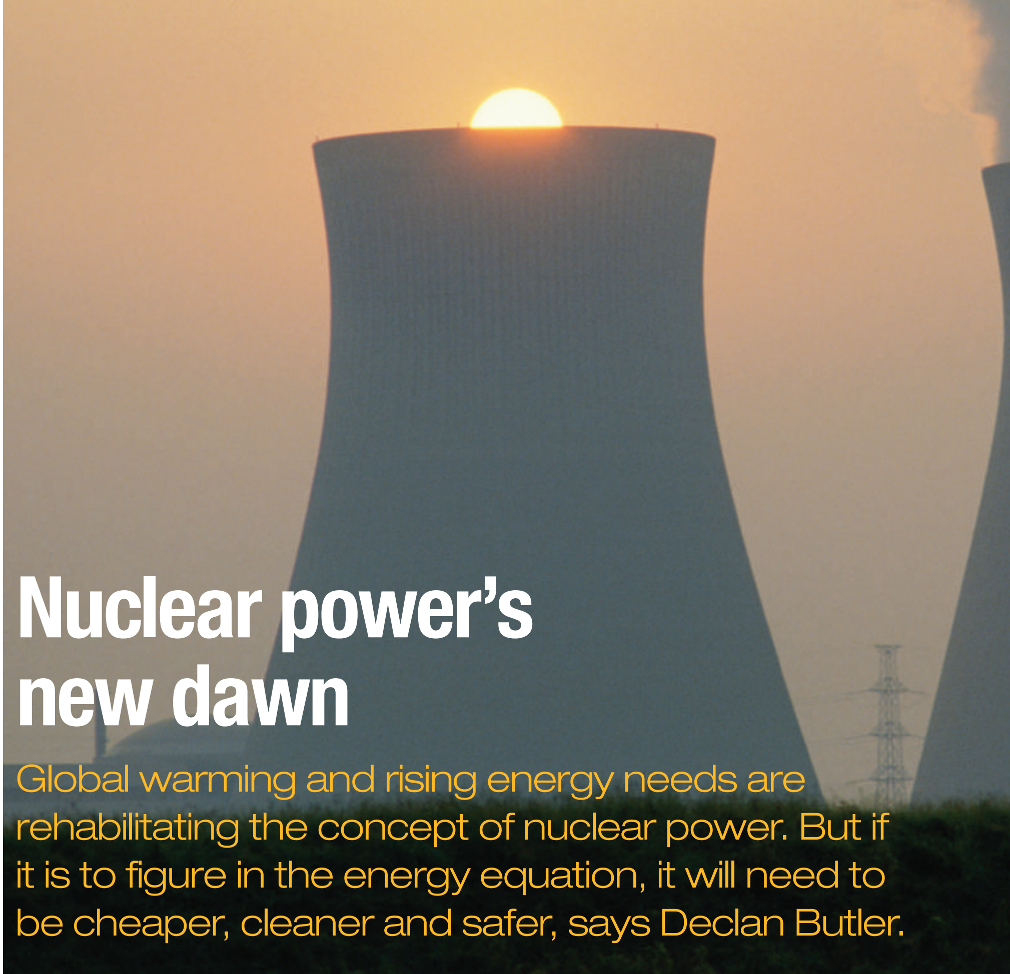

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Nuclear power's new dawn

Global warming and rising energy needs are rehabilitating the concept of nuclear power. But if it is to figure in the energy equation, it will need to be cheaper, cleaner and safer, says Declan Butler.

It's the night shift at a nuclear power plant in upstate New York, and a technician checks on the temperature of the reactor core. It's a searing 800 °C — a temperature that today would spark a major panic and could signal the start of a partial reactor meltdown. Yet this reading doesn't raise an eyebrow. It's 2035, and this state-of-the-art reactor is designed to operate at this temperature, cooled not by the water that keeps today's reactors in check, but by a huge vat of molten lead. And thanks to its high operating temperature, the plant is generating hydrogen fuel as well as electricity.

This vision of the future comes from the Generation IV International Forum (GIF), a consortium of ten nations that is planning the nuclear reactors of tomorrow. These new plants would all operate at high temperatures, improving their efficiency. And they would include simplified safety features that do not rely on sophisticated backup systems or experienced operators — all are, in principle, 'meltdown proof' and can cool themselves down in the event of an accident with minimal, if any, human intervention.

This would also mean that any attempt to trigger an accident deliberately — by shutting off the coolant or power supply — would be in vain. Nuclear reactors would become less of a terrorist target. At least, that's what the nuclear industry hopes.

But given memories of the partial reactor meltdown in 1979 at Three Mile Island, Pennsylvania, and of the 1986 accident at Chernobyl in Ukraine, during which the reactor core exploded, killing some 31 people immediately and spewing radioactive debris across Europe, the public will take some convincing.

No new nuclear power plants have been ordered in the United States since the accident at Three Mile Island. But in March this year, a consortium of US energy companies said that it intends to apply for a licence, the first step towards building a plant. In April, France announced that it would replace its elderly 59 reactors with new ones. And Asian countries are planning to build dozens of reactors to cope with their booming energy demands. Is this the beginning of a nuclear revival?

Fuel for the future?

Nuclear power is not a source of carbon dioxide, and with emissions of this greenhouse gas now soaring, and global energy demands predicted to double by 2050, the nuclear option is finding its way back onto the table. At a 2002 gathering of GIF representatives in Tokyo, Spencer Abraham, the US energy secretary, used these arguments to explain the Bush administration's strong support for nuclear energy. If nuclear engineers can overcome the technical hurdles involved in building the next generation of reactors, Abraham said, then we will have energy that is "safe, abundant, reliable, inexpensive and proliferation resistant".

For nuclear power to undergo a renaissance, experts agree that reactors will need to be a lot cheaper to run. And to sway a nuclear-averse public, the next generation of reactors will need to produce much less radioactive waste at terrorist-proof facilities.

Such technological challenges are too great for one country alone. In 2001, the eight founding nations of GIF decided to pool their research expertise, and later picked what they believe are the six best prospects for the reactors of the future[1] (see Table, opposite).

No more than three of the six designs are likely to survive the feasibility testing phase and go on to become research prototypes, each costing about US$1 billion to build and test, predicts William Magwood, director of the US Department of Energy's Office of Nuclear Energy, Science, and Technology, and chairman of GIF's board.

Unlike today's water-cooled reactors, which tend to run at about 300 °C, all six concepts are designed to run at temperatures from 510 °C to 1,000 °C. This allows for more efficient conversion of heat to electricity — one leading design, the very-high-temperature reactor (VHTR), could squeeze 50% more electricity from the same amount of fuel compared with conventional plants.

But these higher operating temperatures mean that the reactors will need new coolants, as ordinary water can only be used, under typical pressurized conditions, up to 330 °C. Two GIF concepts use inert helium to keep the reactor cool; others use molten lead, sodium or salt.

One of the most popular generation IV concepts, the supercritical-water-cooled reactor (SCWR), uses extreme pressures to prevent water from boiling at temperatures up to 500 °C. Because of the reactor's efficiency and relatively simple design, it would potentially be fairly cheap to build and run, says Jacopo Buongiorno, integration manager for the SCWR system at the Idaho National Engineering and Environmental Laboratory in Idaho Falls. Indeed, if it works, it will churn out electricity at prices that, on paper, are competitive with coal and gas, and vastly cheaper than existing nuclear reactors.

Hotting up

In terms of practical experience, perhaps the most advanced concept is the VHTR. Japan's Atomic Energy Research Institute based in Kashiwa already operates a similar high-temperature engineering test reactor at Oarai, near Tokyo. This reactor is cooled by helium gas, and it reached its operating goal of 950 °C for the first time in a test run last month.

At temperatures of about 700–900 °C, reactors can be used to split hydrogen from water thermochemically. Many countries that largely depend on oil for their energy needs are betting on hydrogen as the fuel of the future, using fuel cells to convert the gas into electricity for cars and homes.

Without a switch to hydrogen, the energy

demand from US transport alone will cause the nation's oil imports to soar by 78% by 2025 (ref. 2), so the US Department of Energy has made the VHTR its number one choice. A US energy bill that would provide $1.1 billion to build a prototype at the Idaho lab by the middle of the next decade is currently held up in Congress by disputes over unrelated issues, such as energy regulation.

"GIF recognizes nuclear's role in transportation. We've raised the stakes by including demonstration of hydrogen production in some of the reactor designs," says Ralph Bennett, the Idaho lab's director of advanced nuclear energy. But generating enough hydrogen to completely replace gasoline for the United States' transport needs would mean building more than 400 nuclear power plants, each generating a gigawatt[3]. There are only 441 nuclear plants in the world today.

"Without successful generation IV concepts, the nuclear industry will struggle to maintain its current position of generating 17% of the world's electricity."

Few in the industry dispute the wisdom of a shift towards high-temperature reactors, but only two of the designs — the VHTR and the SCWR — would be able to operate without having to depend on the controversial reprocessing of plutonium waste (see 'Plutonium wars', overleaf).

All the designs include untested engineering, and also depend on the development of new ultrahard materials that can resist continued high temperatures, intense bombardment by neutrons in the chain reaction, and often corrosive reagents, says David Lochbaum, a nuclear engineer with the Union of Concerned Scientists, an environmental pressure group based in Cambridge, Massachusetts. In the molten salt reactor, for example, uranium fuel is dissolved in the circulating coolant, and this would need new corrosion-resistant materials to prevent any possibility of a radioactive leak.

Magwood agrees that developing new materials will be one of GIF's greatest challenges. There are plans within GIF for a bold international research programme in this area that could also develop materials for nuclear fusion reactors, which face many of the same problems. But no decision is expected until summer 2005, when the GIF partners are scheduled to finish thrashing out plans for who will do what research on each of the six concepts.

Operating at high temperatures also rules out conventional fuel systems, in which uranium pellets are loaded into metal rods, as the rods melt at fairly low temperatures. Instead, the gas-cooled reactors will hold fuel pellets either in a honeycomb graphite structure, as in the Japanese test reactor, or fused into billiard-ball-sized graphite spheres, known as pebbles.

Core issues

In pebble-bed reactors, millions of these billiard balls are loaded into the core, and gas coolant flows through the spaces to remove the heat. The balls can be continually removed from the bottom of the reactor and are sorted automatically — those that are almost spent are sent to a waste stream, and those with some life left in them are returned to the top of the pile.

Each pebble is itself a mini-nuclear-reactor. A core of fuel is coated with a layer of graphite that slows down neutrons to control the nuclear chain reaction. This is covered with an ultrahard ceramic layer, sealing in all the fission products. In principle, this should

The six generation IV reactor concepts

The Generation IV International Forum (GIF) consists of the United States, Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland and the United Kingdom

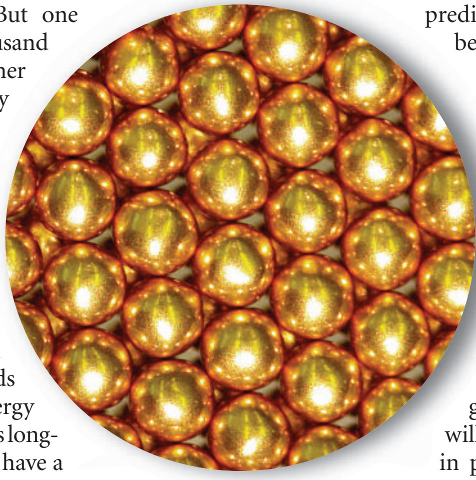
	Coolant	Temp. (°C)	Pressure	Waste recycling	Power output	Research needs	Earliest delivery
Gas-cooled fast reactors	Helium	850	High	Yes	Electricity and hydrogen	Irradiation-resistant materials, helium turbine, new fuels, core design, waste recycling	2025
Lead-cooled fast reactors	Lead–bismuth	550–800	Low	Yes	Electricity and hydrogen	Heat-resistant materials, fuels, lead handling, waste recycling	2025
Molten salt reactors	Fluoride salts	700–800	Low	Yes	Electricity and hydrogen	Molten salt chemistry and handling, heat- and corrosion-resistant materials, reprocessing cycle	2025
Sodium-cooled fast reactors	Sodium	550	Low	Yes	Electricity	Safety, cost reduction, hot-fuel fabrication, reprocessing cycle	2015
Supercritical-water-cooled reactors	Water	510–550	Very high	Optional	Electricity	Corrosion and stress, water chemistry, ultrastrong non-brittle materials, safety	2025
Very-high-temperature reactors	Helium	1,000	High	No—waste goes directly to repository	Electricity and hydrogen	Heat-resistant fuels and materials, temperature control in event of accident, high fuel burn-ups	2020

SOURCE: GIF

prevent any radioactive material escaping in the event of an accident.

The Oak Ridge National Laboratory in Tennessee worked on pebbles back in the 1970s, when high-temperature gas reactors were explored as a source of tritium, a hydrogen isotope once used in nuclear weapons. But one out of every thousand fuel pebbles was either chipped or poorly coated — unacceptable defects for a modern reactor.

All of the generation IV designs face similar hurdles. "The basic research gap is massive," says Alain Bugat, who heads France's Atomic Energy Commission. "This is long-term research; if we have a working demo of some of the designs by 2030 we will be doing well."



R. LOWDEN/OAK RIDGE NATL LAB.

Great balls of fuel: these pebbles are 'mini-reactors' and could be used to power the next generation of nuclear plants.

Without successful generation IV concepts, the nuclear industry will struggle to maintain its current position of generating 17% of the world's electricity. A study published last year[4] by a group of scientists and economists at the Massachusetts Institute of Technology (MIT) in Cambridge looked at the potential for the power generated by nuclear energy to triple by 2050, the level needed for it to have a significant impact on predicted carbon dioxide emissions. The group concluded that, economically, new nuclear plants would not be able to compete with coal and gas. Worldwide, most electricity markets are being deregulated, which means that there are fewer state subsidies to prop up the nuclear industry.

Substantial numbers of new plants will only be built, the MIT study predicted, if their costs can be cut by a quarter from existing designs, or if a hefty carbon tax is imposed on fossil fuels. The latter seems unlikely, so cost cutting is vital.

But the outlook is not quite so gloomy everywhere. "Most of the expected nuclear growth up until 2025 will be in eastern Asia, and in particular in just four countries — China, India, South Korea and Japan," says Peter Fraser, a nuclear analyst at the International Energy Agency in Paris. These will account for more than 85% of all new plants built, he predicts.

The reactors that the Asian countries want to build are mostly generation III systems — revamped versions of today's generation II reactors, but with multiple backup systems to enhance safety, and with simplified, cheaper designs that have fewer parts to go wrong.

Nevertheless, nuclear output worldwide is more likely to shrink until 2025, as older plants close more frequently than new ones open. France is one of the exceptions. It gets 80% of its electricity from nuclear power, and intends to begin replacing its ageing plants using a €3-billion (US$3.5-billion) generation III reactor, built by the Franco-German company Framatome ANP, headquartered in Paris.

Countries such as France and Japan want to maintain their energy independence, so the decision to rebuild is largely political, not economic. And the economic equation is changing all the time — by 2025 other emerging energy technologies may outcompete nuclear power. "We expect solar energy costs to fall dramatically," says Fraser.

Such technologies also fit better with the current trend towards decentralized electricity generation in smaller power plants[5], Fraser notes. In addition, future technologies may help to reduce carbon dioxide emissions from gas and coal plants.

The nuclear industry has to adapt to this rapidly changing global environment. Even if GIF can develop reactors that are supersafe and superclean, unless they are markedly cheaper than competing technologies, the nuclear industry will, for decades to come, be running hard just to stand still. There is likely to be much early morning jogging before any new nuclear dawn. ■

Declan Butler is *Nature*'s European correspondent.

1. *A Technology Roadmap for Generation IV Nuclear Energy Systems* (US DOE NERAC/GIF, Washington DC, 2002) online at http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf
2. International Energy Outlook 2004 (US DOE, Washington DC, 2004) online at http://eee.eia.doe.gov/oiaf/ieo
3. Grant, P. M. *Nature* **424,** 129–130 (2003).
4. *The Future of Nuclear Power* (MIT, Cambridge, MA, 2003).
5. *Nature* **427,** 661 (2004).

Plutonium wars

Reprocessing nuclear waste is controversial because it separates out plutonium, a key ingredient of advanced nuclear weapons. To counter plutonium proliferation, the United States, for example, has historically refrained from reprocessing waste, and discouraged other nations from doing so.

But four of the six proposed generation IV reactors would turn this doctrine on its head, as they would require reprocessing, albeit in a form that is supposed to be 'proliferation resistant'.

Conventional reprocessing recovers plutonium and uranium from waste, and these can be burnt in reactors as mixed oxide fuel (MOX). This process is most-developed in France, which operates a reprocessing facility at La Hague, and at Sellafield in the United Kingdom. Japan, China and Russia also have reprocessing plans.

Reprocessing is attractive because it could cut the final amount of waste produced — 96% of spent fuel consists of uranium and plutonium, whereas troublesome long-lived radionuclides account for less than 1%. So if these long-lived elements could be extracted from spent fuel, all of the uranium and plutonium could be recovered and reused. Only a small volume of spent fuel would be left over as waste.

But conventional reprocessing not only generates weapons-grade plutonium, it is expensive. Reactors also have to be substantially modified to burn MOX, and MOX itself can only be partially burnt, meaning that a lot of the fuel still ends up as waste.

Supporters of the generation IV reactors claim that new forms of reprocessing can be developed that avoid these drawbacks. For example, additional steps in the process could convert the long-lived waste into elements with shorter half-lives, slashing the time this waste needs to be stored from more than 300,000 years to just centuries.

And the plutonium generated could be spiked with heat-producing and radioactive elements to make it too hot to handle, they argue. Unlike a canister of pure plutonium, which can be picked up safely with a pair of thick gloves, such material would be harder to steal or use.

But the latest techniques being tested in the United States fall far short of these goals, says Edwin Lyman, a senior scientist with the Union of Concerned Scientists, an environmental pressure group based in Cambridge, Massachusetts.

"Weapon-usable plutonium could be extracted by turning a dial, or at most, adding a clean-up stage to a reprocessing plant," agrees Frank von Hippel, a nuclear physicist at Princeton University, New Jersey, and a former assistant director for national security in the White House Office of Science and Technology Policy.

Ralph Bennett, director of advanced nuclear energy at the Idaho National Engineering and Environmental Laboratory in Idaho Falls, counters that research on reprocessing is still at a very early stage.

But critics argue that any international research effort in advanced reprocessing would itself spread expertise in the chemistry and metallurgy of radioactive elements, including plutonium. The world should be seeking to eliminate existing stocks of plutonium instead of developing its use, they say.