers, Weart noted, have much to do with anxieties about socially disruptive classes of people. Likewise, fictional tales of technological apocalypse have much to do with anxieties about modern civilization, the role of technology and the social authority of scientists. The plot is what Weart calls "Faust's sin of prideful power divorced from moral responsibility"; the new nuclear technology merely feeds the image by giving the dangerous scientist more expensive and flashier hardware to do it with.

Nuclear fear, Weart concluded, has less to do with our knowledge of atomic structure and its exploitation than with psychology, history and culture. His book explained why public discussions of nuclear power tend not to centre on issues but to be derailed by passions having nothing to do with either the technology or the wisdom of its use.

Has nothing changed? Weart raises this question in a forthcoming revision of his 1988 book and in the article "Nuclear fear 1987–2007: Has anything changed? Has everything changed?", which appears in the new book *Filling the Hole in the Nuclear Future* edited by Robert Jacobs (2010, Lexington Books). Weart's surprising answer,

Martin Bond/Science Photo Library

Public image Examining the culture of the nuclear age.

backed up by polls, surveys and media analyses, is that nuclear fear declined in the wake of two events of 1986. One was the start of *détente* after that year's Reykyavik summit between presidents Reagan and Gorbachev. "A significant part of the fear of nuclear reactors is displaced fear of nuclear war," Weart told me. "With the ending of the Cold War, it was natural for this general fear of being irradiated and blown up to diminish."

The other event was the Chernobyl reactor disaster, coming seven years after the Three Mile Island accident. "[I]n a seeming paradox," Weart writes in his recent article, "the worst civilian nuclear disasters in history ultimately brought a decline in public concern about nuclear power." By silencing the utopian claims of nuclear-power proponents, fostering more cautious technologies, and curtailing reactor start-ups, the accidents leached energy from the anti-nuclear movement.

Those born after 1986, says Weart, "did not grow up in a world where talk of nuclear war, radiation, nuclear reactors and so forth showed up frequently in the news, and even sometimes in personal relations, in a context full of anxiety". Indeed, nuclear reactors are now prosaic enough to be mocked in cartoons. "How many have first met a nuclear reactor in the introductory sequence of the perennially popular cartoon show *The Simpsons*, featuring a lovable but amusingly incompetent reactor operator?"

Changes afoot

So has everything changed? No. Nuclear fear is still potent, losing none of its old associations and gaining new outlets. "Nuclear terrorism", Weart writes, "does trump all." When the Bush administration wanted to mobilize public opinion for its 2003 invasion of Iraq, for example, its most effective tool was an appeal to (imagined) Iraqi weapons of nuclear, rather than biological or chemical, destruction. Nuclear threats are still the terrorist weapon of choice, both in popular culture – films and computer games – and also in the real world. "The complex of imagery walks in the real world, to no good result," Weart writes.

Last summer, a right-wing blogger publicized a 2.5 minute video of Shirley Sherrod, a Department of Agriculture official in the Obama administration, seeming to admit to having mistreated a white farmer. The ugly, racist portrait that the video created was so repugnant that Sherrod was fired immediately, before even being consulted. The blogger, it turned out, had sharply edited a 20-minute speech to make it emotionally repellent. Anyone who listened to the entire speech understood that Sherrod's message was about the need to treat everyone equally. It was a lesson in image manipulation. Sherrod was offered her job back afterwards, when her message was considered coolly and in context.

Reactors, too, are vulnerable to what one might call "Sherroding". Nuclear fear cannot be switched off, for the associative and affective reasons that Weart identified. Until recently, the anti-nuclear movement had skilfully wielded powerful images of worst-case scenarios, mushroom clouds and genetically damaged children to create a "cultural hysteresis" in which nuclear reactors are equated with Chernobyl, and nuclear disasters with Hiroshima. Weart may be right to see a diminution of nuclear fear, but activists can still inflame it. His work helps lessen our dependence on historical events and, by giving us an understanding of the deep non-scientific roots of nuclear fear, helps us address it.

Given the planetary threat posed by global warming, and the possible use of nuclear power as an alternative to ultimately dangerous fossil-fuel technologies – which store their wastes in the atmosphere, for free – optimally addressing global safety requires the ability to debate reactor technology, its strengths and weaknesses, independently of that cultural hysteresis. Otherwise, there may be no afterwards in which to consider it coolly.

Robert P Crease is chairman of the Department of Philosophy, Stony Brook University, and historian at the Brookhaven National Laboratory, US, e-mail rcrease@notes.cc.sunysb.edu

Nuclear's new generation

Physicists are designing new types of nuclear reactor that could be cheaper, greener, safer and more secure than existing plants. But as **Edwin Cartlidge** discusses, these designs must overcome major technical and financial hurdles if they are ever to see the light of day

Edwin Cartlidge is a science journalist based in Rome, e-mail edwin.cartlidge@yahoo.com

After a 20-year slump following accidents at Three Mile Island in the US and Chernobyl in the former Soviet Union, the power of the atom is making a comeback. In the past two years alone, China has begun constructing 15 new nuclear power stations, while Russia, South Korea and India are also initiating major expansions in atomic power. Some Western countries look set to join them: at the end of 2009, licence applications for 22 new nuclear plants had been submitted in the US, while the Italian government has said that it will reverse a ban on nuclear power and start constructing reactors by 2013.

The reasons for this resurgence are not hard to spot. One is the political importance of fighting anthropogenic global warming: nuclear reactors do not emit greenhouse gases during operation, and are more reliable than other low-carbon energy sources such as solar or wind power. The other is energy security: governments are keen to diversify their energy sources and distance themselves from politically unstable suppliers of fossil fuels. As a result of such pressures, a report published in June this year by the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development's Nuclear Energy Agency anticipated that the world's total nuclear generating capacity could more than triple over the next four decades, rising from the current 370 GW to some 1200 GW by 2050.

However, the agencies believe that countries must develop more advanced nuclear technologies if this form of energy is to continue to play a major role beyond the middle of the century. Today's reactors are mostly "second generation" facilities that were built in the 1970s and 1980s. The "third generation" facilities that are gradually replacing them often incorporate additional safety features, but their basic designs remain essentially the same. Moving beyond these existing technologies will require extensive research and development, as well as international co-operation. To this end, in 2001 nine countries set up the Generation-IV International Forum (GIF), which aims to foster the development of "fourth generation" reactors that improve on current designs in four key respects: sustainability, economics, safety and reliability, and non-proliferation.

Since then, the forum has expanded to 13 members (including the European Atomic Energy Community, EURATOM) and it has identified six designs that merit further development. The hope is that one or more of these will be ready for commercial deployment in the 2030s or 2040s, having proved their feasibility in demonstration plants in the 2020s. But the scientists and engineers working on these designs have many formidable technical challenges to overcome, and must convince funders that the advantages of these advanced reactors over existing plants will be worth the billions needed to deploy them.

> The scientists working on these advanced reactors have many formidable technical challenges to overcome, and must convince funders that the advantages of these designs will be worth the billions needed to deploy them

A slow (neutron) start

Nuclear-fission reactors generate energy by splitting heavy nuclei, with each splitting giving off neutrons that go on to split further nuclei. This process creates a stable chain reaction that releases copious amounts of heat. The heat is taken up by a coolant that circulates through the reactor's core and is then used to produce steam to drive a turbine and generate electricity. Most existing nuclear plants are "light-water reactors", which use uranium-235 as the fissile material and water as both the coolant and moderator. A moderator is needed to slow the neutrons so that they are at the optimum speed to fission uranium-235 nuclei.

Of the six designs for generation-IV reactors (see table on page 32), the closest to existing light-water reactors is the "supercritical water-cooled reactor". Like light-water reactors, this design uses water as the coolant and moderator, but at far higher temperatures and pressures. With the coolant leaving the core at temperatures of up to 625 °C, the reactor's thermodynamic efficiency – the ratio of power generated as electricity to that produced in the fission reactions – can reach as high as 50%. This compares favourably to the 34% typical of today's reactors, which operate at just over 300 °C. Moreover, because the cooling water exists above its critical point, with properties between those of a gas and a liquid, it is possible to use it to drive the turbine directly – unlike in existing designs, where the coolant heats up a secondary loop of water that then drives the turbine.

Photolibrary

Challenges ahead The next generation of nuclear reactors will be difficult to implement, both technically and financially.

Reactors for a new generation – promises and problems

Design	How it works	Advantages	Disadvantages
Supercritical water-cooled reactor	Water is heated to above its critical point (where it has both liquid and gas properties) and used to drive a turbine directly	High efficiencies; reduced plant cost due to a simpler heat- exchange system	New materials needed to withstand high temperatures and pressures; chemistry of supercritical water poorly understood
Very-high-temperature reactor	Uses helium as a coolant, allowing the reactor to reach temperatures of up to 1000 °C; fuel is contained in pebbles or blocks to improve safety and refuelling	Very high efficiencies; potentially able to produce heat and hydrogen as well as electricity	New fuels and reactor components needed for such high temperatures
Sodium-cooled fast reactor	Builds on existing sodium-cooled reactors, which use "fast" rather than "thermal" neutrons	Potential to breed plutonium fuel and burn radioactive waste, thus "closing" fuel cycle	Reactivity and radioactivity of sodium coolant complicate operation and upkeep, and increase plant cost
Gas-cooled fast reactor	Fast reactor with helium coolant	Fuel breeding and waste burning; potential to provide heat and hydrogen; uses inert coolant	Helium is much poorer coolant than sodium
Lead-cooled fast reactor	Fast reactor with liquid-lead coolant	Fuel breeding and waste burning; inert coolant	Corrosion of other metals in reactor
Molten-salt reactor	Uses nuclear fuel dissolved in a circulating molten-salt coolant; could use either fast or thermal neutrons	No need to fabricate fuel; could be used to breed fissile thorium	Chemistry of molten salt not well understood; corrosion is a problem

Both of these improvements would reduce the cost of nuclear energy. However, a number of significant technological hurdles must be overcome before they can be implemented, including the development of materials that can withstand the high pressures and temperatures involved, plus a better understanding of the chemistry of supercritical water.

Another generation-IV option, the "very-high-temperature reactor", uses a helium coolant and a graphite moderator. Because this design uses a gas coolant rather than a liquid one, it could operate at even higher temperatures – up to 1000 °C. This would boost efficiency levels still further and also allow such plants to generate useful heat as well as electricity, which could potentially be used to produce hydrogen that is needed in refineries and petrochemical plants (figure 1).

Some elements of this concept for a very-high-temperature reactor have already been investigated at lower temperatures in prototype gas-cooled reactors built in the US and Germany. A number of countries are also developing reactors that operate at intermediate temperatures of up to 800 °C. Until recently, one of the most advanced intermediate-temperature projects was South Africa's "pebble-bed modular reactor", which was designed to use hundreds of thousands of fuel "pebbles" – cricket-ball-sized spheres each containing about 15 000 kernels of uranium dioxide enclosed inside layers of high-density carbon to confine the fission products as the fuel burns. The reactor core would also contain 185 000 fuel-free graphite pebbles to moderate the reaction.

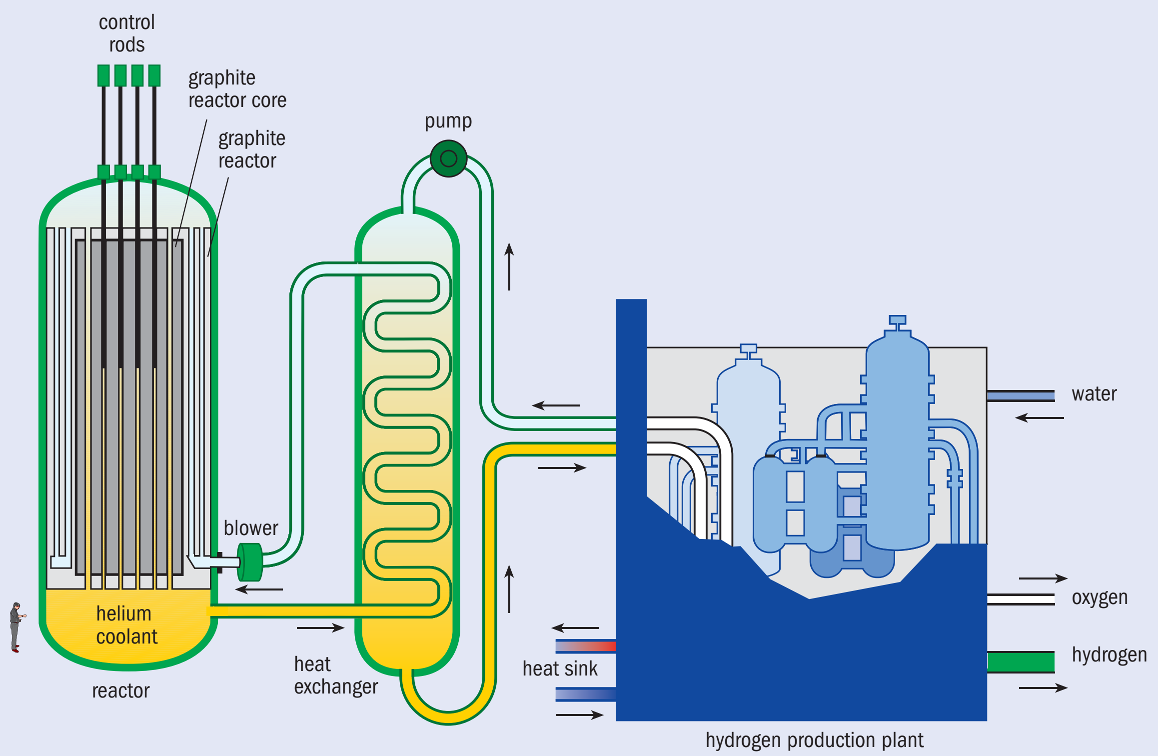
Packaging the fuel in this way confers two major potential advantages over the fuel rods used in conventional light-water reactors. One is that pebble-bed-type reactors could be refuelled without shutting them down; the pebbles would simply fall to the bottom of the reactor core as their fuel burned and then be reinserted at the top of the core, thus allowing the reactor to supply energy continuously. Pebble-bed reactors could also be designed to be "passively safe", meaning that any temperature rise due to a loss of coolant would reduce the efficiency of the fission process and bring the reactions to an automatic halt.

However, in July the South African government decided to end its involvement in pebble-bed research. Jan Neethling, a physicist at the Nelson Mandela Metropolitan University in Port Elizabeth who has worked on developing the fuel pebbles, believes that following elections in 2009, the new government decided that the country's urgent energy needs would be better met with coal and conventional nuclear plants – rather than with a potentially more efficient and safer but untried and problematic alternative.

One factor that may also have played a role in the South African government's decision to abandon the peeble-bed idea is a 2008 report by Rainer Moormann of the Nuclear Research Centre at Jülich, Germany, which operated a small pebble-bed reactor between 1967 and 1988. The report indicated that radiation may have leaked out of the pebbles, making repairs and maintenance of pebble-bed reactors potentially more costly than previously envisaged. Also, customers and international investors never really got behind the South African project, mirroring the Jülich centre's earlier failure to sell their pebble-bed technology to Russia. "We had a very good flagship project that combined the work of many scientists and engineers," says Neethling, "but more time and money is needed to commercialize this concept."

Opinion is divided on the significance of the South African project's termination. Stephen Thomas, an energy-industry expert at the University of Greenwich in London, calls it a "major setback" for the development of very-high-temperature reactors, since, he says, South Africa's efforts appeared to be more advanced than research being carried out elsewhere. However, Bill Stacey, a nuclear engineer at the Georgia Institute of Technology in the US, disagrees with this assessment, adding that South Africa was "just one of many players and not one of the major ones". China, Japan, France and South Korea are also developing technology for high-temperature reactors, some of which is

1 A useful sideline



Very-high-temperature reactors could generate the heat required to produce hydrogen by splitting water molecules.

also designed to use pebbles.

For its part, the US is pursuing a variant of the pebble-bed design known as the Next Generation Nuclear Plant (NGNP). Intended to reach temperatures of 750–800 °C, the NGNP will allow for different fuel configurations, with the coated fuel kernels held either in pebbles or hexagonal graphite blocks. According to Harold McFarlane, technical director of GIF and a researcher at the Idaho National Laboratory, the US Congress approved the construction of a prototype NGNP in 2005 but has so far awarded funding only for preliminary research and development. The US Department of Energy is now trying to set up joint funding for the project with industry. The reactor is unlikely to be completed by its original target date of 2021, McFarlane says, and where it will be built still needs to be determined, although speculation so far has concentrated on sites along the Gulf Coast.

Faster neutrons

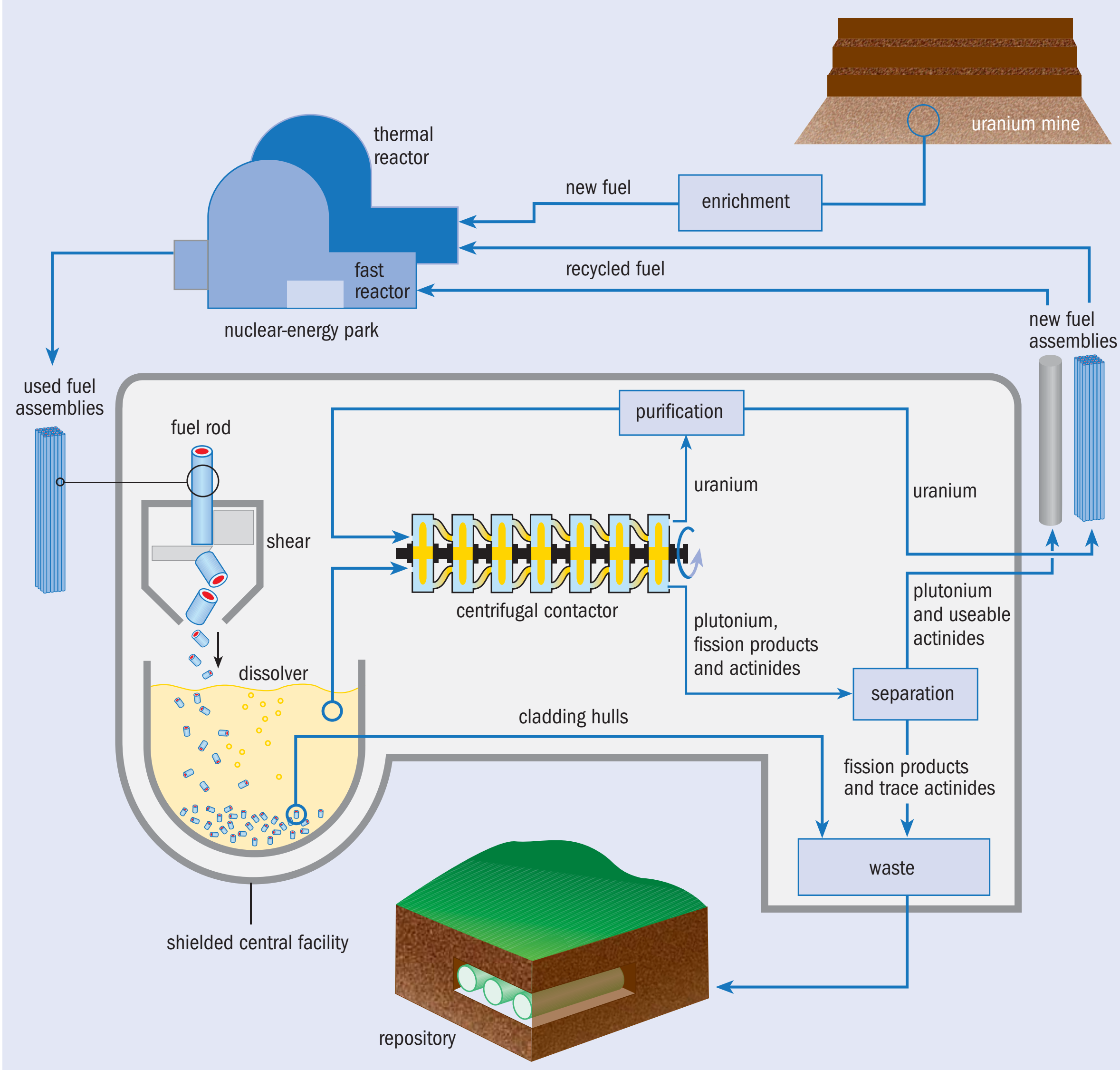
Both the supercritical water-cooled reactor and the very-high-temperature reactor would use uranium-235 as fuel. However, less than 1% of naturally occurring uranium comes in this form: the remaining fraction is uranium-238, which ends up as "depleted uranium" after uranium ore is enriched to produce reactor-grade fuel (typically about 5% uranium-235, 95% uranium-238). Significant amounts of uranium-238 are also discarded as waste after the fissile fraction of reactor-grade fuel has been consumed. Many nuclear experts therefore believe that this "open fuel cycle" is a waste of resources. It would be better, they say, to recycle the uranium and plutonium that make up the bulk of spent fuel as well as the depleted uranium in what is known as a "closed fuel cycle" (figure 2).

The most efficient way of doing this is to use "fast reactors", which do not moderate the speed of fission neutrons. Such reactors require a far higher concentration of fissile material, usually plutonium-239, to generate sustained chain reactions than moderated, or "thermal", reactors do. But they are far better at converting non-fissile uranium-238 into plutonium-239 via neutron absorption. In fact, fast reactors can be made to produce more plutonium-239 than they consume – a process known as "breeding" – by surrounding the reactor core with a "blanket" of uranium-238. Using uranium-238 in this way would extend the lifetime of the world's uranium resources from hundreds to thousands or even tens of thousands of years, assuming no increase in current nuclear generating capacity. Fast reactors could also be made to burn some of the long-lived, heavier-than-uranium isotopes (known as "transuranics") that make up spent fuel, converting them to shorter-lived nuclides and thereby reducing the volume of nuclear waste that needs to be stored in long-term geological repositories (see review of *Into Eternity* on p55).

All four of the remaining generation-IV reactor designs could be configured to work as fast reactors. The main difference between them is in their cooling systems – an aspect of fast-reactor design that seems to offer plenty of scope for innovation. So far, nearly all of the world's fast reactors have used sodium as a coolant, taking advantage of the material's high thermal conductivity. Unfortunately, sodium reacts violently when it comes into contact with either air or

Significant amounts of uranium-238 are discarded as waste after the fissile fraction of reactor-grade fuel has been consumed

2 More fuel, less waste



An illustration of a "closed" fuel cycle where fast reactors are employed to generate energy from plutonium and uranium-fission by-products.

water. As a result, at least two sodium-cooled reactors have been shut down for significant periods due to fires. One of them, Japan's Monju prototype fast reactor, experienced a major sodium–air fire in 1996 and only restarted earlier this year, almost a decade and a half later. Even without such incidents, the very fact that sodium and air need to be kept apart means that refuelling and repairs are more complicated and time-consuming than for water-cooled reactors. The one commercial-sized fast reactor built to date, France's Superphénix (figure 3), was shut down for more than half the time it was connected to the electrical grid (between 1986 and 1996).

Scientists working on generation-IV sodium fast reactors are aiming to make them cheaper through improved plant layout and steam generation

Sodium also becomes extremely radioactive when exposed to neutrons. This means that sodium-cooled fast-reactor designs must incorporate an extra loop of sodium to transfer heat from the radioactive sodium cooling the reactor core to the steam generators; without it, a fire in the generators could release radioactive sodium into the atmosphere. This extra loop adds significantly to the cost of such reactors. Indeed, according to a recent report from the International Panel on Fissile Materials (IPFM) – a group promoting arms control and non-proliferation policies – the fast reactors constructed so far have typically cost twice as much per kilowatt of generating capacity as water-cooled reactors.

Scientists working on generation-IV sodium fast reactors are aiming to make them cheaper through improved plant layout and steam generation. They are also experimenting with more inherent safety features, such as arranging the reactor vessel and other components so that if the system overheats, the sodium naturally transports the excess heat out of the system, not back into it. Researchers in both France and Japan hope to start operating new sodium reactors that incorporate such advanced features at some point in the 2020s.

The three non-sodium-cooled fast-reactor designs being explored by the GIF each have their own advantages, but major technological hurdles mean they are more of a long-term prospect. The "gas-cooled fast reactor", like its thermal equivalent, would operate at high temperatures (up to 850 °C), generating electricity more efficiently than a sodium plant and raising the possibility of producing hydrogen or heat as well. Unfortunately, although the helium gas coolant in such a plant would be inert, helium is a much poorer coolant than sodium. Given the high concentrations of fissile material needed in a fast-reactor core, this makes gas-cooled designs extremely challenging to implement.

No less challenging is the "lead-cooled fast reactor". Like helium, lead does not react with air or water, which would potentially simplify the plant design. Unfortunately, a liquid-lead coolant would corrode almost any metal it touched, so new kinds of coatings would be needed to protect the reactor's components from corrosion.

The final and most ambitious generation-IV concept is the "molten-salt reactor". This design calls for the nuclear fuel to be dissolved in a circulating molten-salt coolant, the liquid form doing away with the need to construct fuel rods or pellets and allowing the fuel mixture to be adjusted if needed. Such a reactor could use either fast or thermal neutrons, and could also be used to breed fissile thorium (see "Enter the thorium tiger" on p40) or burn plutonium and other by-products. However, the chemistry of molten salts is not well understood, and special corrosion-resistant materials would need to be developed.

3 No phoenix rising


Yann Forget

The world's only commercial-scale fast reactor, France's Superphénix, suffered a range of maintenance problems and frequent shut-downs during its 11-year lifetime.

Thinking ahead

In addition to the considerable research and development needed to implement each of the individual fast-reactor designs, new kinds of plants for reprocessing and refabricating the fuel would be required to commercialize the technology. Beyond this, however, lies an even bigger problem associated with fast reactors: the freeing up of weapons-grade plutonium during reprocessing. According to the IPFM, there is currently enough plutonium in civilian stockpiles to make tens of thousands of nuclear weapons, and the continued development of fast reactors would only add to this. Advocates of fast reactors have proposed keeping the reprocessed plutonium bound up with some of the transuranics inside spent fuel, which would in theory make it more difficult to steal because the mixed plutonium–transuranic packages would be more radioactive than plutonium alone. However, panel co-chair Frank von Hippel of Princeton University in the US points out that radiation levels in such packages would still be lower than those found in spent fuel before reprocessing. A report produced last year by a group of nine scientists working at the US's national laboratories did not find that this transuranic bundling would significantly reduce the risk of proliferation, von Hippel adds.

Edwin Lyman of the Union of Concerned Scientists in Washington, DC, agrees. "Fast reactors should not be part of future nuclear generating capacity at all," he says. "Around $100bn has been wasted on this technology with virtually nothing to show for it. Research and development on nuclear power should instead be focused on improving the safety, security and efficiency of the once-through cycle without reprocessing."

This view is not shared by Stacey. Although he acknowledges that the technical challenges in commercializing fast reactors are "sobering", he believes that the arguments in favour of closing the fuel cycle are still compelling. "You can't provide nuclear power for a long time using 1% of the energy content of uranium," he says, referring to the tiny fraction of natural uranium that is fissile. "And as it is, the spent fuel is stacking up and at some point we are going to need to do something about it. We can bury it but we would need sites that can contain it for a million years. That stretches credibility."

Whether or not any of the generation-IV designs are commercialized will depend on a broad range of issues, including those beyond the purely technical. These include the need to build up a skilled workforce and maintain safety standards at existing plants, as well as the political problem of what to do with nuclear waste. The industry's progress on constructing third-generation plants will also influence what follows them.

But as William Nuttall of Cambridge University's Judge Business School points out, perhaps the most important factor is economics. Nuttall, an energy-policy analyst specializing in nuclear power, says it is still not clear how far governments are prepared to go in implementing policies such as carbon taxes that could make nuclear energy cost-competitive with fossil fuels. As for fast reactors, higher prices for uranium could make them more attractive in the future, he suggests, as long as their capital costs and reliability measure up.

"The question is what the scale of the nuclear renaissance will be, especially in Europe," says Nuttall. "If it means simply replacing nuclear with nuclear, then there is probably no need to go beyond light-water reactors. But if you want to, say, replace coal with nuclear, then there could be room for generation-IV." The important thing, he believes, is to keep the option open. "We don't want to be in a position 20 years down the line when we wish we could have done it, but find we can't," he says. ■

Beyond the envelope

Accelerator-driven sub-critical reactor

How it works
Conventional fission involves a self-sustaining nuclear chain reaction, with the neutrons produced in one reaction going on to split more nuclei, and so on. Once a chain reaction is established, then the reactor is said to be "critical" and must be carefully controlled to ensure that the number of neutrons does not escalate and result in "super-criticality". If, on average, fewer than one neutron goes on to split more nuclei, then the reaction is "sub-critical" and the fission will eventually die away. Accelerator-driven sub-critical reactors (ADSRs) are purposely kept sub-critical. The reaction is sustained by actively supplementing the reactor core with extra neutrons using an external accelerator. It fires beams of protons at a heavy-metal target within the reactor, where neutrons are chipped off to maintain fission. The chain reaction keeps going as long as the accelerator is still firing protons; to put an end to the reaction, the proton beams are simply turned off. It is proposed that the reactor could burn thorium as a fuel and use lead as the coolant.

Who is behind it?
First suggested by the Nobel-prize-winning physicist Carlo Rubbia, the idea has since been taken on by various research organizations, including the Belgian Nuclear Research Centre SCK•CEN, which has funding for a test reactor. The Thorium Energy Amplifier Association (ThorEA) in the UK has called for a public–private partnership in which a public investment of £300m would finance a five-year period of research and development, which it says would stimulate £1.5–2bn of commercial support.


STFC
Round and round The EMMA proof-of-principle prototype accelerator can now store a particle beam.

Plus points
The design is inherently safe, and thorium has many advantages over uranium as a nuclear fuel (see "Enter the thorium tiger" on p40). Thorium is three times as abundant as uranium and, moreover, breeder reactors such as ADSRs use all the fuel, meaning supplies will last thousands, rather than hundreds, of years. As a sideline, excess neutrons from the heavy-metal target could be used to convert waste from conventional reactors into isotopes that are much less radioactive.

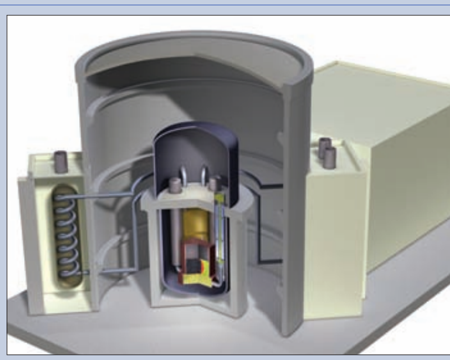
Drawbacks
At present, existing accelerators are just too expensive – each accelerator costs in the region of a billion dollars. Also, accelerators with sufficient reliability – i.e. making sure that the proton beam remains turned on – have not yet been demonstrated. This means that several pricey accelerators are required, not just one. Little ADSR research has so far been carried out.

Prospects
One promising idea for delivering a reliable beam of high-power protons is the non-scaling fixed-field alternating-gradient accelerator (nsFFAG). A prototype nsFFAG called EMMA has been built at the Daresbury Laboratory in the UK to test the concept, and is now conducting experiments. ThorEA expects that the technologies required for ADSRs will be developed, and functioning demonstrations delivered, within five years and that a privately funded prototype could be built and commissioned by 2025.

Travelling-wave reactor

How it works
The core of this reactor is essentially a log of depleted uranium several metres in length with a small amount of enriched uranium at one end. The enriched uranium is used to kick start a fission reaction, which then moves very slowly along the log. This "travelling wave" of fission would reach the other end of the log after about 40–60 years. Depleted uranium does not undergo fission itself, but add a fast-moving neutron and it will convert via neptunium into plutonium, which then fissions to release energy. As the 40 cm-wide wave moves through the reactor it breeds plutonium fuel at the front, uses this as fuel for fission and then leaves behind by-products and unused fuel. The heat is transported away using liquid sodium.

Who is behind it?
Microsoft founder Bill Gates, who describes it as a possible "energy miracle". Gates is one of the key investors in TerraPower, a company seeking to commercialize this technology. TerraPower is a spin-off from Intellectual Ventures, which is headed by ex-Microsoft chief technology officer and former physicist Nathan Myhrvold (*Physics World* March 2007 pp12–13). Microsoft has provided much of the supercomputing required to model the reactor design and fuel cycle.


TerraPower
Travel log This quirky design has the valuable financial and public support of Bill Gates.

Plus points
The reactor would help to dispose of nuclear waste, since depleted uranium is its main resource. The reaction is self-sustaining, so refuelling is not required beyond its 40–60 year lifetime, and it is also self-limiting – good from a safety perspective. The risk of proliferation is low because the enrichment step is only done once to produce the small amount of enriched uranium needed to initiate the reaction.

Drawbacks
This technology is novel, and no prototype has yet been built to prove that the principle works, which could mean the licensing is a long way off. Another criticism is that research and development should focus on near-term applications, not divert resources away from technologies that are known to work.

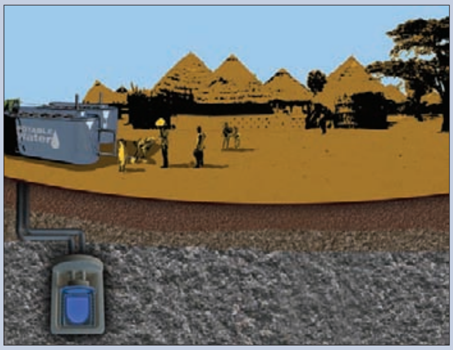
Prospects
The conceptual design for a gigawatt-scale reactor has already been completed and patented by Intellectual Ventures. Plans are now under way to design a small modular unit that can generate 500 MW. TerraPower boss John Gilleland claims that its operation can be demonstrated in less than 10 years, and commercial deployment can begin in less than 15 years, costing several billion dollars per power plant.

Out of thousands of proposed new reactor designs, only a select few have gathered enough momentum to even stand a chance of seeing the light of day. *Physics World* looks at four that, despite not being in the "generation-IV" collection, are developing under their own steam

The Hyperion Power Module

How it works

Hyperion Power Generation, Inc. – a US firm based in Denver, Colorado – unveiled the first design for its Power Module in November 2008. Two different versions now exist, but the main selling point is the same for both: the units are small – about the size of a hot tub – and therefore transportable, making them useful for remote locations such as the Alberta oil sands, military facilities and rural areas in the developing world that need electricity for clean water. The first Power Module design would have no moving parts. The idea is to fuel a reactor core with uranium hydride (UH_3) at a factory, before transporting and then installing it under the ground. Heat pipes would transfer the heat to water above ground for power generation. The neutrons released in uranium fission would be moderated by the hydrogen. If the UH_3 gets too hot, then the hydrogen would be driven out of the uranium metal and the reaction would stop. But as the container is sealed, the hydrogen could then return to allow the reaction to resume. The second design, unveiled in 2009, is a less-adventurous liquid-metal-cooled fast reactor (see "Nuclear's new generation" on p30). Hyperion says it brought in this more conventional design to meet customer demand in the short term, but that it will continue to develop the more elegant uranium-hydride design.



Hyperion

Nuclear hot tub These diminutive reactors would be buried underground for a decade at a time.

Who is behind it?

Otis Peterson, then at the Los Alamos National Laboratory (LANL), designed the uranium-hydride reactor together with colleagues. Hyperion Power Generation, Inc. was set up in 2006 to commercialize this technology, and Peterson left LANL to join the firm as chief scientist. The venture-capital company Altira Group has invested several million dollars in Hyperion.

Plus points

The Power Modules can be transported by rail, heavy hauler or barge in licensed nuclear-fuel transport containers. Their small size also means that companies and organizations can realistically afford to buy them. Useful in remote locations where connecting to the electricity grid is not an option, Hyperion says the reactor is then buried underground, making it less vulnerable to human incompetence or hostile tampering. Also, the fuel is manufactured in such a way as to make it much less of a proliferation concern than industry-typical nuclear fuel.

Drawbacks

Each Power Module would need replacing every 10 years. This would mean installing a second unit while the first is still running in order to maintain continuity of the power supply.

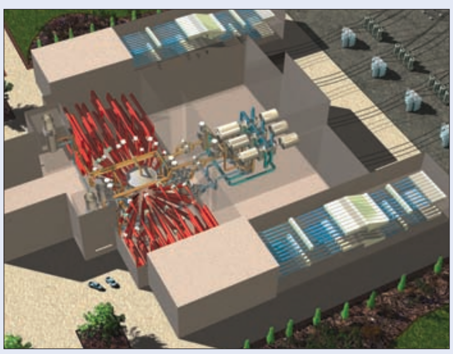
Prospects

The US Nuclear Regulatory Commission has stated that the Power Module will require 3–5 years of review. By early 2009 Hyperion said that it had secured more than 100 orders for the original design. Deliveries for its $50m 2009-vintage reactors are scheduled for late 2013. Hyperion plans to build manufacturing facilities in the US, the UK and Asia.

Fusion–fission reactors

How it works

As the name suggests, hybrid fusion–fission reactors would combine nuclear fusion and fission in a single device. They would resemble a fusion reactor, with a hot ball of plasma (magnetic-confinement fusion) or a series of exploding fusion targets (inertial-confinement fusion) at the centre. The problem with current fusion reactors is that they cannot generate more power than they consume. One of the main stumbling blocks, especially for magnetic-confinement fusion, is temperature: getting the plasma hot enough will require very large reactors. Any commercial fusion reactor will also require a reactor wall and "blanket" that can withstand immense heat and neutron bombardment (see "Hot fusion" on p46). A hybrid fusion–fission reactor might solve this problem by using a layer of fissioning material as the blanket, which would absorb the high-energy neutrons produced in fusion and protect the outer reactor wall. In magnetic-confinement fusion the fission blanket would in turn provide heat to the fusion reaction.



LLNL

Stronger together A fusion–fission hybrid reactor such as LIFE could combine the best of both worlds.

Who is behind it?

Originally conceived in the 1950s, the concept is now being pursued by scientists at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in the US, and at the University of Texas at Austin. If NIF succeeds in using lasers to ignite fusion and demonstrate a net energy gain, then the likely next focus at the LLNL will be LIFE: a project to ignite fusion within a reactor, or a sub-critical fission-reactor blanket.

Plus points

The deuterium fuel, found in seawater, is practically unlimited, while the tritium fuel is derived from lithium, a common mineral. The blanket could burn a range of fuels, including spent nuclear fuel and thorium. The fission would be sub-critical and so relatively safe.

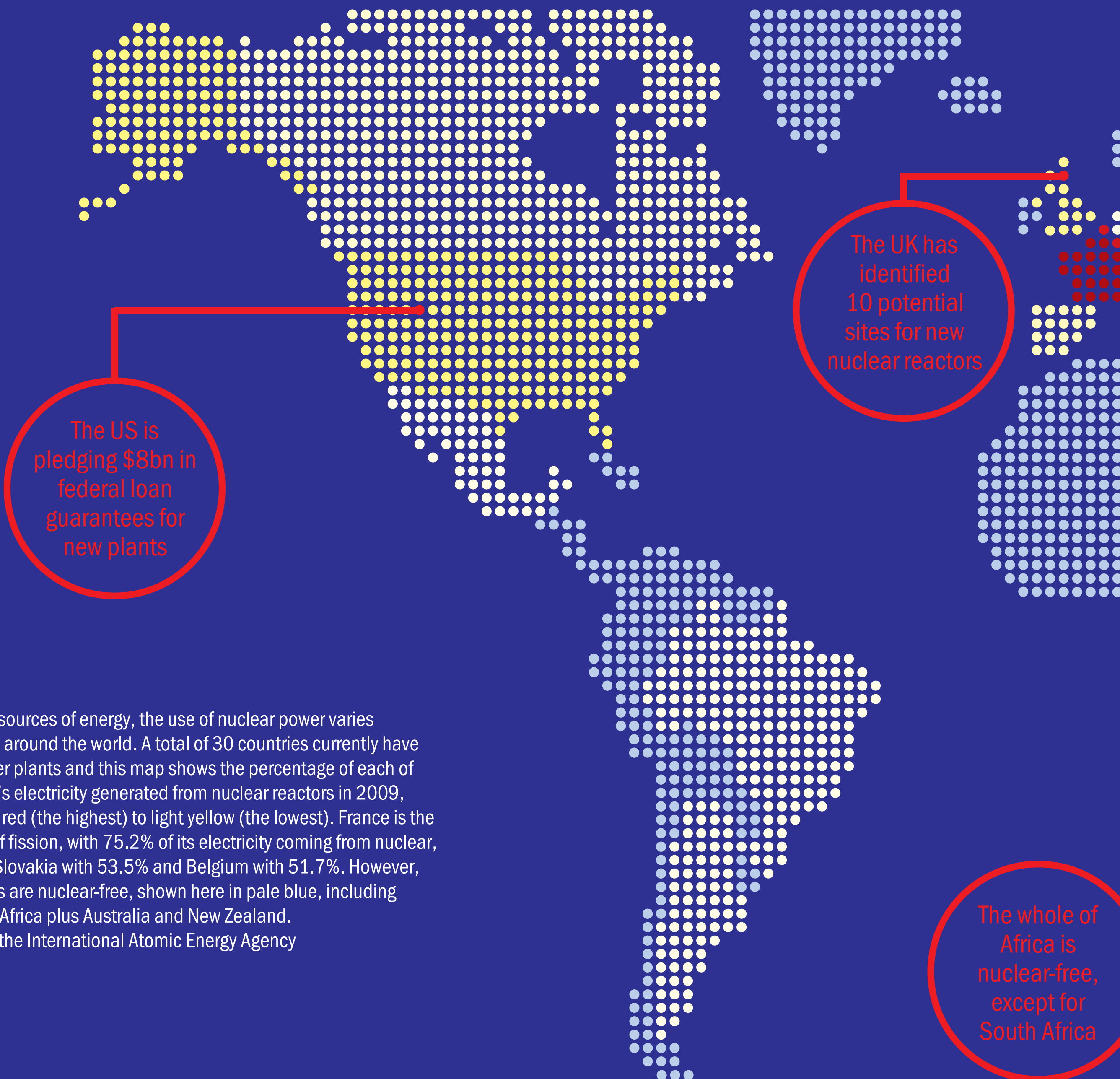
Drawbacks

This technology is decades away. The concept of combining fission with fusion has never been tested experimentally, so it is not clear how the energy balance would work out – and, crucially, whether there would be a net power gain.

Prospects

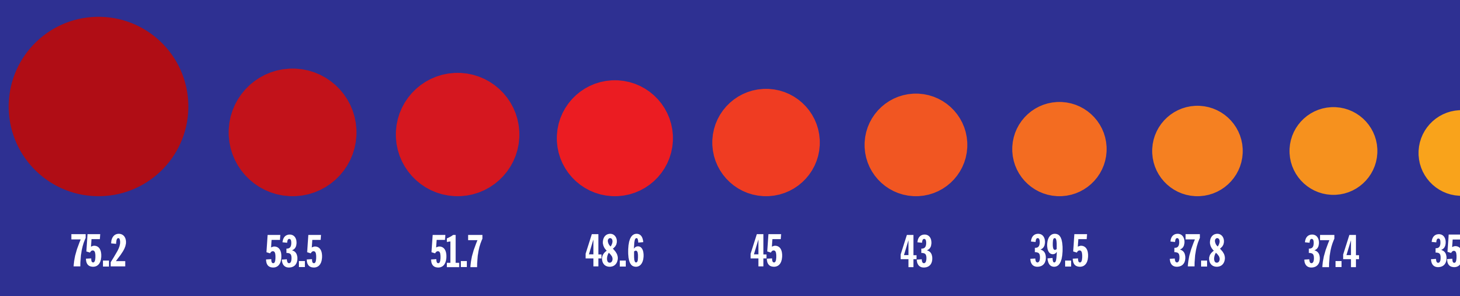
Steven Chu, the US Energy Secretary, has said that hybrid fusion–fission is a means to both make power and to break down nuclear waste. Earlier this year, Paul Drayson, then the UK Science Minister, also called for research into hybrid fusion–fission reactors. China's Institute of Plasma Physics has gone one step further and plans to build a prototype by 2020.

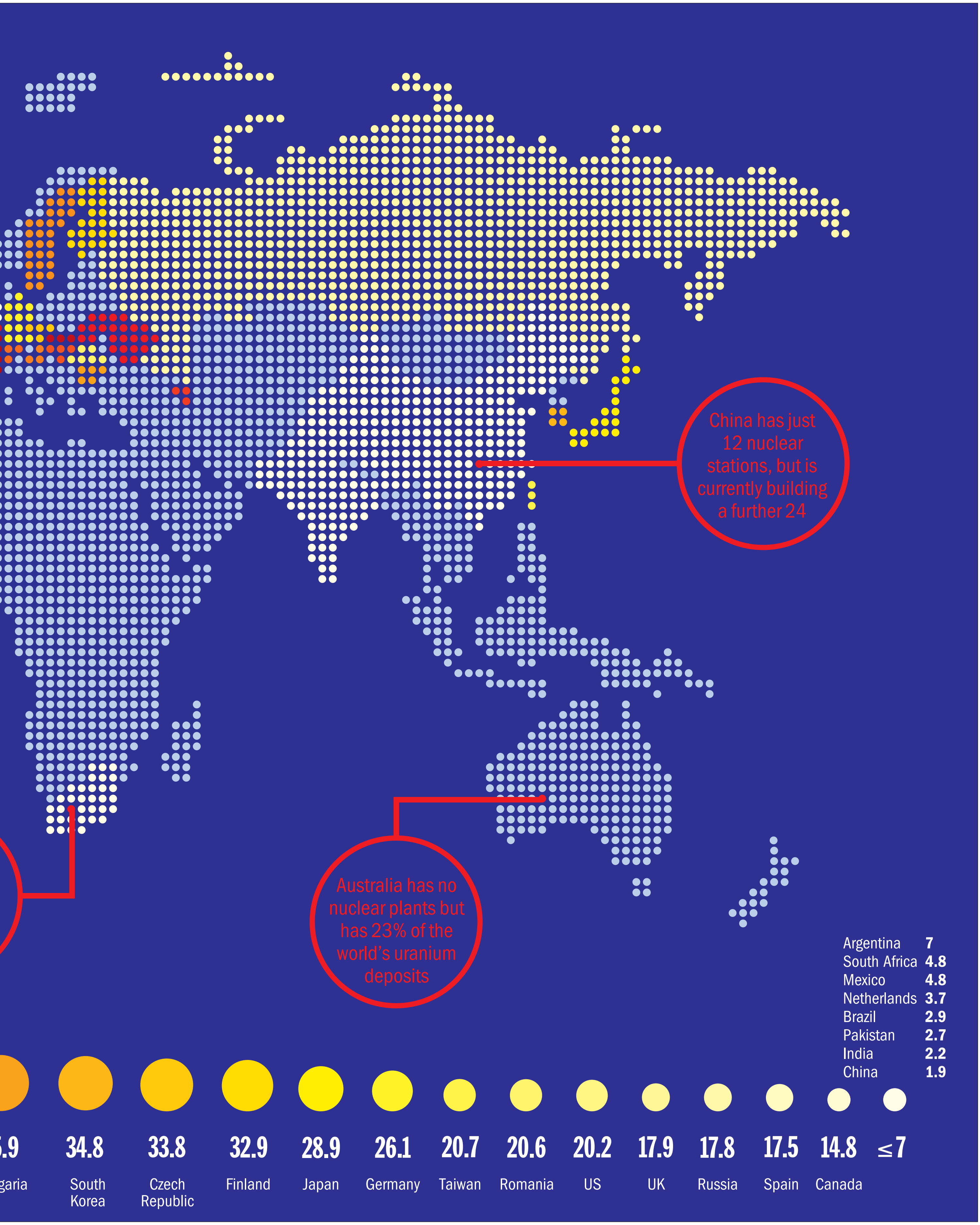
A world of difference



Unlike other sources of energy, the use of nuclear power varies considerably around the world. A total of 30 countries currently have nuclear power plants and this map shows the percentage of each of those nation's electricity generated from nuclear reactors in 2009, ranging from red (the highest) to light yellow (the lowest). France is the biggest fan of fission, with 75.2% of its electricity coming from nuclear, followed by Slovakia with 53.5% and Belgium with 51.7%. However, many nations are nuclear-free, shown here in pale blue, including almost all of Africa plus Australia and New Zealand.

● Data from the International Atomic Energy Agency




China has just 12 nuclear stations, but is currently building a further 24
Australia has no nuclear plants but has 23% of the world's uranium deposits
Argentina 7
South Africa 4.8
Mexico 4.8
Netherlands 3.7
Brazil 2.9
Pakistan 2.7
India 2.2
China 1.9
.9
34.8
33.8
32.9
28.9
26.1
20.7
20.6
20.2
17.9
17.8
17.5
14.8
≤7
garia
South Korea
Czech Republic
Finland
Japan
Germany
Taiwan
Romania
US
UK
Russia
Spain
Canada

Enter the thorium tiger

India has a unique vision for a secure nuclear-energy future based on thorium. As the UK enters a new era of civil nuclear collaboration with India, **Matthew Chalmers** tours India's nuclear labs with a British High Commission team helping to bring physicists from both countries together

Matthew Chalmers is a science writer based in Bristol, UK, e-mail mdkchalmers@googlemail.com

A road trip through Mumbai is a survival course in coping with fumes and traffic, but amid the bafflement and mass of humanity, it is impossible to ignore the vast scale of construction taking place in India's most populous city. Concrete office blocks and apartments spring from impossible spaces, some draped in tarpaulins long before they are completed to give squatters shelter from monsoon rains. The scenes are testament to the dynamism of India's economy, which is currently growing by about 8% each year. But for this growth to continue, India needs a similar expansion in its energy supply, with the country's per-capita consumption of electricity expected to soar to seven times its current value by 2050. More than 300 million people – 40% of India's population – are not yet connected to the electricity grid.

India is therefore backing another type of construction that is relatively rare in Europe and the US these days: new nuclear power stations. India currently has 19 operational nuclear reactors, which generate 3% of the country's electricity (the global average is about 15%). But it is also building eight more reactors and, according to the World Nuclear Association, is eyeing at least a further 35 on top of that. India's near-term nuclear growth is topped only by that in China.

That India sees nuclear power as vital to its energy mix is nothing radical. Many countries faced with growing energy demands, a desire for increased energy security, and the need to reduce greenhouse-gas emissions are turning or returning to the nuclear option. The UK government, for example, has identified 10 potential sites on which vendors can bid to build what would be the first reactors in the country since Sizewell B was switched on in 1995. In the US, meanwhile, the Obama administration has pledged loans that would see the first orders for new-build nuclear reactors since the early 1980s. Italy, Sweden and others are also dusting off their nuclear plans or reversing previous decisions to halt nuclear construction.

India could find itself as a leading exporter of an alternative nuclear technology that is more efficient than today's uranium–plutonium fuel cycle and produces less and shorter-lived radioactive waste products

But the Indian government's plans are bolder than most. Not only does it want to increase its nuclear contribution from its current 5 GW to 28 GW in the next 10 years, but the reactors generating this power are the first stage of a unique "three-stage" nuclear vision. First formulated back in the 1950s, this vision would see India producing 270 GW of electricity from nuclear sources by 2050 – a quarter of the country's projected power needs and two-thirds of today's global nuclear capacity. India could then find itself as a leading exporter of an alternative nuclear technology that is more efficient than today's uranium–plutonium fuel cycle, produces less and shorter-lived radioactive waste products, and that offers resistance against malevolent use. It is a technology based on thorium.

One vision

Two large portraits dominate Srikumar Banerjee's wood-panelled office in downtown Mumbai. One is of Albert Einstein. The other is of Homi Bhabha: the physicist and founder of India's nuclear programme who, more than 40 years after his death, remains very much alive in the minds of those working on that effort. As the secretary to India's Department of Atomic Energy (DAE) – a post first occupied by Bhabha in 1954 – Banerjee shares his predecessor's vision, insisting that India is planning not just for the next 100 years but for the next 1000. "Growth will come from fast-breeder reactors, sustainability from thorium," he says.

Bhabha was also the founding director of what is now the Bhabha Atomic Research Centre (BARC), which lies on the outskirts of Mumbai. Set among geometrical flower-beds and thick forest looking out over Elephanta Island in the Arabian sea – it is said that Bhabha desired a sea view from his office – BARC is the hub of India's nuclear programme. Surrounded by heavy security, it currently employs some 16 000 staff across 20 groups and 90 divisions, although several thousand other researchers are based at the handful of other DAE labs around the country.

Having studied at Cambridge University in the UK in the late 1920s and early 1930s, and made breakthroughs in cosmic-ray and quantum physics, Bhabha returned to India in 1939 – befriending future Indian premier Jawaharlal Nehru on the voyage home – and soon began work on his grand three-stage plan for nuclear power. The plan was, and still is, rooted in a desire for energy security, given that India has fairly meagre amounts of uranium – the fuel powering the world's 440 existing commercial reactors. Although India is aggressively searching for more uranium, known supplies are only sufficient to generate about

In its own hands
India envisages a new range of nuclear power stations fuelled by thorium pellets.

10 GW of electricity if burned in the usual "once-through" fuel cycles.

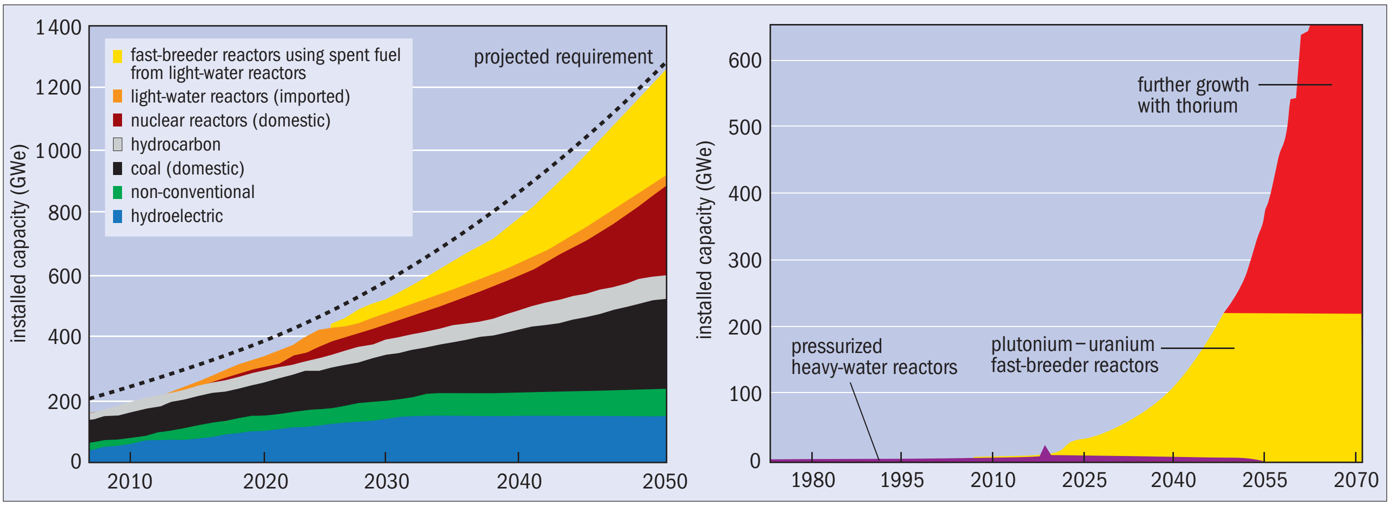
Locked up in monazite in the sands of India's southern and eastern beaches, however, are some of the world's largest reserves (at least 225 000 tonnes) of thorium – uranium's lighter and at least three times more abundant neighbour in the actinide series. Thorium is not technically a nuclear fuel because it is not "fissile" – that is, it cannot sustain a chain reaction whereby neutrons released from the disintegration of one thorium nucleus go on to split another. But if bathed in an external supply of neutrons, a thorium-232 nucleus can capture a neutron before undergoing a couple of beta decays and transmuting into uranium-233, which *is* fissile.

It is analogous to the conversion of uranium-238 into plutonium-239 in conventional reactors. However, the balance between neutron-induced fission and neutron-capture events in the thorium cycle is more favourable than for the uranium–plutonium cycle, enabling more useful energy to be extracted from the thorium. Another benefit of thorium is that it has a lower atomic mass than uranium, which means that it produces less long-term waste in the form of plutonium and long-lived minor actinides such as americium, although other long-term hazards such as protactinium are still present.

In the early days of nuclear power, several other countries (including Germany, the former Soviet Union and the US) tried using thorium to expand their fissile inventories – uranium-233 being one of just a few fissile isotopes, along with uranium-235 and plutonium-239. But by the 1970s the uranium–plutonium cycle – given a head start by the initial military objective of breeding plutonium for weapons – had conquered the commercial power market. Given that uranium is the only naturally occurring fissile material and it seemed plentiful, choosing thorium instead "is a bit like trying to build a fire with fresh green shoots that blow smoke into your eyes rather than use some dry, dead wood lying nearby", as Vijay Kumar Raina, BARC's reactor-group director, puts it.

New deal

As well as possessing far more thorium than uranium, India has had another reason to stick with thorium: more than 30 years of isolation from mainstream uranium technology, which came about after the country detonated a nuclear device in 1974. That isolation inevitably hampered India's nuclear programme, yet today it boasts some of the world's best performing pressurized heavy-water reactors (PHWRs), plus top-of-the-range research facilities. "Progress could well have been quicker were it not for international politics that resulted in India having to plough a lonely



India's energy gap (Left) India currently gets about 75% of its power from fossil fuels (mostly coal), 20% from hydroelectricity and the rest from nuclear and renewables. Although the country currently produces just 5% of global carbon-dioxide emissions, continuing to rely on coal is not an attractive environmental option. Unless it imports light-water reactors and reprocesses spent fuel from those reactors, India sees itself ending up with a 400 GW "power deficit" by 2050 that could only otherwise be filled by importing 1.6 billion tonnes of coal. (Right) The growth in installed capacity of electricity generated by nuclear reactors in India will be taken up by its pressurized heavy-water reactors (purple), plutonium–uranium fast-breeder reactors (yellow) and thorium-fuelled reactors (red). Source: Department of Atomic Energy

furrow," admits former Indian government scientific adviser Vallampadugai Arunachalam, who is chair of the Centre for Study of Science Technology and Policy in Bangalore.

However, in October 2008 India and the US reached a landmark agreement on civil nuclear co-operation that led members of the Nuclear Supplier Group – which represents 46 nations, including Canada, China, Russia, the UK and the US – to open up trade in uranium technology. At the time, India's prime minister Manmohan Singh said that the deal would not adversely affect India's three-stage programme. In fact, senior researchers at BARC say that no government in 50 years has interfered with its thorium vision, which is quite a feat given that India – the world's largest democracy – is and has been run by coalition governments of more than a dozen parties.

The final step of the deal – the legal framework for liability in the event of an accident – was thrashed out in the Indian parliament in late August. It lets India, in principle, import fuel and reactors that will help it meet near-term energy demands while adding to its fleet of indigenous PHWRs, which make up the first stage of the country's three-stage plan. These reactors burn uranium while irradiating thorium oxide to produce plutonium and uranium-233, respectively. In stage two, reprocessed plutonium fuels "fast reactors" that breed further uranium-233 and plutonium from a thorium and uranium "blanket", respectively, while also helping to plug a 400 GW deficit in electricity production predicted by 2050. In stage three, advanced heavy-water reactors (AHWRs) with lifetimes of a century will burn uranium-233 while converting India's vast reserves of thorium into further uranium-233 in a sustainable "closed" cycle. All three stages are taking place in parallel, and each has been demonstrated on a laboratory scale.

Founding father India's three-stage nuclear-energy plan was formulated in the 1950s by the physicist Homi Bhabha (1909–1966), who remains its inspiration more than 40 years after his death.

Not surprisingly given its ambitions, India is the world's biggest producer of scientific papers on thorium, and it has an enviable nuclear road map. Indeed, following a trip to the subcontinent in September 2009, three UK nuclear experts – Tim Abram of Manchester University, Mike Fitzpatrick of the Open University and Robin Grimes of Imperial College London – wrote that India has "a national strategy of development and deployment of nuclear-power technologies that, frankly, puts current UK policy to shame". If India's senior nuclear scientists are to be believed, its three-stage programme is bang on track, which means that Bhabha's plan will be realized by the middle of this century.

Bhabha's legacy

Each year since 1957 a couple of hundred graduate physicists, chemists and engineers, drawn from more than 10 000 applicants, are tutored in the ways of India's indigenous nuclear-power programme – most of whom then go on to be employed at India's government labs. Indeed, those who work on India's nuclear-power programme talk about themselves and their colleagues as if they are "eggs" hatched to carry forward Bhabha's vision, each knowing their own (and their colleagues') "batch number". "Bhabha's master stroke was to set up the BARC training school," says C S Sundar, who graduated as part of batch 17 in 1974 and is now director of materials science at the Indira Gandhi Centre for Atomic Research (IGCAR) in Chennai – the DAE's other main lab.

It is hard not to sense Bhabha's presence at BARC, not least thanks to the portraits – some of which are set in what look like shrines. As one is guided around a food-irradiation laboratory, where genetically modified seeds are developed and distributed to farmers to improve their crops, a giant collage of Bhabha made from different shades of mutant beans suddenly appears. But his real legacy is the infrastructure, such as BARC's 100 MW uranium-fuelled research reactor called Dhruva and an older reactor called CIRUS, where the first and third stages of India's thorium vision were and are being played out.

Standing next to the humming Dhruva device, Raina explains how, for example, thorium was irradiated in

Indo-Anglo collaboration

During a visit to India in late July, the UK Prime Minister David Cameron signalled a new era in nuclear trade between the two countries based on a joint declaration of civil co-operation signed in February. While new business opportunities for companies such as Rolls Royce and Serco hit the headlines, in the background five nuclear-research proposals worth more than £2m were jointly funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) and by India's Department of Atomic Energy.

Robin Grimes of Imperial College London, who joined the prime-ministerial trip as an adviser, says such collaboration is not without its sensitivities given that India is outside the Nuclear Non-Proliferation Treaty. But he says that the deal presents a "marvellous opportunity" for the UK's nuclear sector, which has been in slow decline since the mid-1980s, to get involved with India's national programme and to take advantage of its expertise and facilities.

UK nuclear researchers are particularly keen to use facilities such as India's full-scale sodium cooling loop in its Fast Breeder Test Reactor (FBTR) in Chennai. Materials engineer Mike Fitzpatrick of the Open University, for example, who is about to take up one of the five jointly funded proposals, is eyeing up India's research reactors. "The facilities that previously existed in the UK have gone, and although the National Nuclear Laboratory has great potential, we don't yet have access to a place where we can test our irradiation models," he says.

IGCAR

Indian researchers, meanwhile, are keen to get beam time at the UK's ISIS neutron source and Diamond synchrotron to characterize the properties of materials such as the glasses used to store long-term waste and those used to make metallic fuel for fast reactors. UK universities and companies also have modelling, engineering and materials expertise that will be useful, for example, to develop the welding for the high-pressure joints in fast-reactor plumbing.

Three further joint proposals are in the pipeline. "We want Indo-Anglo grants to be business as usual," says EPSRC's power and energy manager Stephen Elsby. And despite different scientific cultures and national nuclear ambitions, both sides are brimming with enthusiasm. "I'll be honest, I wasn't expecting much commonality when I went over," says Fitzpatrick of his first trip to the Bhabha Atomic Research Centre (BARC) in Mumbai. "But when I got there, I was amazed at the ambition and resource behind India's nuclear programme, and how much UK researchers could benefit from being associated with it."

CIRUS back in the 1960s and the resulting uranium-233 was first separated from irradiated thorium at BARC in 1970. In the next 18–24 months, he says, all the necessary steps for starting construction of a BARC-designed 300 MW AHWR will be completed – a technology demonstration for a thorium–uranium-233 plant. The reactor physics of the AHWR is already being validated in a separate "critical facility" reactor commissioned in 2008.

With Dhruva busily transmuting uranium into plutonium in the background, and India being one of just eight nations known to possess nuclear weapons, nervous laughter erupts among our tour group when Raina seems to say – while describing some of the condensed-matter research that takes place at Dhruva – that "missiles" have been studied in one of the many neutron beam lines emerging from the off-yellow cylindrical reactor. (In fact, he had said "micelles" – an aggregation of molecules dispersed in a liquid.) Yet during lunch with new BARC director Rata Kumar Sinha, who took over from Banerjee in May, the BARC boss makes no mention of what India terms its "strategic" (i.e. weapons) programme as he reels off all the additional activities taking place at BARC. On being asked, he replies that it involves a tiny minority of staff spread across its many programmes.

As a result of the Indo-US deal, CIRUS will close down at the end of this year, while 14 of India's reactors will come under the auspices of the International Atomic Energy Agency (IAEA). No longer the nuclear outsider, India is open to civil nuclear collaboration with other countries, including the UK. Soon, following more than two years of efforts by the British High Commission in New Delhi, Research Councils UK and the DAE to forge links between researchers in both countries, a dozen or so postdocs will swap countries under a £1.2m research grant from the Engineering and Physical Sciences Research Council and similar amounts from the DAE (see box above). India has also signed co-operation deals with France, Russia and Canada to allow nuclear trade between the two nations.

Fast reactors

A two-hour internal flight from Mumbai brings you to Chennai on the south-east coast of India, and to IGCAR – the laboratory enacting stage two of India's nuclear-power programme. Security is less severe than at BARC, and, being 15 years younger, the large leafy campus has a fresher feel to it. Sipping tea in director Baldev Raj's office beneath photos of Bhabha together with Nehru, IGCAR chiefs talk of their pride in seeing various reactors grow and evolve with home-grown technology. As for what other countries such as the UK have to offer India, chemistry group director Vasudeva Rao says collaboration in areas such as materials, mechanics and computational fluid dynamics should "enhance the economics, performance and safety" of India's three-stage nuclear programme.

IGCAR's 40 MW Fast Breeder Test Reactor (FBTR) makes India one of just four countries, along with Russia, Japan and China, to have an operational fast reactor. These devices, which use highly energetic neutrons to cause fission in isotopes such as uranium-238, differ from thermal reactors in that they can breed more nuclear fuel than they consume. They do this by using their higher neutron flux to convert fertile material to fissile material in breeder blankets, which can then be reprocessed to produce new uranium–plutonium mixed oxide (MOX) fuel and fed back into the reactor. Two of the main challenges of fast reactors are to extract heat safely and efficiently from the core and to design fuel that can withstand the high neutron flux and "burn

Thorium utopia elsewhere

Unlike uranium-235, which makes up about 0.7% of natural uranium, thorium is not fissile and so it needs an initial "inventory" of fissile material to achieve criticality in a reactor core. India's ultimate aim is to utilize uranium-233 and thorium in a closed, self-sustaining cycle (see main text). However, India is also maintaining an interest in another approach called an accelerator-driven system (ADS), which may allow the country's vast thorium reserves to be exploited sooner than its "third stage" AHWRs.

The ADS or "energy amplifier" proposed by particle physicist Carlo Rubbia and others in the early 1990s produces neutrons by firing a beam of high-energy protons at a spallation target, usually lead or tungsten, in the reactor core. The advantage of the ADS is that it is inherently protected against reactor power excursions because shutting down the reactor is just a matter of switching off the proton accelerator. It could also be used to transmute existing high-level waste – something common to all attempts to use thorium but for which the ADS offers greater scope.

Although there is a large push in the UK from the Thorium Energy Amplifier Association (ThorEA), which envisages a privately built 600 MW prototype ADS reactor generating electricity by 2025, the energy amplifier is unlikely to be commercialized any time soon, partly because there is not yet a particle accelerator reliable enough to be hooked up to a national grid. "You're trying to marry complex particle-accelerator technology with complex fast-reactor technology," says Tim Abram of the University of Manchester in the UK. "France looked into ADS in great detail and concluded that conventional fast reactors were a better solution for large-scale power generation."

Another vision for a thorium utopia is the molten-salt reactor (MSR). First demonstrated in 1965 as part of an attempt by the US military to build a nuclear-powered aircraft, today it is being resurrected in the form of liquid-fluoride thorium reactors (LFTRs). Rather than use fuel rods, which become degraded in efficiency as more reaction products build up, LFTRs would use a liquid form of thorium salt dissolved in a bath of lithium and beryllium fluoride salts. The LFTR concept does not need a particle accelerator to maintain criticality or expensive pressure-containment vessels to house the reactor core, and, say proponents, it can be shut down safely and passively with human intervention.

Elsewhere, the US firm Lightbridge is developing a fuel with Russia's Kurchatov Institute that burns uranium-233 bred from thorium *in situ*, and is intended for once-through cycles in light-water reactors. Lightbridge's fuel would extend the lifetime of existing LWRs, cut the volume of waste by about 40% and slash long-term radio-toxicity of used fuel by up to 90%. Meanwhile, Thor Energy in Norway – a country rich in thorium but with no commercial reactors – is also developing a thorium–plutonium-oxide fuel for light-water reactors, although a 2008 government-commissioned report saw no impetus to start a national thorium programme. Similarly motivated by healthy thorium reserves, Atomic Energy of Canada is developing single-use thorium-based fuel for use in its CANDU and other heavy-water reactors.

up" rates.

Based on a French design and operational since 1985, India's FBTR removes heat from the core via a liquid-sodium loop and runs on a unique uranium–plutonium–carbide fuel because of India's historical lack of access to enriched uranium (fast reactors need fuel with a higher fissile content). This has provided "burn up" – a measure of the total energy extracted from a fuel – of 165 GWd per tonne (where 1 GWd = 24×10^6 kWh), which is 20 times that of a typical PHWR. Recently, IGCAR researchers loaded mixed-carbide fuel pellets containing material reprocessed from spent FBTR fuel back into the reactor, thereby "closing" the fuel cycle.

Driving along sandy roads towards IGCAR, one passes the construction site of the 500 MW Prototype Fast Breeder Reactor (PFBR), the foundation pit of which was flooded when the Indian Ocean tsunami struck the Kalpakkam coast in 2004. Due to switch on in 2012, the PFBR is the stepping stone to six 500 MW fast reactors that will be the workhorses of India's nuclear-power programme from about 2020. Initially, India's fast reactors will burn MOX fuel with a thorium and uranium blanket, but, gradually, advanced metal-alloy fuels that increase the plutonium breeding ratio will be introduced. Before then, however, the PFBR has to demonstrate the safety of India's fast reactors, particular its sodium cooling loop.

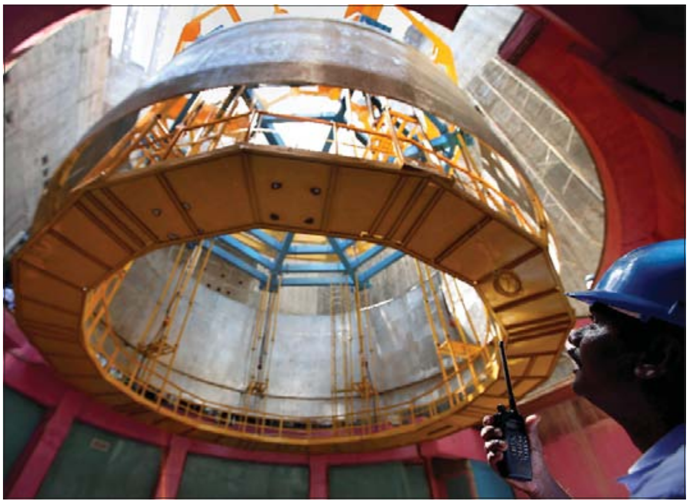
Described by Raj as a "mega-challenge", India's fast-reactor programme will involve, some time after 2020, rolling out a fleet of 1 GW metal-fuelled fast reactors that will increase uranium-233 stocks for use in the third stage of the thorium fuel cycle in multiple AHWRs. IGCAR already has the world's first and only uranium-233-fuelled reactor, the 30 kW KAMINI reactor built in conjunction with BARC, which demonstrates the transition to stage three – its fuel being produced from thorium irradiated in India's PHWRs and reprocessed at IGCAR.

21st-century fuel

India's three-stage plan may be unique, but it is not the only way to exploit thorium (see box left) and neither is it necessarily the quickest. There are also tough challenges ahead for the scientists and engineers going through BARC's training programme, particularly in separating thorium and uranium-233 from spent fast-reactor fuel. "Slowly, some experience is being accumulated in low-level irradiation of thorium fuel in PHWRs and reprocessing to recover uranium-233," says Arunachalam, "but the third stage of India's programme is quite some decades away."

The problem with uranium-233 is that it comes intimately bound with uranium-232 – a short-lived isotope that has among its decay products isotopes that emit dangerous levels of gamma radiation. On the other hand, the presence of uranium-232 makes it hard to use uranium-233 for a bomb because the material has to be handled remotely and cannot be easily concealed from a radiation detector. Although this increased resistance to proliferation is billed by its proponents as one of thorium's greatest assets, a report published in August by the UK's National Nuclear Laboratory (NNL) – an independent nuclear-technology service provider owned by the UK government – suggests that such claims have been overstated. The NNL recommends that uranium-233 poses a proliferation risk comparable to enriched uranium-235, and points out that "significant though reduced" amounts of plutonium will always be produced when burning thorium in anything other than a breeding cycle.

The NNL also treats claims about thorium's improved waste characteristics with caution. It says that regardless of the reactor system, uranium and plutonium will remain an integral part of the thorium fuel cycle unless the uranium-233 is fully recycled. As far as the commercial utilities are concerned, NNL says the potential savings that thorium fuel offers and other claimed benefits are insufficiently demonstrated and too marginal to justify the technical risk. "The reason that uranium is still and will continue to be the fuel of choice for decades to come is that it is proven, relatively inexpensive and abundant for some years," say NNL's Andrew Worrall and Kevin Hesketh. "Why would anyone wish to move to a new, unproven, risky venture that



Press Trust of India

Planning ahead Set to open in 2012, the Prototype Fast Breeder Reactor at the Indira Gandhi Centre for Atomic Research is the forerunner to a series of Indian fast-breeder reactors to open from about 2020.

will not be available for some decades?"

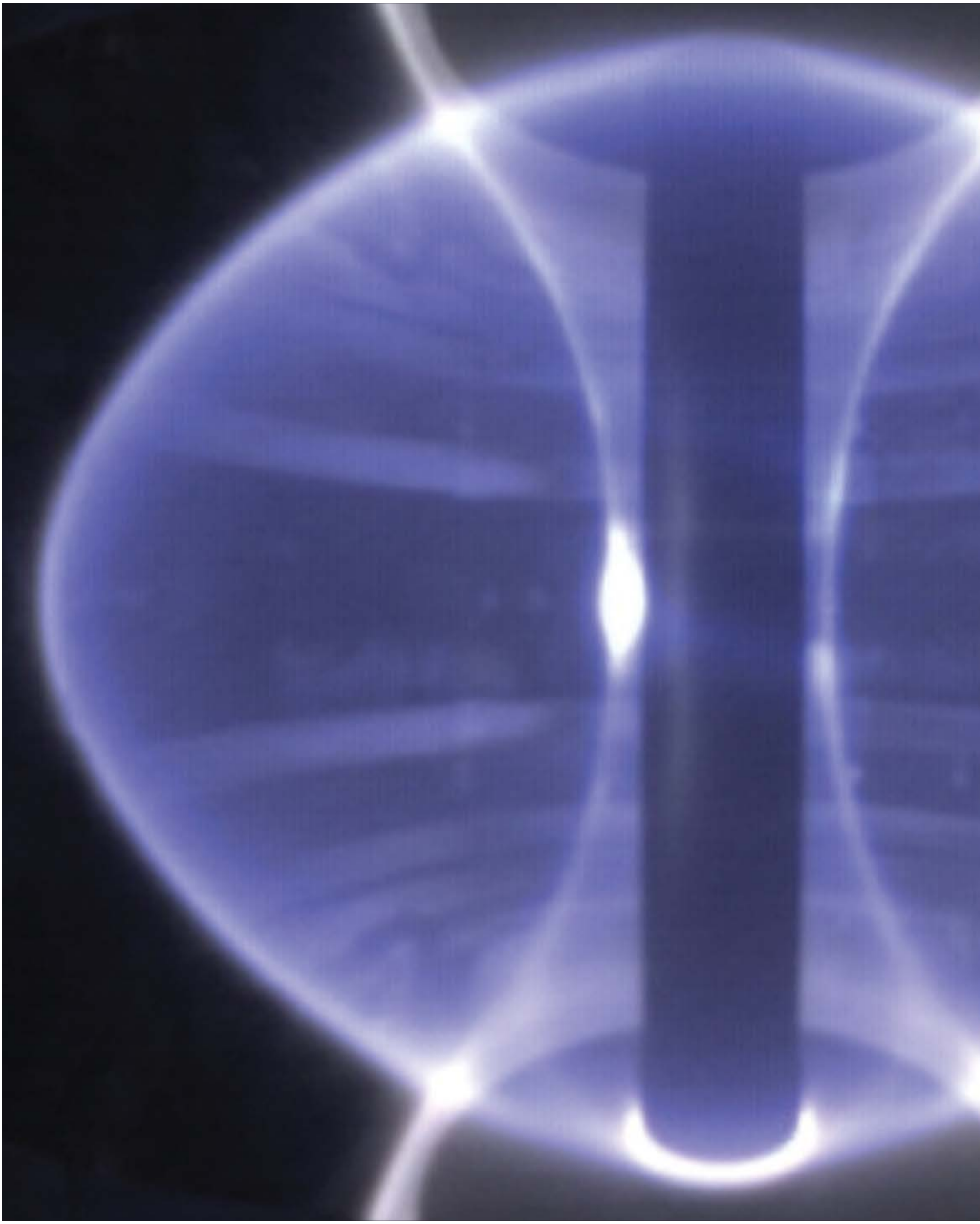
But India's three-stage vision has very much been about security of supply and less about the cost per kilowatt-hour, says Grimes, who adds that the economic arguments even for conventional reactors are not entirely settled. Moreover, he argues, it is not even clear what the winning ticket for nuclear power is: massive recycling with MOX fuel, fast reactors or thorium. "What is clear", he says, "is that the silly claims of the 1960s, when people talked about energy too cheap to meter, remain positively silly."

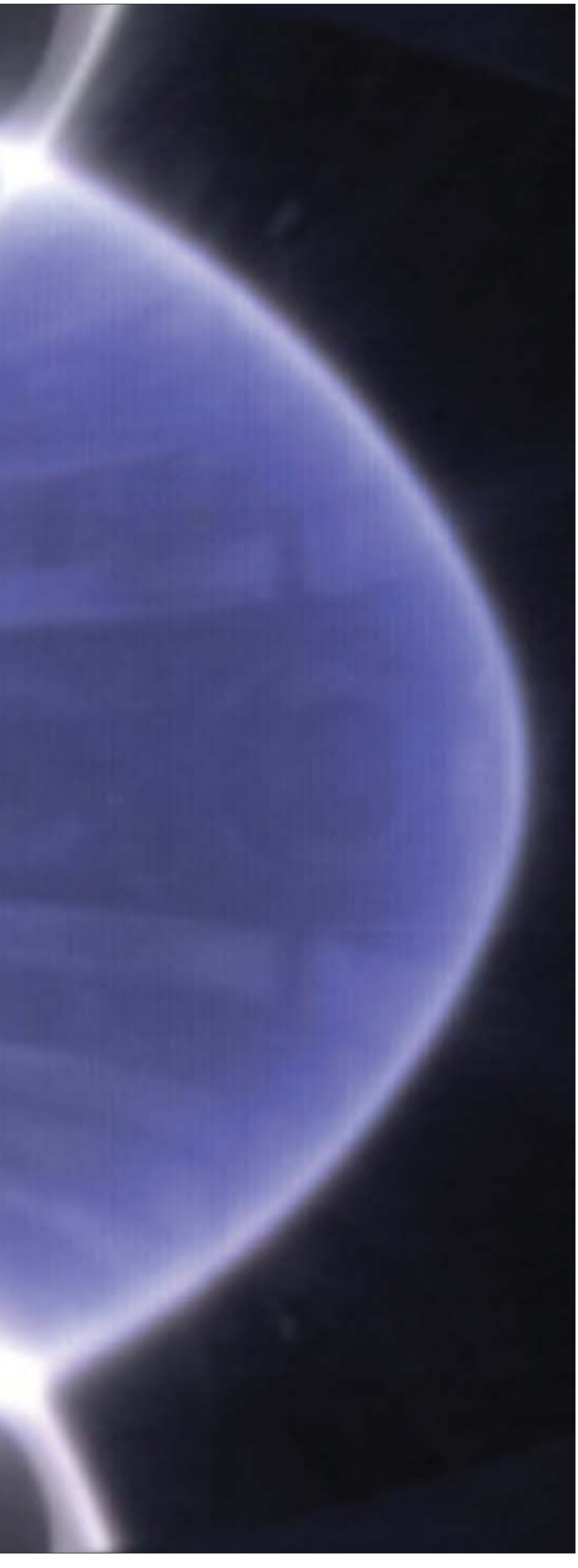
Cultural power

Back in downtown Mumbai, one thing Banerjee does not see as a hurdle to India's nuclear future is anti-nuclear groups – not because India does not have them, but because the DAE runs projects to show the benefits of nuclear power. He also thinks there is less protest because India has such pressing energy needs. "Attitudes towards nuclear power in the UK would soon change after a week of power cuts," he says.

In a modern context, Bhabha's nuclear vision is part of a wider goal for clean, affordable energy also in the form of solar, wind and hydroelectricity – all of which India is investing in heavily. India's nuclear programme could even one day encompass nuclear fusion, with the country already a partner in the ITER project currently being built in France. Indeed, despite its large coal reserves, Raj thinks India might one day opt out of the fossil-fuel race altogether, saying that an intensive and consumption-rich materialistic lifestyle is not advocated by traditional Indian values.

That said, I find myself sitting across a table from C S Sundar in a beach resort a short drive along the coast from IGCAR talking about the all too real prospect of Indian car ownership rising 25-fold this century. Sundar describes India as a chaotic system from which everything somehow always seems to turn out okay. Earlier in the day, with his hands behind his back strolling along a thick-carpeted and sunlit corridor at IGCAR, passing another portrait of Bhabha, he had turned and asked "Who is the father of your nuclear programme?".


CCFE



Hot fusion

Despite more than 50 years of effort, today's nuclear-fusion reactors still require more power to run than they can produce. **Steve Cowley** says the next step is to get the fusion plasma to generate its own heat – to make itself hotter than the centre of the Sun

It has to be one of the greatest public lectures in the history of science. Indeed, the presidential address by Arthur Stanley Eddington to the 1920 meeting of the British Association in Cardiff is still worth reading for the simplicity and clarity of the arguments alone. But it is his extraordinary vision that stands out nearly a century later. Until Eddington's lecture, it was widely accepted that the Sun was powered by gravitational contraction, converting gravitational potential energy into radiation. Some 60 years earlier, Lord Kelvin had argued that this mechanism means that the Sun can be no more than 20–30 million years old. But using simple arguments based on a wide range of observations, Eddington showed that the Sun must be much older than Kelvin's estimate and that stars must draw on some other source of energy.

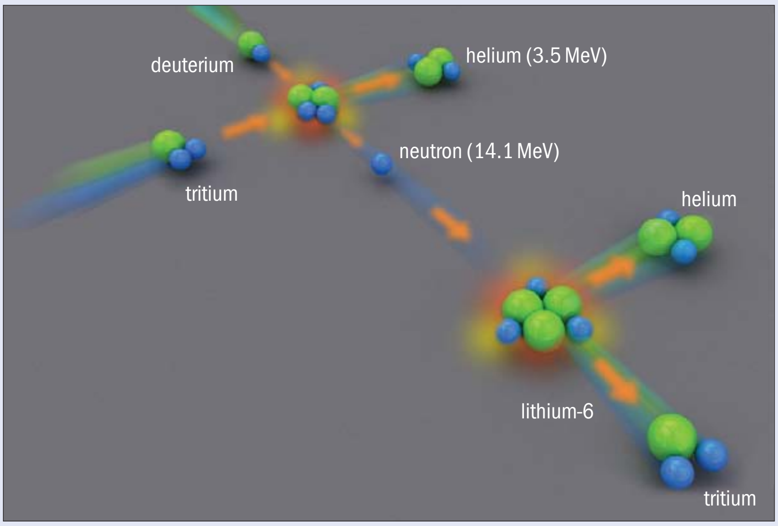
It was fortunate that just prior to Eddington's address his Cambridge University colleague Francis Aston had measured the masses of hydrogen and helium to be 1.008 and 4, respectively. Eddington argued that the Sun is being powered by converting hydrogen to helium – by combining four hydrogen nuclei (protons) with two electrons and releasing energy in the process. The exact details were wrong of course – the process is more complicated and involves deuterium, positrons and neutrinos, for example – but the basic idea was correct: the Sun is indeed converting hydrogen to helium.

The energy released in this transformation can be calculated using $E = mc^2$ and the measured masses of hydrogen and helium. From this, Eddington estimated that the Sun has enough energy to shine for 15 billion years – remarkably close to modern estimates of approximately 10 billion years from formation until the Sun enters its red-giant phase, when it will have exhausted the hydrogen fuel in its core. He had deduced the existence of what we now call nuclear fusion. Although Eddington cautioned about being too certain of his conclusions, he realized that the potential was staggering and he immediately saw the enormous benefits fusion could bring society. As he told his audience in Cardiff, "we sometimes dream that man will one day learn how to release it and use it for his service".

Eddington's vision is now within our reach, although it has not been easy getting this far. Along the way we have needed to develop the field of plasma physics, which studies gases heated to the point where the electrons separate from their atoms. Despite the struggles, it is fair to say that scientists have now captured the Sun's power.

Steve Cowley is Chief Executive Officer of the United Kingdom Atomic Energy Authority at the Culham Centre for Fusion Energy and professor of plasma physics at Imperial College London, e-mail steve.cowley@ccfe.ac.uk

1 Deuterium–tritium fusion



Deuterium (heavy hydrogen) and tritium (superheavy hydrogen) fuse to make helium and a neutron – releasing 17.6 MeV of energy as fusion power. This is the easiest fusion reaction to initiate since it has a high reaction rate at low temperature (where "low" means 100–200 million kelvin). Tritium does not occur in nature as it decays with a short 12-year half-life to helium-3. Thus it must be "bred" from lithium using the neutron produced in the deuterium–tritium fusion reaction. Here, the neutron causes a tritium-breeding reaction with the isotope lithium-6, which comprises roughly 7.5% of naturally occurring lithium. The fuels for this fusion reaction are therefore deuterium and lithium, which are plentiful in seawater.

From dream to reality

The modern fusion programme really began in the closing moments of the Second World War at Los Alamos in the US, when Enrico Fermi and other members of the team that built the first atomic bombs speculated that a fusion reaction might be initiated in a plasma confined by a magnetic field. In May 1946 George Thomson and Moses Blackman of Imperial College London applied for a patent for a magnetically confined fusion device in which powerful magnets could be used to hold a plasma in place while it is heated to high temperatures.

By the early 1950s it was clear that the easiest fusion reaction to initiate is that of two isotopes of hydrogen – deuterium and tritium. To initiate significant fusion, a plasma of deuterium and tritium must be heated to temperatures of about 150 million kelvin. Some 10 times hotter than the centre of the Sun, this was a daunting goal. However, in 1997 scientists achieved it in a magnetically confined plasma at the Joint European Torus (JET) at the Culham Centre for Fusion Energy in the UK. JET produced 16 MW of fusion power while being driven by 25 MW of input power.

Eddington would no doubt be pleased with the scientific progress on his vision. But despite the successes, we are not yet at a point where we can generate commercial electricity and fusion's home stretch still involves significant challenges. Exactly what needs to be done to make a commercial fusion power source? What are the key scientific issues? How should countries position themselves to participate in a future fusion economy? These are essential questions. Before turning to them, however, it is worth addressing the most important question of all: why bother? Perhaps other energy sources would be simpler options. In reality, there are worryingly few long-term energy sources with sufficient resources to replace the roughly 80% of our energy that is generated by fossil fuels.

In the coming decades, current nuclear-fission technology will play a critical role in generating low-carbon electricity. But in the long term, aside from fusion, only solar and nuclear fission with uranium or thorium breeders (advanced reactors that breed nuclear fuel and so extend the resource of fission fuel) have the capability to replace fossil fuels. These technologies still need extensive research before they are ready to be deployed on a large scale. But despite this potential, it is clear, however, that no energy source offers the extraordinary promise of fusion: practically unlimited fuel; low waste; no carbon-dioxide production; attractive safety features and insignificant land use. These are compelling reasons to develop fusion even if success is not fully assured.

Self-heating fusion reactors

What then needs to be done to capitalize on JET's achievement of significant fusion power? The next stage is clearly to demonstrate that a plant producing a net amount of electricity can be constructed – something that JET was not designed to achieve. The ratio of fusion energy produced to the electrical energy consumed to initiate and sustain the reaction must be increased. This requires a self-heated plasma – one heated by the energetic helium nuclei produced in deuterium–tritium fusion (figure 1).

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory uses a different approach to fusion than the magnetic-confinement method discussed here. The facility is designed to concentrate 500 TW of power onto a millimetre-scale fuel pellet using an array of 192 lasers. The fusion energy produced is expected to be roughly 10 to 20 times what the laser driver delivers as light. This would be a significant demonstration of fusion "burn", i.e. self-heating. However, the NIF laser is less than 1% efficient and thus the facility is still short of the critical demonstration that net energy production is possible.

For magnetically confined fusion, the crucial demonstration is at hand. Seven international partners – China, the European Union, Japan, South Korea, India, Russia and the US, together representing more than half the world's population – are now, after years

At a Glance: Fusion energy

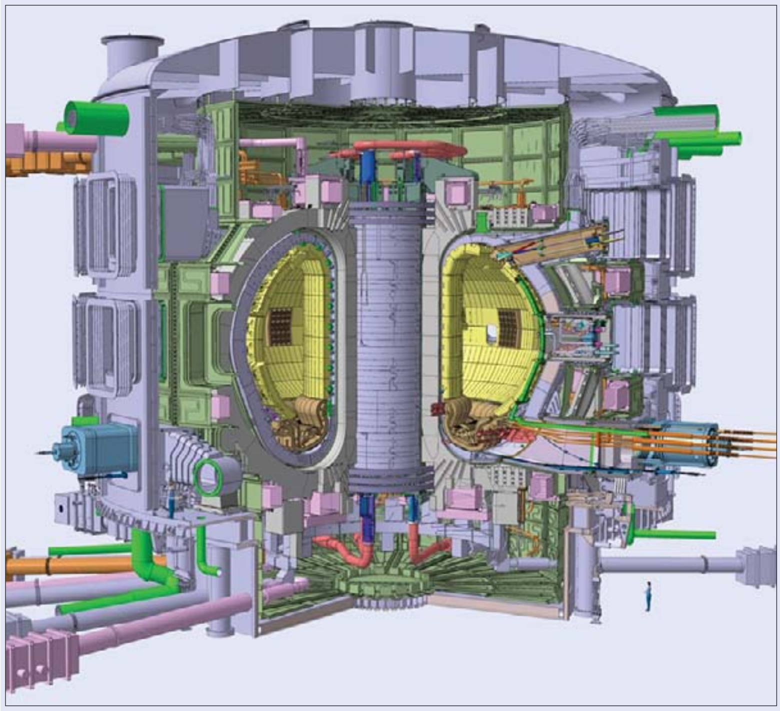
- Fusion power has the extraordinary promise of practically unlimited fuel, no carbon-dioxide production, good safety and insignificant land use
- Controlled fusion was realized in the 1990s by the Joint European Torus (JET) and the US Tokamak Fusion Test Reactor. JET needed more energy to run than it produced – 25 MW input power to the plasma produced 16 MW of fusion power
- We could reach net electricity production by building a reactor that can support the hot burning-plasma regime, where fast-moving fusion products self-heat the reaction, so that less input power is required
- Simulations and measurements predict that the ITER facility being built in France will reach this regime by having a less turbulent fusion plasma and a greater volume – therefore making more fusion and losing less energy – than its predecessors
- For commercial fusion, a wall and "blanket" for the reactor must be engineered that can withstand many years of heat and radiation without weakening

of delays, building a self-heated device called ITER at Cadarache in southern France (figure 2). Like JET, this experiment will have a magnetic configuration denoted by the Russian acronym "tokamak". ITER will be completed in 10 years and a few years after that is expected to be producing roughly 500 MW of output power from less than 50 MW of input power – a 10-fold amplification, or "gain", at least. One-fifth (roughly 100 MW) of the fusion power will be released as energetic helium nuclei, which get trapped by the magnetic field and self-heat the plasma. The target is to sustain this power level for a duration of 400 s or more. However, recent experiments using JET and other machines, coupled with detailed modelling, show that it should be possible to significantly increase that duration – and the gain. Even without these increases, ITER will generate industrial levels of fusion power while being largely self-heated; this is the *burning-plasma* regime. This demonstration of the scientific feasibility of high-gain fusion is a critical step on the road to fusion power.

But how do we know that ITER will reach these performance levels? The key physics parameter is the "energy confinement time", τ_E, which is the ratio of the energy in the plasma to the power supplied to heat the plasma, where the latter is both the self-heating due to the fusion-produced helium (one-fifth of the fusion power, $P_{fusion}/5$) and the external heating (P_{heat}). The energy confinement time parametrizes how well the magnetic field insulates the plasma – it might be thought of as roughly the time it takes the heat put in to the plasma to work its way back out. The plasma is sustained for many energy confinement times (in principle indefinitely) by the heating. Clearly, a larger τ_E makes a fusion reactor a better net source of power. The energy gain is defined as $Q = P_{fusion}/P_{heat}$. The deuterium–tritium fusion power produced per cubic metre of plasma at a given temperature and density (the fusion power density) can be calculated using the measured fusion cross-section (the reaction rate for a given fusion collision). In the temperature range 100×10^6–200×10^6 K, the fusion power density is approximately $0.08p^2$ MW m^{-3}, where the plasma pressure, p, is measured in atmospheres.

At high pressure the fusion power is large and the plasma is entirely self-heated ($P_{heat} = 0$ and $Q \to \infty$) – this is termed "ignition". Heating the plasma externally (supplying P_{heat}) reduces the net output and complicates the reactor design. Therefore, high gain is essential. The gain of a fusion device depends on the state of the plasma – specifically the fusion product, $p\tau_E$, and the plasma temperature, T. Ignition occurs roughly when $p\tau_E > 20$. In ITER the central plasma pressure will reach about 7 atmospheres and the confinement time is expected to be in the range 3.5–4 s (recall that ITER's plasma will be sustained for more than 400 s – perhaps thousands of seconds). A plot of $p_i\tau_E$ versus T enables a performance comparison for different tokamaks, where $p_i = p/2$ is the ion pressure in the centre of the toroidal plasma (figure 3).

2 ITER



ITER

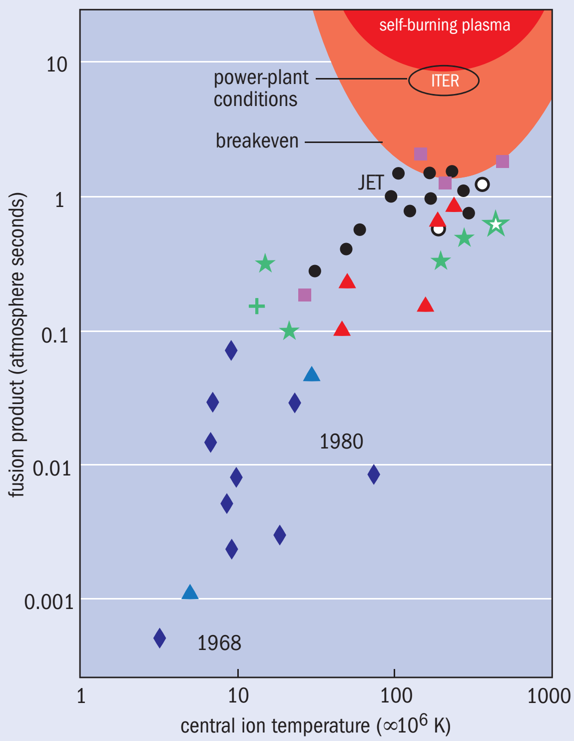
Now being built at Cadarache in southern France, ITER will contain roughly 830 m^3 of hot plasma inside a toroidal-shaped cavity. Confinement is provided by a magnetic field of approximately 5.2 T created by a niobium–tin superconducting coil at a temperature of 4 K. The plasma will be heated to fusion temperatures by radio waves and energetic neutral particles that are injected into the plasma. Once at fusion temperatures (about 200 million kelvin) ITER is expected to produce about 500 MW of fusion power for more than 400 s and be largely self-heated – such plasmas are termed burning plasmas. ITER is designed to have a "duty cycle" of at least 25% – i.e. the gap between burning-plasma shots is less than three times the shot duration.

Predictions of high power at ITER

The most challenging technical question faced by the fusion community is determining what the confinement time is and how we can be sure that it will reach 3.5–4 s. We know that the loss of heat from magnetically confined plasmas is controlled by small-scale turbulence. The turbulence consists of plasma-density and electromagnetic-field fluctuations that cause little swirls of plasma flow – eddies. The turbulent fluctuations are essentially unstable sound waves driven by the temperature gradient in the plasma. Like convection in a saucepan, eddies transport hot plasma out and cold plasma in. Progress in tokamak performance over the last 40 years has been achieved by increasingly suppressing the turbulent convection of heat and thereby increasing τ_E. One of the scientific triumphs of the last decade has been the ability to calculate this turbulence using high-performance computers to provide state-of-the-art simulations (figure 4).

Detailed comparisons of the simulations and measurements show that in many cases the calculations are indeed correctly capturing the complex dynamics. There is, however, still room for improvement, especially in the intriguing cases where the simulated turbulence is almost entirely suppressed. The analytical theory of this turbulence is complicated and is only now just beginning to be understood. However, a qualitative understanding of the turbulent transport can be obtained from a simple random-walk argument based on the characteristics of the unstable sound waves that form the eddy structures. This argument yields the estimate $\tau_E \propto L^3B^2T^{-3/2}$, where L is the size

3 Progress towards the promised land



Selected data from different tokamaks demonstrate substantial progress over recent decades, with ion temperatures of more than 100 million kelvin now routine. With JET, an energy gain (Q) of about 0.7 has been reached – this is labelled as "breakeven" in this diagram. The Japanese experiment JT60 ran without tritium but if it had been using tritium, then the gain would have been 1.25. ITER is expected to obtain an energy gain of more than 10 – commercial reactors would need more than 20.

of the device, B is the magnetic field strength and T is its temperature. Clearly, bigger devices should perform much better due to the steep L^3 scaling. Indeed, empirical scaling derived from many experiments differs only a little from the simple estimate. ITER's energy confinement time has been predicted in two ways: first, by extrapolation from the existing machines using the empirical scaling; and second, using sophisticated local-transport models derived from simulations. These predictions are expected to be very accurate, with confinement times in the range 3.5–4 s. This prediction is the basis of our confidence that ITER will reach the self-heated burning-plasma regime. We can get a qualitative feel for the extrapolation using the simple random-walk scaling: JET achieves roughly $\tau_E \sim 0.5$–1 s confinement times and therefore ITER (which will be roughly twice as big, 30% hotter and have a field approximately 30% larger) will have roughly $\tau_E \sim 4$ s.

Given our current knowledge, it is more than reasonable to assume that ITER will achieve its goal of a burning plasma in the mid-2020s

Blanket engineering

Given our current knowledge, it is more than reasonable to assume that ITER will achieve its goal of a burning plasma in the mid-2020s. However, as any engineer will confirm, there is much more to commercial power generation than simply proving a design is scientifically feasible. Indeed, several components of any future fusion reactor – in particular the systems that breed tritium from lithium (the second reaction in figure 1) and convert neutron power to electrical power – have yet to be tested at any scale. The neutrons produced in deuterium–tritium reactions, which carry four-fifths of the fusion power, are not confined by the magnetic field and therefore leave the plasma and pass through the surrounding wall. Inside the wall there must be a complex system that absorbs the neutrons, extracts heat and "breeds" tritium from lithium – this is known as a "blanket".

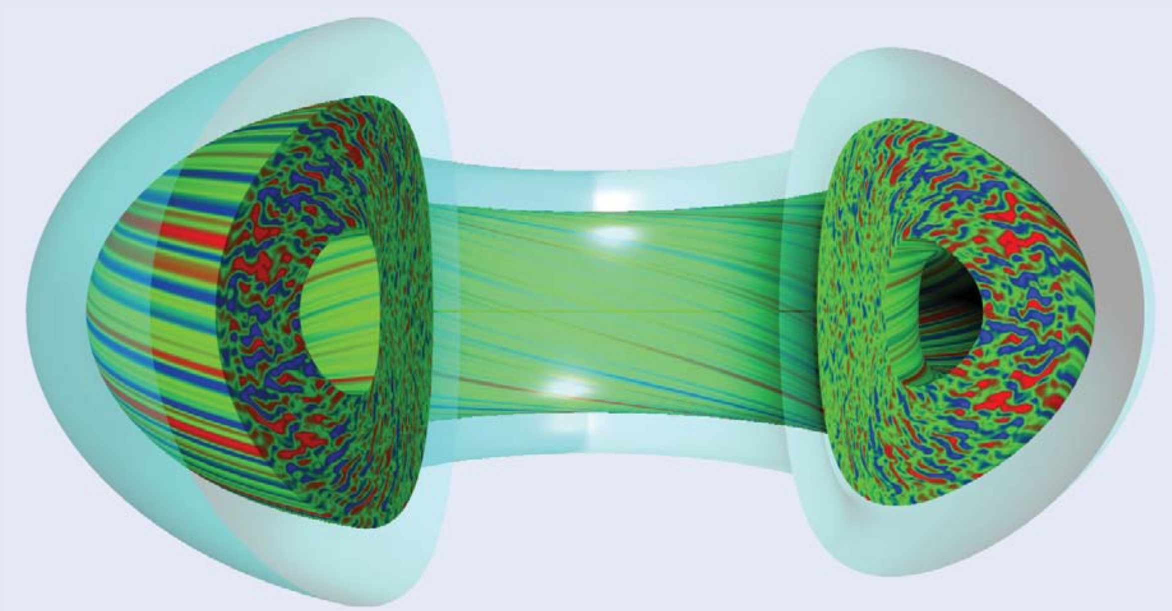
There are many blanket designs but they all have a few things in common: they are typically 0.5–1 m thick, separated from the plasma by a steel wall and bounded on the outside by a steel shield. The blanket contains lithium, which absorbs neutrons from fusion to breed tritium (figure 1) that is then fed back into the plasma as fuel. Also in the blanket are neutron multipliers and a coolant used to flush out tritium and heat, which is used to power a turbine and generate electricity.

The blanket must satisfy some key requirements: to be economically viable it should operate robustly at high temperature in a harsh neutron environment for many years; and for tritium self-sufficiency it must breed more tritium than the fusion reactions consume. The technologies of the blanket, as well as the wall, are becoming a major focus of the fusion programme and will represent much of the intellectual property associated with commercial fusion. These reactor-system technologies are critical for a future fusion economy – we cannot wait for ITER's results in order to start developing them.

A prerequisite for a viable blanket–wall system is robust materials. Structural materials, breeder materials and high-heat-flux materials are needed. In typical reactor conditions the atoms in the first few centimetres of the wall facing the plasma will get moved, or displaced, by neutron bombardment more than 10 times per year. Each displacement causes the local structure of the solid wall to be rearranged. Often this will be benign but sometimes it can weaken the structure. Materials must therefore retain structural integrity in these very challenging conditions for several years. To minimize the environmental impact of fusion, the walls must also be made of elements that do not become long-lived radioactive waste following high-energy neutron bombardment.

We do not know for certain whether such materials exist, but several promising candidate materials have been proposed. For example, various special steels have been shown to have suitable structural properties in theoretical calculations and ion-beam tests undertaken at Culham and UK universities. But we will not know for sure until samples have been subjected to a fusion-type neutron-radiation environment. The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-driven neutron source being developed by the international research community to test small samples of the promising materials; its design team is based in Japan as part of the deal that brought ITER to Europe. The neutron spectrum of IFMIF will mimic the high-energy neutron spectrum of a fusion reactor. Samples will be irradiated in a beam of neutrons for several years to evaluate the changes in their structural properties.

4 Heat loss through turbulence



Jeff Candy and Ron Waltz

Fluctuations of plasma density caused by turbulence, as simulated for the DIII-D tokamak at General Atomics in La Jolla, California, using a computer code called GYRO. Magnetic field lines lie on nested doughnut-shaped surfaces – toroidal surfaces. In this image we can see two such surfaces, the turbulence between them and two cuts across the surfaces. The hot middle of the plasma is omitted. The field lines are not shown but the fluctuations are elongated along the magnetic field lines and are thus visible as the red and blue streaks along the toroidal surface. Turbulent flow is roughly along lines of constant colour and is perpendicular to the magnetic field lines. As can be seen from the cuts across the surfaces, the swirls – eddies – are shorter in scale across the field (they are a few times the width of the helical orbit of the ions about the field lines). GYRO solves kinetic equations for the rings of charge formed by the helical motion of particles around the magnetic field lines. The fields are calculated from Maxwell's equations using the calculated charge and current.

We need a testing facility

If, as expected, ITER proves to be successful, then blanket development is probably the critical path for fusion. Blanket designs are being developed and tested with weak sources of neutrons, and it appears that these designs will breed tritium efficiently enough to be self-sufficient. But they must be tested at full neutron power before we can ensure a reliable commercially viable system. Although test-blanket modules will be placed in the walls of ITER in the later stages of operation, definitive tests require a continuous neutron flux of 1–2 MW m^{-2} for several years, which will not be technically possible at ITER. Thus I believe that a "component test facility" (CTF) that can deliver reactor-level neutron flux over many square metres is needed to significantly accelerate the development of blanket and wall structures. For such a device to be affordable it must be compact with low power consumption.

Researchers at Culham have pioneered a compact device called the spherical tokamak that is a prime candidate for a CTF. Indeed MAST (the MegaAmp Spherical Tokamak) has achieved impressive plasma conditions at a very modest scale. Calculations and measurements suggest that MAST achieves good confinement by suppressing the turbulence by spinning the plasma at supersonic speeds. The National Spherical Tokamak Experiment (NSTX) at Princeton in the US also operates at about the MAST scale.

Results from these devices suggest that the spherical tokamak is an ideal candidate for a compact and affordable fusion device – i.e. a suitable candidate for a CTF. Culham and the Oak Ridge National Laboratory in the US have therefore developed conceptual designs of CTFs based on spherical tokamaks. These facilities could test whole components of the blanket and wall at full power for many years. Both Princeton and Culham are upgrading their machines to prove the viability of these conceptual designs. The MAST upgrade will deliver near-fusion conditions, sustained plasmas and a test of the new exhaust system for gaseous plasma-burn products – the Super-X divertor.

If the MAST upgrade confirms the viability of a spherical CTF, then one could be built during the early years of ITER's operation. Wall and blanket development on the CTF coupled with ITER's programme could enable the construction of the first demonstration reactors in the 2030s. The current international programme has no plans to build a CTF – but surely it is essential if we are to deliver commercial fusion when it is needed.

It seems inevitable, given what has been achieved, that Eddington's dream will come true eventually – but when? Although we cannot say for sure, for a world that is hungry for energy, a reduction of the time to commercial fusion by even one decade could have an enormous impact.

More about: Fusion energy

ITER: www.iter.org

NIF: https://lasers.llnl.gov

K Ikeda *et al.* 2007 Progress in the ITER physics basis *Nuclear Fusion* **6** 47

R Pitts, R Buttery and S Pinches 2006 Fusion: the way ahead *Physics World* March pp20–26

Reviews

Peter Williams

Absence of evidence

Martin Bond/Science Photo Library

A warning sign
Debating the real danger of radiation.

Radiation and Reason: The Impact of Science on a Culture of Fear
Wade Allison
2009 Wade Allison Publishing
£15.00/$23.00pb
216pp

Just how dangerous is radiation? Scientists have been debating this question for decades yet, despite extensive studies, there is still controversy. The working assumption, which is currently accepted as the basis for regulation and legislation, is that radiation raises the risk of cancer at a rate that is directly proportional to dose at all dose levels. A consequence of this "linear no threshold" (LNT) model is that it assumes that there is no safe level of radiation dose. The other possibility is that below a certain threshold level, radiation is essentially harmless: any damage done by ionization and the consequent radiochemical and radiobiological effects is effectively and quickly repaired by the human body, with neither lasting harm nor elevated risk of cancer.

Conclusive evidence in favour of one model or the other would be of enormous interest. Scientists who design and operate nuclear power plants and radioactive-waste repositories would benefit from greater clarity. Medical physicists, who routinely weigh up the benefits of diagnostic tests and radiation treatments against the risks to patient health, would be on firmer ground – as would the politicians who approve the necessary regulations. But any changes in policy or clinical practice must be driven by data. Bold claims that radiation-protection regulations are a factor of 1000 too cautious may be appealing, but they should be dismissed out of hand unless they are supported by both a reasoned argument and unequivocal data.

In *Radiation and Reason: The Impact of Science on a Culture of Fear*, Wade Allison, a physicist at the University of Oxford, sets out a reasoned argument in favour of the threshold model, and against the LNT assumption outlined above. To support this argument, Allison provides examples from engineering and biology where there are indeed thresholds for irreparable effects. For example, an individual who suffers a bruise or laceration will recover completely from such a minor injury, but beyond a certain threshold, laceration is irreparable and possibly life-threatening. Why, Allison asks, should radiation carcinogenesis be different? After all, we know that damaged DNA can be repaired, and that in some cases irreparably damaged cells can be eliminated by apoptosis, or programmed cell death. Surely this is evidence that the LNT model is flawed?

In the course of researching this self-published book, Allison clearly became convinced that the radiobiological processes underlying carcinogenesis are well enough understood that the LNT assumption can be dismissed. However, the reader should be aware that the data he uses to support this argument have also been reported and discussed extensively by researchers in the field, and their conclusions were rather different. Notably, the L H Gray Conference in June 2008, which brought together international experts in radiobiology, epidemiology and risk assessment, concluded that "at the present time, although the possibility of a low-dose threshold cannot be ruled out, current thinking on radiation protection suggests it is likely that low doses of radiation will carry some risk".

The threshold hypothesis set out in *Radiation and Reason* is based on observations from human populations. In particular, data on survivors of the Hiroshima and Nagasaki atomic bombings and those exposed to radiation in the aftermath of the Chernobyl incident show that the number of "excess" cancers is lower than would be expected from the LNT model. However, the evidence from radiotherapy patients, who Allison claims are safely exposed to doses many orders of magnitude higher than radiological-protection dose constraints, is not completely appropriate in this context, nor is it complete.

In radiotherapy, the volume of tissue irradiated to very high doses is typically less than 1% of the whole body. A much higher volume of tissue receives dose levels that can produce functional side effects (such as damage to the integrity of the skin or blood vessels, or reduced saliva production) rather than carcinogenesis. Allison correctly cites the repair processes for these side effects as being

Allison suggests that overzealous regulation has persuaded the public to believe that radiation is more dangerous than it actually is

the mechanism whereby therapeutically effective doses can be delivered to tumours without doing irreparable damage to normal tissue.

Repairing functional damage is, however, very different from the repair at the molecular level that is necessary to reverse the genetic damage that leads to cancer. Moreover, there is also an unavoidable whole-body dose associated with radiation therapies – typically 4 mSv per day from leakage and scattered radiation. (In comparison, the average annual dose from background radiation is approximately 2.4 mSv.) This scattered radiation is known to induce "second cancers", which can occur far away from the regions of high dose. For example, a large study of men with prostate cancer demonstrated an increased subsequent risk of lung cancer for those treated using radiotherapy compared with a matched cohort treated by surgery. Although the appearance of such cancers does not preclude the existence of a threshold, it does undermine the grounds for rejecting the LNT model on the basis that radiotherapy is risk-free.

The bottom line is that the scientific debate on the existence of a threshold cannot be resolved by population studies alone, simply because the data are so sparse (thankfully, since they stem largely from nuclear wars and accidents). As the old saying goes, "absence of evidence is not evidence of absence". Resolution of the threshold question, if it is possible, will be indirect and will depend on quantitative basic radiobiology rather than epidemiology.

While the book draws on data from many applications of radiation, it is the nuclear-power industry that would, its author believes, benefit most from relaxed regulation. Yet Allison acknowledges that most of the vast expense involved in designing safe reactors and appropriate storage systems is directed at avoiding or reducing the risk of major incidents; as such, these costs do not depend on the existence of a threshold dose. The necessary storage time for fission products and other medium-half-life radioactive waste *would* be influenced by the level of a threshold, and by public and scientific acceptance of it. However, the costs of constructing a waste-storage facility will not be very sensitive to the threshold dose, nor to the timescale required. A facility built to last 500 years is unlikely to cost three times as much as one designed to last 150 years – another example of nonlinearity.

Radiation and Reason also poses questions of a sociological and political nature. Why, Allison asks, is radiation perceived as being particularly harmful? Can that perception be changed to ensure that nuclear power can be made more affordable and available, leading to worldwide societal benefits? In exploring these questions, the author suggests that overzealous regulation has persuaded the public to believe that radiation is more dangerous than it actually is. He argues that this has produced an ever-tightening spiral of constraints, which others have described as the "ratchet of radiation protection". Perhaps, he says, the time has come to release it. In this respect, Allison may have a point: a relaxation of constraints may indeed be in order, and it should certainly be on the agenda.

However, such sensible thinking is undermined by Allison's statements regarding would-be nuclear terrorists. In particular, his suggestion that terrorists will be deterred if regulations on the storage and use of radioactive materials are relaxed, in response to evidence of reduced risk, strikes me as fanciful. For one thing, it wrongly assumes that terrorism is based on rational behaviour. It also ignores the fact that if radiation were known to carry a lower risk than current thinking suggests, then terrorists would simply need to steal a bigger flask of radioactive material to cause the same effect.

So is this a book about science, the public understanding of science, or politics? Perhaps all three, but the author's emotive language in stating that "the public need to know the truth" implies that in the past they have been told lies. This puts the matter squarely in the political domain. For scientists, the threshold debate is not about truth or lies; rather, it is about how to deal with facts in a world of uncertainty, where decisions have to be made on the basis of the balance of probabilities. Allison is acerbic in his criticism of international bodies such as the International Commission on Radiological Protection, but their conservatism is not, as he says, "an abrogation of scientific responsibility". Rather, it is a recognition that scientists have a responsibility to make judgments as well as reporting their results. Until the radiobiological and radiological-protection communities reach a consensus, it would be unreasonable to expect legislators to relax regulation and undertake an experiment that will take generations to mature.

Peter Williams retired as director of medical physics at the Christie Hospital in Manchester, UK, in October 2009 and is a past-president of the Institute of Physics and Engineering in Medicine, e-mail peter.williams@physics.cr.man.ac.uk

Margaret Harris

A problem for the future

Magic Hour Films

Burying the future
Inside the Onkalo nuclear-waste repository in Finland.

Into Eternity: A Film for the Future
Michael Madsen
2009 Magic Hour Films, 75 min, www.intoeternitythemovie.com

The archaeologists who excavated the tombs of the pharaohs were lucky. When they stumbled upon the remains of an ancient civilization, they found gold and valuable artefacts. Their descendents will not be so fortunate. When explorers go digging for *our* last remains, what they find may be valuable, and it will certainly tell them something interesting about our culture. But it could also kill them, because the longest lasting monuments of our civilization will probably be our nuclear-waste repositories, and the radioactive "treasure" they harbour will remain dangerous for thousands of years.

What does this say about us? This is the central question posed by the film *Into Eternity* – a fascinating and troubling documentary about a waste repository in southwest Finland called Onkalo, a name that means "hiding place". Currently under construction, Onkalo is due to receive its first consignment of radioactive waste in 2020. When it is completely full, sometime in the early 22nd century, its entrance will be sealed. Its designers hope that it will remain that way for at least 100 000 years. But no human-built structure has ever lasted a 10th of this time, so every decision made about Onkalo rests on uncertain ground.

Subtitled "A film for the future", *Into Eternity* explores this uncertainty in detail. The film, which will get its UK première in Sheffield at the Doc/Fest event in November, discusses the physics of radioactivity, the practicalities of interim and permanent storage, the requirements of the law, and the vexed question of how to keep our descendents safe from Onkalo. Between interviews with various Finnish and Swedish officials, filmmaker Michael Madsen takes us round the Onkalo site, including the unfinished tunnel, which will eventually stretch for 5 km and reach depths of more than 450 m.

The tunnel is a surreal place, covered in unintelligible markings and suffused with a dim blue light. One interviewee – a workman called Sami Savonrinne – likens it to a time capsule. We hear Savonrinne's words as he crouches on the tunnel floor, a lonely figure in a high-visibility jacket preparing to blast away the next section of bedrock (see image). It is a striking image, one of many in this surprisingly beautiful film. The music is also well chosen, with a multinational soundtrack featuring music by the Finnish composer Jean Sibelius as well as Arvo Pärt, Kraftwerk and – to great effect, in the film's final scene – Edgard Varèse.

Such artistry would be wasted if the interviews did not provide content to match. Fortunately, Madsen has put together a remarkably candid bunch of experts – some affiliated with Onkalo, others not – and they all have interesting things to say. One of the most fascinating discussions concerns the chances of Onkalo being found, and the consequences of any such "human intrusion". The experts generally agree that the repository will, at some point, be forgotten – certainly by the next predicted ice age in 60 000 years, and probably well before then. As a result, says Onkalo's senior manager of communications Timo Seppälä, "My personal belief is that no human intrusion will take place at any timescale ever."

Timo Älkäs, the facility's vice president for engineering, is more equivocal. Someone *might* break into Onkalo, he concedes, but if they did, they would have tools to measure the radiation. One of the external experts, Peter Wikberg of Sweden's Nuclear Fuel and Waste Management Company, elaborates on Älkäs' point: any civilization advanced enough to dig into Onkalo, he says, would also be advanced enough to know what it was dealing with.

That is a comforting thought, but his colleague Berit Lundqvist immediately casts doubt on it, noting that 16th-century Swedish miners were able to dig several hundred metres below the surface even though they were unfamiliar with steam engines, let alone radioactivity. Over such an immense stretch of time, we cannot assume that humankind will become ever more technologically advanced; any number of events could send our descendents back to the Middle Ages. The moderate-technology society that might follow is a nightmare scenario for Onkalo's designers, one where "people may drill but may not understand", concludes Mikael Jensen, an analyst with Sweden's Radiation Safety Authority.

Would it help to warn them? Possibly – but there is no guarantee that a warning would be understood. Even if it is, the advice might not be heeded. As the film points out, one Norwegian rune stone, carved less than 1000 years ago, bears a warning that it "should not be touched by misguided men". The stone was found lying face down.

Yet Finnish law states that the future must be informed, so it will be – in Finnish-language archives that are unlikely to last more than a fraction of Onkalo's useful life. In the film, the task of explaining this legal lunacy falls largely to Esko Roukola, principal advisor for regulation at Finland's Radiation and Nuclear Safety Authority. He looks distinctly uncomfortable about it. Asked if he trusts future generations, at first he squirms and waves the camera away. Eventually, he stammers "I cannot say that I trust but I cannot say that I don't trust." It is one of the film's best lines, succinctly capturing the problem Onkalo's builders face.

There are a few gaps in the film, mostly on the technical side. For a place that is meant to be stable and unchanging, the Onkalo tunnel appears to contain an awful lot of running water. It would have been nice to hear at least one expert explain in more detail how waste is to be kept segregated from groundwater over the next several thousand years. A more nuanced approach to the facility's 100 000-year lifespan would also have been welcome. Half-lives being what they are, at some point Onkalo's waste, though still hazardous, will no longer pose an immediate threat to life. How long will that take? 500 years? 1000? 10 000? The film does not say.

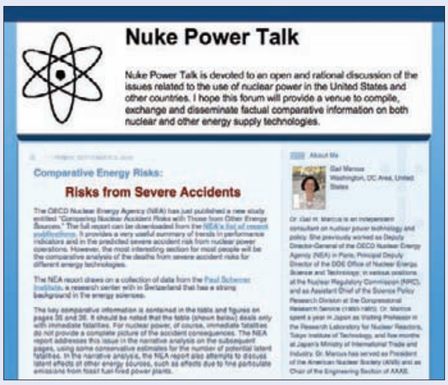
> Any civilization advanced enough to dig into Onkalo would also be advanced enough to know what it was dealing with

On a related note, it is a pity that Madsen's interviewees give short shrift to the possibility of transmuting waste into less hazardous substances with shorter half-lives. Although Juhani Vira, Onkalo's senior vice president for research, accurately points out that transmutation would not make all the waste disappear, it would certainly reduce the total volume and perhaps the required isolation period. This is not a small advantage. Building a handful of Onkalos to last 1000 years would be a manageable engineering problem. Building several hundred to last 100 000 seems dangerously close to a crime against the future.

Unfortunately, there does not seem to be an alternative: if we want nuclear power, we will get nuclear waste. Indeed, we have accumulated more than 200 000 tonnes of waste already, so even if we shut down all our nuclear power plants tomorrow, we would still have a massive problem. Places like Onkalo represent an implicit promise that we can keep this waste safe – not only in our own time, but for what might as well be an eternity. So are they the solution? *Into Eternity* has no answers, but it is a beautiful film about an ugly problem, and anyone interested in nuclear power should see it.

Margaret Harris is Reviews and Careers Editor of *Physics World*, e-mail margaret.harris@iop.org

Web life: *Nuke Power Talk*



URL: http://nukepowertalk.blogspot.com

So what is the site about?

Nuke Power Talk is primarily a forum for discussing important issues related to the nuclear-power industry. You'll find information here about new reactor designs and recent conferences, plus commentary on speeches by major figures in the industry. What really distinguishes this blog, though, is the insightful way that it connects nuclear power with the bigger picture. For example, an entry posted shortly after the BP Deepwater Horizon oil-rig disaster discusses how safety procedures that were developed for the nuclear industry are now being applied in other fields. Other entries focus on how nuclear power fits into the energy industry as a whole, and how it stacks up in comparison with solar and wind power.

Who is behind it?

Blog author Gail Marcus has an impressive string of previous appointments on her CV, including a stint as president of the American Nuclear Society and deputy directorships at the Nuclear Energy Agency and the US Department of Energy's Office of Nuclear Energy, Science and Technology. Now an independent consultant on nuclear power and technology, Marcus started blogging in 2009 after "seeing a lot of information in news articles or on the Web that was only telling part of the story", she told *Physics World*. Although clearly a supporter of the industry, she is sometimes critical as well, and tries hard to maintain a balanced viewpoint. Her goal, she says, is to be "a voice of reason in a sea of rhetoric" about nuclear power.

Who is it aimed at?

Nuclear insiders will appreciate Marcus's posts about news she picks up from attending meetings and reading various specialist publications. Others may be drawn more to entries where she dissects, in clear and intelligent language, the policy issues surrounding nuclear power.

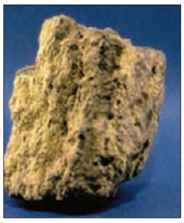
Can you give me a sample quote?

In a post about "unintended consequences", Marcus writes "I'm not completely sure why the scientists and engineers have not been able to develop the ability to try to project such consequences. I do realize it is difficult...We've got to anticipate ways that people will misuse appliances. We've got to anticipate all conditions under which a system may operate – rain, snow, heat, humidity. We've got to anticipate the resource requirements, competition with other needs, etc, when a new technology grows from limited to large-scale use...For example, questions are raised from time to time about the impacts of the increased use of nuclear power. Will there be enough uranium? What will the land impacts be of mining lower-grade ores? The questions are good ones, and will need better answers if we are to realize a nuclear renaissance."

Are there any other nuclear blogs that are worth investigating?

Absolutely. Dan Yurman's *Idaho Samizdat* (djysrv.blogspot.com) is a great site for the latest nuclear-industry news and gossip, and it covers non-proliferation issues as well. *Energy From Thorium* (energyfromthorium.com) is more specialized, offering an in-depth look at...well... deriving energy from thorium (see "Enter the thorium tiger" on p40). *Blogging About the Unthinkable* (sovietologist.blogspot.com) is a bit off the beaten track. The author, a historian with an interest in Soviet atomic culture, has recently posted photos from a field trip to Chernobyl – including several taken in the Unit 1 reactor control room, which looks exactly as it did in 1986, when the neighbouring Unit 4 reactor melted down. With an incredibly diverse community of nuclear bloggers out there, though, this is just the tip of the iceberg.

Between the lines


Shock and ore
The story of the impact of uranium on humankind.

History of an uneasy element

Among the Bemba people of central Africa, the word "*shinkolobwe*" is slang for "a man who is easy-going on the surface but who becomes angry when provoked". It is also the name of the Congolese uranium mine that yielded raw material for the atomic bomb that flattened Hiroshima. As historical coincidences go, this one seems almost too good to be true. Still, one can hardly blame author Tom Zoellner for seizing upon it in *Uranium: War, Energy and the Rock that Shaped the World*, a very readable (if somewhat chaotic) history of how this normally easy-going element has provoked anger on five continents. After a scene-setting visit to the Shinkolobwe mine, Zoellner's description of the Manhattan Project will contain few surprises for anyone who has read more comprehensive histories. One notable exception is his explanation of how the scientists got the uranium for the bomb. This tale of costly enrichment programmes, dubious middlemen and colonial skulduggery has important ramifications for the entire subsequent history of uranium. In chasing this history, Zoellner goes to an impressive amount of trouble to tell some of the less-heralded stories of the uranium age, talking to prospectors from Darwin, Australia, to Moab, Utah, and to one of the last survivors of an East German uranium gulag, where political prisoners dug the ore that built the Soviet nuclear arsenal. The price they paid was high – thousands died from radiation, non-existent safety precautions and maltreatment – but it was scarcely lower for miners in the West, where labour was unforced but just as hazardous. The universally cavalier attitudes to radiation during this period are sobering to contemplate. The book's final chapters cover a grab-bag of topics from endemic fraud in Canadian uranium stocks to the question of whether terrorists could get enough uranium to build a bomb. It is not a question Zoellner cares to answer directly, but some may feel that the facts speak for themselves: on his visit to Shinkolobwe, he found the still-productive mine almost completely unguarded.

● 2010 Penguin £11.99/$16.00pb 368pp

Questioning the cosmos

As a means of conveying scientific information, the "question and answer" format has a lot to recommend it: it is simple, straightforward and easy to follow. The downside is that books in this style tend to misjudge their audiences – after all, how do the authors know which questions readers want answered? For this reason, *A Question and Answer Guide to Astronomy* is a pleasant surprise. Written by engineer Pierre-Yves Bely and astrophysicists Carol Christian and Jean-René Roy (and recently translated from the original French into English), the book claims to give "simple but rigorous explanations" in "non-technical language", and it does exactly what it says on the tin. Split into 10 sections, it answers hundreds of questions in fields ranging from planetary science ("What is the greenhouse effect?") to astronomy and cosmology ("How do stars die?"). It also tackles trickier concepts such as "Can anything go faster than the speed of light?" and various big mysteries, including "What was there before the Big Bang?". All the explanations are well expressed and usually aided by a full-colour illustration or photograph. Within explanations, the authors helpfully have embedded cross-references to other pages that may help to explain common concepts, allowing readers to skim through the questions focusing on the areas that interest them most. Towards the end, the book becomes more specialized, with 30 or so questions on telescopes followed by a propaganda-like section on how to get involved in astronomy. Despite this, the majority of the guide is informative, and by successfully tackling ideas that are often misunderstood, it makes for a worthwhile and enjoyable read.

● 2010 Cambridge University Press £18.99/$28.99pb 294pp

First you have to look for them

The ever-expanding catalogue of worlds discovered outside our own solar system contains all sorts of planets: hot, cold, icy, rocky – you name it. But what about watery planets? Or those lovely, not-too-cold, not-too-hot "Goldilocks" ones with an active geology and perhaps a biggish moon nearby, just to keep things interesting? In *How to Find a Habitable Planet*, James Kasting begins by describing various factors that geophysicists, astrobiologists and others have deemed necessary (or at least desirable) for producing planets capable of supporting life. He then examines the evolutionary histories of the planets we know best – the Earth, Venus and Mars – in an attempt to determine why they developed the way they did. The book's second half looks at ways of finding new planets using indirect methods (like measuring the tiny gravitational wobble imparted to a star when a planet passes nearby) before moving on to the challenges associated with detecting them directly. Being able to separate the faint reflected light of individual planets from the much brighter light of their parent stars "turns out to be a tall order", writes Kasting. As a planetary scientist at Pennsylvania State University in the US, Kasting was involved in a design study for a space-based telescope that would have examined light reflected from the surfaces of extrasolar planets for clues about their composition. Unfortunately, the mission was cancelled while it was still in the design phase, and NASA has not yet revived it. *How to Find a Habitable Planet* offers an eloquent explanation of why such a mission would still be desirable.

● 2010 Princeton University Press £20.95/$29.95hb 360pp

Weird science

Tired of biscuits that crumble into a soggy mess at the bottom of your teacup? Uncertain of the best technique for skimming stones across water? If you need answers to these pressing problems – plus advice on how to win at Trivial Pursuit and a rather invasive way to cure hiccups – then *Dunk Your Biscuit Horizontally* is the place to look. This light-hearted book of bite-sized strange science was compiled by the Dutch journalists Rik Kuiper and Tonie Mudde, and would make a great gift for anyone whose sense of humour encompasses both the scientific and the scatological. It is probably not one for younger children, though: the best cure for intractable hiccups turns out to be either good sex or "digital rectal massage".

● 2010 Summersdale Books £7.99pb 128pp

Playing it safe with reactors

With new nuclear reactors on the horizon, **Mike Yule** explains why helping to keep the UK's existing plants running safely is a great job for a physicist


AMEC

Putting safety to the test Graduate analyst Mike Yule finds lots to challenge him at consultancy firm AMEC.

After a period of decline, there is now a real sense of excitement in the UK's nuclear industry. The previous UK government's commitment to allow new reactors to be built on 10 sites has proved invigorating for the entire sector. Even firms that had traditionally focused on keeping the current power stations operational are now making "new build" a growing part of their business.

My own employer, AMEC, is one such firm. As contractors, we do work that other companies cannot do, either because they do not have enough people or because they lack the right skills. Following the company's acquisition of the nuclear consulting firm NNC in 2005, the nuclear part of AMEC's UK business has expanded considerably. There are now offices around the country, including one in London near the headquarters of EDF Energy (one of the main companies planning to build new reactors in the UK), which lends project-management support and other expertise.

I joined AMEC two years ago after completing an MSci in maths and physics at Durham University. I had planned to continue my studies with a PhD, but after doing a final-year project in theoretical physics, I decided that this was enough theory for me. At a careers fair, I came across AMEC, which was looking for physicists to work in its nuclear sector. I applied, was accepted onto its graduate scheme and I now work as an analyst at AMEC's Booths Park site in Cheshire.

AMEC is split into three divisions: Natural Resources, which deals with the oil and gas industries; Power and Process, which works in the nuclear sector; and Earth and Environmental, which provides geoscience services. The Booths Park site is part of the Power and Process division, and has been home to nuclear scientists since the 1950s. Back then, the offices were in a mansion house, and the workers were helping to design the Magnox reactors – the UK's first commercial nuclear plants. Today, the offices are more modern, but the same view of a small local lake, Booths Mere, is available – along with cows making the daily parade for milking! There is also a nice link to the original work, as AMEC has recently been involved in decommissioning the Magnox reactors.

Safety first

In my team of about 30 analysts, project managers and planners, most of our consulting work comes from British Energy, although we also work with Rolls Royce and BAE Systems. British Energy (now part of EDF Energy) owns the majority of the UK's commercial reactors, which are mainly advanced gas-cooled reactors (AGRs). Some of these reactors were constructed 30 years ago and they are now coming to the end of their lives. But with power stations able to generate £1m worth of electricity a day, keeping them online for even a few extra years is big business. A lot of AMEC's work therefore deals with life extension – determining whether or not the reactors are safe to operate for a little longer.

Deciding when a reactor needs to be decommissioned can be a challenge. Everything gets weaker as it ages – even in coal power stations, parts must be replaced continuously. But once you throw irradiation into the mix, dealing with ageing power plants gets more complicated. For example, in an AGR, the reactor core is constructed from graphite blocks that fit together to form what is known as the diagrid. Over time, the graphite is irradiated, and also gets oxidized by any small quantities of air present, making it weaker and lighter. Eventually, such "core ageing" processes will render the reactor unsafe for continued operation.

Safety is paramount in this industry, so if the Nuclear Installations Inspectorate – the regulatory body that issues licences for running a reactor in the UK – is not happy, then a reactor will simply be shut down. Getting the evidence we need to prove that a reactor is still safe has required some novel approaches to testing. One of these is AMEC's "test rig", which is essentially a steel cage with a quarter of the footprint of a real reactor core, containing quarter-size "graphite" blocks (actually made from aluminium) in various states of wear and tear. Tilting this rig allows cameras to see whether the ageing blocks would cause problems during normal operation, or in more extreme conditions, such as a major earthquake.

Measuring the damage

One of the main projects I have been involved in is proving that it is safe to connect inspection equipment to empty reactor channels, to allow video equipment to be slid into the channels and video footage to be obtained from inside the core. The idea is to see how many cracks are present: even though it will not be possible to fix any that are found, given the extreme environment, it is still useful to know how much the core has degraded.

Within this project, my specific job is to evaluate the consequences of what are known as "dropped fuel faults". In a reactor, the uranium fuel is contained in bullet-like pellets within stainless-steel tubes, called fuel rods or pins. An arrangement of 36 fuel pins in three concentric rings, held inside a graphite "sleeve" using steel braces, is known as a fuel element. These fuel elements are lifted into and out of the reactor and various other components during refuelling or discharging operations. If a element drops at any point, then its potential energy goes into processes such as crumbling the sleeves and buckling the pins.

Thanks to specially conducted drop tests of fuel elements, we have a good idea of how they can be damaged, and how much energy can be absorbed in the various processes. By incorporating energy-absorption mechanisms into spreadsheets, we can calculate how much damage would occur in a particular situation, and can show how damage depends on drop height, channel diameter, ductility and many other factors.

> The AMEC graduate scheme is a great introduction to the nuclear industry

Another problem is that because the pins contain fuel, they generate heat even when the reactor is shut down (so-called decay heat). If the pins buckle due to mechanical loading in a dropped fuel fault, the fuel becomes more concentrated and less easy to cool. We need to model this too, so some of the work I do uses software (written in good old Fortran) to predict how faults will affect fuel temperatures, which have to stay within limits to ensure safety.

I have found this work interesting because it has built on knowledge gained over the course of my degree, particularly that of spreadsheets and programming languages. My degree has also helped by giving me a better understanding of physical situations, such as where heat is being transported by flows and radiation.

The AMEC graduate scheme is a great introduction to the nuclear industry, and a good way of meeting the other graduates who joined the firm at around the same time. I have greatly benefited from the supervision of specialists, who are always ready to share their expertise. I enjoy the work I do and it has given me confidence in the safety of our reactors. In a growing industry, that is no bad thing.

Mike Yule is an analyst in AMEC's Power and Process division, e-mail mike.yule@amec.com

Once a physicist: John Hemming

John Hemming is the Member of Parliament for Birmingham Yardley, UK

What sparked your interest in physics?

I have always been interested understanding how things work. I prefer maths and physics as academic subjects because they have more of an objective truth or falsity about them, whereas the humanities are more about agreeing with a consensus. Philosophically, I prefer the idea that there is such a thing as objective reality that we attempt to measure, and it is not something that varies depending on the opinion of senior members of society.

Did you enjoy studying it at university?

Yes, although admittedly there was one term I went to more PPE (politics, philosophy and economics) lectures than physics lectures. I was also someone who did not do enough practical work during the term and I therefore had to do a practical exam both in my first year and in my final year. This did, however, make physics more time-efficient as a subject, allowing me more time to do other things. Luckily, in the early 1980s one could get an honours degree in physics without doing lots of practicals – unlike chemistry, which required more practical work. I am someone who is happy doing practical things, but I tended to spend more time repairing bicycles, playing croquet and punting than doing physics practicals.

Why did you go into the software business?

After I left Oxford University in 1981, finding work was a challenge. My first job was to clear up the rubbish at Edgbaston Cricket Ground. That did not really have attractive career possibilities. I tried various things, including offering to teach physics and introduce croquet at a school in the Black Country, but I was told they wanted a postgraduate teaching certificate first. Then I managed to get employed as a computer programmer by offering to learn from the manuals. After a few changes of employer, I started my own business in late 1983 – the same year I fought my first general election, standing as the Liberal Party candidate in Birmingham Hall Green.

How did you become interested in politics?

I joined the Liberal Party in 1976 at the age of 16 because I wanted to see a fairer world where proper attention is given to environmental issues and people are treated justly as individuals. I was also interested in constitutional improvements, including electoral reform. Initially, I was agent for various elections, but I felt unhappy at the calibre of one early candidate and after that I concluded I should offer to be the candidate myself. I fought every general election between 1983 and 2001, and also served on Birmingham City Council before winning the Yardley parliamentary seat in 2005, and retaining it in 2010.

The Liberal Democrat Party is opposed to nuclear power. As someone with a physics background, what is your view on this?

The view of the [Conservative–Liberal Democrat] coalition government is that fission should not be subsidized. We do have fission-based electricity generation in the UK, but there is a medium-term issue with the availability of easily refined uranium-235. Hence, in the long term fission can only really be relied upon if a breeder technology can be made to work. However, I take the view that we should be aiming for sustainable energy sources. I am quite happy to rely on nuclear fusion as long as the power plant is kept on average some 93 million miles away. I do not have a problem with research on operating fusion at a closer distance; however, that project has generally been one that is constantly 40 years away from completion. If you were to forecast the true completion date by calculating the velocity at which it tends towards the value of "now", you would conclude that the fusion project will never be completed.

What do you think is the greatest challenge that the UK faces in terms of science policy?

A culture based on subjectivity and the celebration of celebrity.

Do you have any advice for the physics students of today?

Remember that it is normally a cock-up rather than a conspiracy, and yes, people really don't understand. Don't be surprised.

Careers and people

Top maths prize for former physicist

Elon Lindenstrauss, who gained undergraduate degrees in physics and mathematics before turning to pure mathematics, is among four winners of the 2010 Fields Medal. A researcher at the Hebrew University of Jerusalem's Einstein Institute of Mathematics, Lindenstrauss is recognized for work that focuses on the applications of ergodic theory – a branch of mathematics that grew out of statistical physics in the early 20th century – to number theory. The Fields Medal is awarded every four years to scholars up to the age of 40 and is viewed as the equivalent of a Nobel prize for mathematics. Also honoured in 2010 were Ngô Bào Châu of Paris-Sud 11 University and the Institute for Advanced Study in Princeton, US; Stanislav Smirnov of the University of Geneva, Switzerland; and Cédric Villani of the Ecole Normale Supérieure de Lyon, France.

Physics trio wins research awards

Three physicists are among 12 scholars to receive the Royal Society's Wolfson Research Merit Award in 2010. David Manolopoulos of the University of Oxford, Mervyn Miles of the University of Bristol and Sheila Rowan of the University of Glasgow will each receive grants of up to £30 000 per year over five years for research projects on atomic physics, nanophysics and astronomy, respectively. The awards, which are jointly funded by the Wolfson Foundation and the UK Department for Business, Innovation and Skills, are designed to support scientists in any discipline who wish to do research at UK universities.

Biophysics acknowledges key players

Six researchers working in a broad range of fields have been named as Fellows of the Biophysical Society for 2011. Bioengineer Valerie Daggett of the University of Washington; biophysicists Donald Engelman and Lynne Regan of Yale University; cell biologist Jennifer Lippincott-Schwartz and computational biologist Ruth Nussinov of the US National Institutes of Health; and biochemist Anthony Watts of the University of Oxford were honoured for "expanding the field of biophysics".

Movers and shakers

The Materials Research Society has given its David Turnbull Award to spintronics pioneer **David Awshalom** of the University of California, Santa Barbara.

Pallava Bagla and **Roberta Kwok** have won the American Geophysical Union's 2010 awards for excellence in science journalism.

Two Durham University researchers have won the Society of Rheology's top annual prizes. **Suzanne Fielding** received the Metzner Award for early-career researchers, while **Tom McLeish** won the Bingham Medal for contributions to the science of the deformation and flow of matter.

Fusion scientist **Martin Peng** of the Oak Ridge National Laboratory in the US has received the 2010 Fusion Power Associates Leadership Award for showing "outstanding leadership qualities in accelerating the development of fusion".

Theoretical physicist **Michelle Povinelli** of the University of South Carolina is one of 35 people named in *Technology Review* magazine's annual list of top scientists and technologists under the age of 35.

Next month in Physics World

Multiverse pioneer

US quantum physicist Hugh Everett III was the inspiration for the idea of multiple universes, but he led a troubled life that led to an untimely death at aged just 51

Living with a star

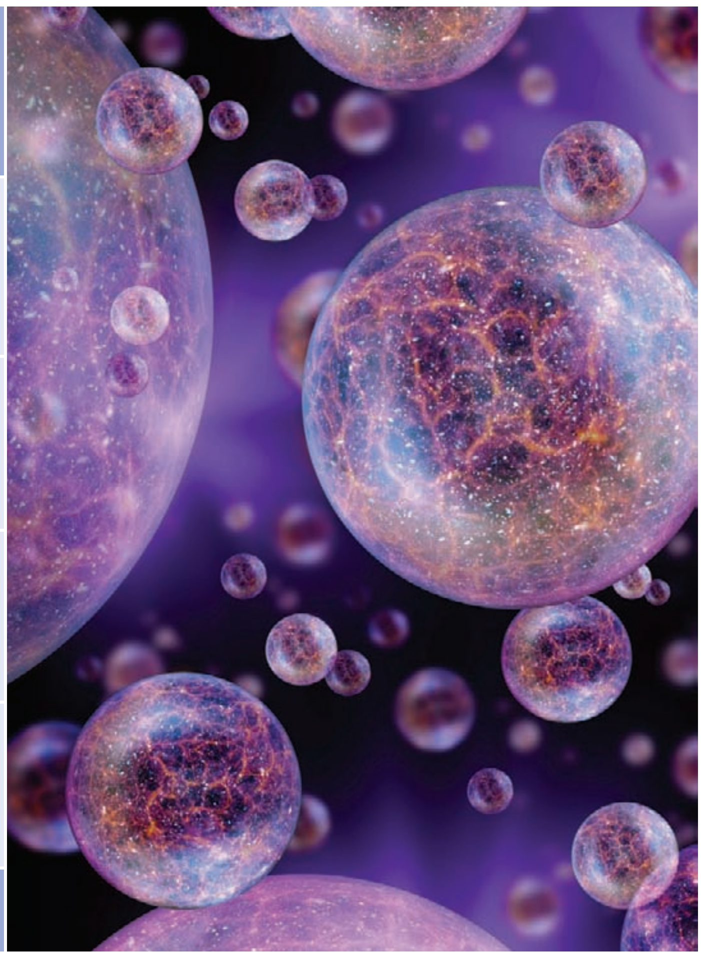
How a series of space missions dedicated to observing the Sun are enriching our knowledge of space weather and star behaviour

Microscopy frontiers

Scanning probe microscopy has transformed our ability to understand matter at the nanoscale, but what exactly does it mean to "see" atoms?

***Plus** News & Analysis, Forum, Critical Point, Feedback, Reviews, Careers and much more*

physicsworld.com



Detlav van Ravenswaay/Science Photo Library