

# Nuclear Industry Dares to Dream of a New Dawn

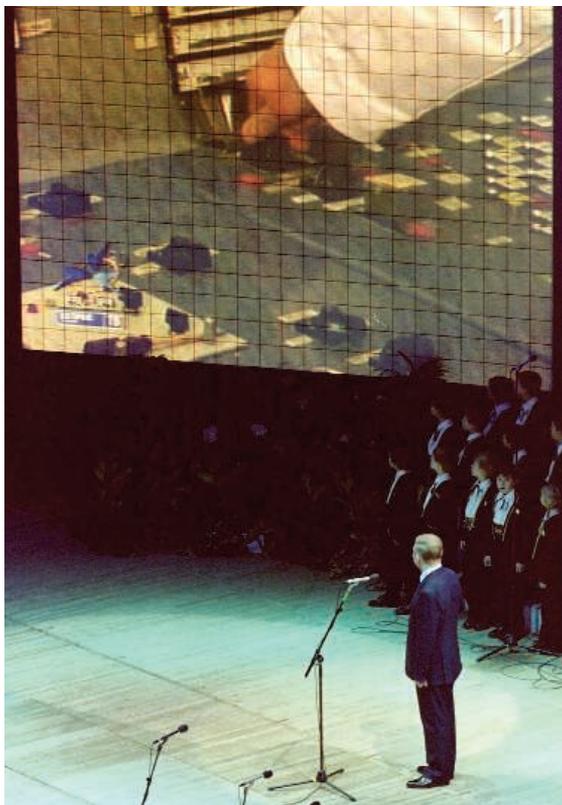
Reactor builders think that fossil fuel prices and climate fears will revive nuclear power. But will new reactor designs overcome the concerns of utilities and the public?

The nuclear industry is biding its time. Amid all the hullabaloo about climate change, rising prices of natural gas, dwindling oil stocks, and the environmental impact of wind farms, the makers of nuclear power plants feel that their time is about to come. Sometime soon, they believe, people will realize that the only carbon-free way to keep our society humming along—and fuel the rapidly growing economies of China and the developing world—is to use nuclear reactors. “The signposts are there for a renaissance” of nuclear power, says Peter Wells, marketing manager for GE Energy’s nuclear business.

The industry has not been idle during the 2 decades since the Chernobyl accident brought reactor building to a virtual standstill. Designs for light water reactors (LWRs), the main type in use today, have been thoroughly reworked. They are now simpler and incorporate so-called passive safety measures—simple systems that automatically kick in when something goes wrong. A trickle of orders from countries such as Japan, Korea, and China has kept companies afloat, and the energy bill signed by President George W. Bush this month contains generous measures to coax U.S. power utilities to start building nuclear again.

But many nuclear experts think that the coming boom will not be a simple rerun of nuclear power’s heyday in the 1960s and ’70s. For a start, many more countries want nuclear power, but not all want the 1000-plus-megawatt-sized plants favored by large industrialized nations. They want reactors to be quick to build and safe and easy to run, whereas the leading nuclear nations want to ensure that spent fuel can’t be diverted to other purposes. In some cases, the plants may not even generate electricity. Alternative uses include powering desalination plants in arid areas, providing heat for petrochemical processes, and even generating hydrogen for the much-touted hydrogen economy.

In such situations, some experts say, large monolithic LWRs do not fit. Instead,



**End of a nightmare.** Ukraine’s President Leonid Kuchma speaks at the Chernobyl closure ceremony in Kiev in 2000.

they point to the high-temperature gas-cooled reactor. Plants cooled with air or carbon dioxide have been around for decades, but a few companies are in the process of reinventing them for the 21st century. New-generation plants are cooled with inert helium, which directly drives a gas turbine to generate electricity. They work best at smaller sizes—a few hundred megawatts—and run at much higher temperatures than conventional reactors, between 500° and 1000°C. High temperature makes energy conversion more efficient and suits applications such as hydrogen production.

But perhaps their best trick is that they go one better than passive safety: Their cores are designed so that a runaway nuclear reaction simply can’t happen. You can fire up such a reactor to full power, vent away its coolant, pull the control rods right out, and nothing bad will result. “It’s a walkaway reactor,” says Dave Nicholls, chief technology officer of South African reactor builder

PBMR (named after its Pebble Bed Modular Reactor). “You can come back in a few days and sort things out.”

Enthusiasts say gas-cooled reactors will eventually displace LWRs. Although they don’t achieve the economies of scale possible with big plants, reactor builders can make a virtue of their small size by mass-producing components and shipping them to construction sites by road or rail. And if utilities want big megawatts, they can install a battery of small reactors at the same site, sharing facilities. Twenty years from now, “gas-cooled reactors will begin to dominate. Every new reactor ordered will be gas-cooled,” says Mike Campbell, senior vice president at U.S. nuclear company General Atomics.

Not everyone agrees that the nuclear industry is poised for revolution. “All big utilities look at the costs and want the cheapest possible electricity,” says Philippe Garderet, vice president for research and innovation at French reactor company AREVA. “There just isn’t a market” for small reactors.

The Bush Administration, however, is prepared to take a gamble. The new energy bill authorizes \$1.3 billion for the Department of Energy (DOE) to construct a new experimental nuclear reactor at the Idaho National Engineering and Environmental Laboratory. Industry watchers expect this Next Generation Nuclear Plant (NGNP) to be a high-temperature gas-cooled reactor for producing electricity and hydrogen. “We need to show that gas will work. That’s why the NGNP is so vital for the next step into gas,” says nuclear engineer Andrew Kadak of the Massachusetts Institute of Technology in Cambridge.

## Liquid vs. gas

Although nuclear power generation has long been dominated by water-cooled reactors, there have been frequent attempts to establish gas-cooled designs. The first—Britain’s Dragon reactor, which began operating in 1965—led to a number of carbon dioxide-cooled plants in the U.K., some of which are still in use today. General Atomics pioneered their use in the United States, and in the early 1970s it had orders for 10 machines. All were canceled when the 1973 oil crisis led to a collapse in energy demand. Meanwhile, water-cooled reactors were getting larger and larger and increasingly complex. Then the twin shocks of Three Mile Island in 1979 and Chernobyl in 1986 caused a major rethink of reactor design.

Most of the plants being built today in Asia and elsewhere are “evolutionary” improvements on the water-cooled designs from the boom years. Westinghouse’s current offering, the AP1000, uses gravity, natural circulation, and compressed gas to cool its core in an emergency. As a result, the reactor

CREDIT: MIKHAIL CHERNICHKIN/REUTERS

has 50% fewer valves, 83% less piping, 87% less control cable, and 35% fewer pumps than a conventional plant. With less equipment, there is less to go wrong. Similarly, GE's latest design, the Economic Simplified Boiling Water Reactor, holds emergency cooling water high up in the reactor vessel. If anything gets too hot, a release valve is automatically triggered and water flows down under gravity. "The reactor then remains below water level, and you don't get the core exposed," says GE's Wells.

But, according to Kadak, "these evolutionary designs are still too expensive. No one is buying." At the vanguard of the movement to sweep aside such leviathans are two efforts to build small gas-cooled demonstrator reactors, one in South Africa and one in China, by around 2010. Both use a reactor design that has its origins in the postwar scramble to find new uses for atomic power.

**A rocky road**

Just after World War II, researchers at what was soon to become the Oak Ridge National Laboratory in Tennessee investigated a reactor for generating electricity designed by physical chemist Farrington Daniels of the University of Wisconsin, Madison. He proposed encapsulating enriched fuel in small graphite balls, placing a large number of them in a reactor vessel, and cooling them with helium. The design, known as a pebble bed reactor, was considered too complicated and was abandoned in 1948.

In the 1950s, German physicist Rudolf Schulten resurrected the idea and built a small demonstrator reactor which operated from 1968 for 22 years. In 1985, a firm in Germany also built a commercial-scale reactor, but both machines were closed down soon after the Chernobyl accident.

There the pebble bed story might have ended, except that in the 1990s, South African utility company Eskom began looking for new power plants. South Africa has abundant coal, so power is cheap. But the coalfields are all in the high interior of the country; Eskom wanted a new type of plant to power coastal cities. Pebble bed seemed to fit the bill, so Eskom licensed the German technology.

Today the company PBMR is poised to start building a demonstrator plant at Koeberg near Cape Town, which it hopes to connect to the grid in 2010. "Nuclear must change technology to meet the needs of society," says PBMR's Nicholls.

The pebble bed design is simple. Tiny flecks of low-enriched uranium are coated in

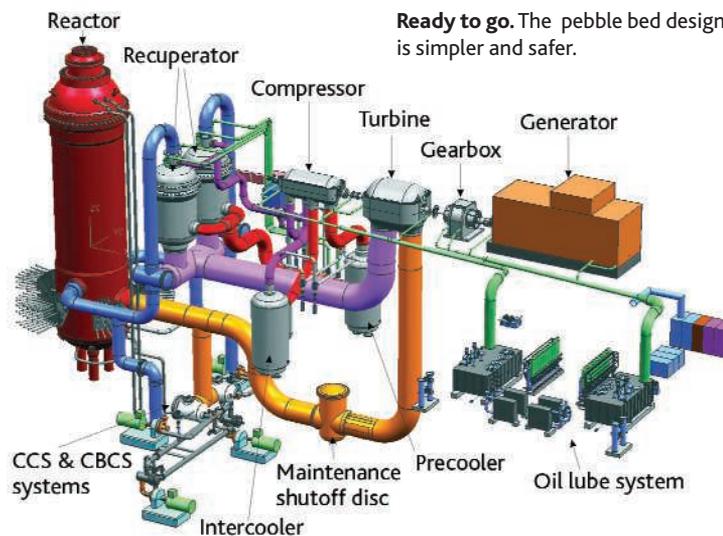


**New ground.** Pebble bed pioneer Dave Nicholls plans a new reactor here at Koeberg, South Africa.

layers of silicon carbide and carbon to make particles 1 millimeter across. Some 15,000 such particles are then mixed with graphite powder and pressed into a sphere the size of a tennis ball, which is again coated and hardened. Each "pebble" is only 4% uranium. When the reactor is ready for commissioning, engineers load 456,000 pebbles into the ring-shaped core. Control rods run through cavities in the graphite reflector material around the edge. The helium coolant simply flows

reactor and weighed to see if they still have usable fuel inside; those that do are fed back onto the top of the pile. In this way the fuel is continually moved around to achieve an even burn and full utilization. Each pebble passes through the reactor six times over the course of 3 years. Much of the equipment is straight off the shelf, Nicholls says. "We're not trying to push the state of the art at the component level," he says. "We just put it together better."

Meanwhile, researchers at the Institute of Nuclear and New Energy



**Ready to go.** The pebble bed design is simpler and safer.

Technology (INET) at Tsinghua University near Beijing, China, also took a leaf out of Schulten's book during the 1990s and in 2003 fired up their 10-megawatt High-Temperature Reactor. According to INET director Zhang Zuoyi, this experiment-sized pebble bed has been steadily churning out power ever since. On three occasions, he says, the team has tested the reactor's safety by pulling out its control rods and leaving it to its

own devices—producing a short-lived rise in temperature but no danger to the reactor.

Pebble beds are considered inherently safe because their cores are only sparsely loaded with nuclear material; they also exploit a natural ability of uranium-238, the nonfissile isotope that makes up the bulk of uranium fuel. As the temperature of the reactor rises

through the pile of balls, is heated, and drives a turbine directly connected to a generator.

One great benefit of the pebble bed design is that it does not need to be shut down to rearrange or renew the fuel. Instead, every day some pebbles are taken from the bottom of the

CREDITS (TOP TO BOTTOM): LOUISE GUBBI/CORBIS; PBMR

## India's Homegrown Thorium Reactor

**KALPAKKAM, INDIA**—For more than 5 decades, India has followed its own path on nuclear power. After refusing to join the Nuclear Non-proliferation Treaty and detonating a nuclear device in 1974, it was excluded from the international group that shares fission technology. In isolation, it launched an ambitious nuclear electric program that relies heavily on homegrown technology.



What makes India's strategy unique is its plan to build commercial reactors that run not on uranium but on a lighter element, thorium-232. India has one of the world's largest reserves of thorium—about 225,000 metric tons—but little uranium ore. Thorium does not fission; when irradiated with neutrons from a source material such as uranium-235, however, some of the thorium becomes uranium-233 (U-233), which does fission and can sustain a nuclear reaction.

In 1958, India announced that it was embarking on an ambitious, three-stage plan to exploit its thorium reserves. The first stage required building pressurized heavy-water reactors powered by natural uranium; they yield plutonium as a byproduct. Twelve are now operational. The plan called for stage two to kick in after sufficient plutonium had been extracted from spent cores; it would be used as a fuel in future fast-neutron reactors, which can irradiate thorium and produce U-233 as a byproduct. In the third stage, Advanced Heavy Water Reactors will burn a mixture of U-233 and thorium, generating about two-thirds of their power from thorium. Other nations—including the United States, Russia, Germany, and Israel—have studied the route but have not attempted to use it to generate electricity.

Stage two of this grand strategy began officially last October. In the sleepy south-

**First of a kind.** Project director Prabhat Kumar at the site of a new thorium-uranium reactor in Kalpakkam.

above its normal operating level, uranium-238 starts to become better at absorbing neutrons, the particles that spark the nuclear chain reaction. So when the coolant or the reaction-damping control rods are removed, the reactor temperature begins to rise, but as uranium-238 starts to make the core less reactive, it cools naturally by radiation and conduction. "We can calculate the peak temperature the fuel will reach," says Nicholls.

With this experience in its pocket, the INET team and the company Chinergy are planning to build a commercial prototype in Shandong province in the east of China by 2011. INET also signed an agreement last month to join a consortium with Westinghouse to put in a bid to build the NGNP in Idaho. Westinghouse is one of the backers of the PBMR, and the South African company is part of the consortium. Pebble bed enthusiasts hope that their design will be chosen for this \$1.3 billion test reactor.

The pebble bed approach is not the only way to make a high-temperature gas-cooled reactor. General Atomics, for example, has developed the Gas Turbine Modular Helium Reactor (GT-MHR). As in pebble beds, the uranium fuel starts out as tiny coated particles, but instead of pebbles, the fuel for the GT-MHR is formed into hexagonal prisms

about the size of two large paint cans stacked up. The prisms are arranged in an array in the reactor core and stacked 10 high. Japanese researchers have built an experimental "prismatic" gas-cooled reactor, the High Temperature Test Reactor, which has been operating successfully since 1998.

Arkal Shenoy, director of the GT-MHR project at General Atomics, says the design is pretty well worked out now. "We're waiting for someone to say 'Do you want to build this thing?'" Shenoy says that in a conventional reactor, one-third of all systems are safety-related, and you hope you will never have to use them: "We've eliminated the need for safety systems. The physics is such that the worst case of accident can never happen."

### Idaho or bust

Despite all the advantages of the new generation of gas-cooled reactors, proponents concede that utilities are going to be wary of unproven technology. "Without a full demo reactor, utilities won't buy. They're used to 90% availability. No amount of analysis will get you this," says Shenoy. The South African and Chinese demo reactors are being heavily subsidized by their governments, and U.S. researchers hope their government will follow that example. "Until the NGNP is fin-

ished, you won't see a gas reactor being built in the U.S. We need to reduce the risk [for utilities]," says General Atomics' Campbell. "It must be an Administration priority. Otherwise it won't be real."

Researchers are also confident that DOE will want a high-temperature gas-cooled reactor because of its interest in hydrogen production. "All the buzz about the hydrogen economy really comes from gas-cooled reactors," says Nicholls. There are various ways of extracting hydrogen from water, including electrolysis and thermochemical splitting, and they are all much more efficient at high temperature. "Nuclear is the only really practical source of hydrogen, and the only nuclear technology that gets you there is the high-temperature gas-cooled reactor," Nicholls says.

One thing these reactors do not do is resolve the issue of waste. The highly encapsulated fuel in gas-cooled reactors is very effective at containing nasty fission products, and it would be extremely difficult for any potential terrorist to extract any usable bomb-grade material from it. But the downside is bulk. All that graphite and multiple coatings make for large volumes of waste. The nuclear industry in the United States has never reprocessed its spent fuel, nor has the government come up with an accepted solution for long-term waste storage.

ern township of Kalpakkam, a government-owned company began building a 500-megawatts-of-electricity (MWe) fast-breeder reactor that will use fast neutrons to produce U-233. In its core, the reactor will use a "seed" fuel containing uranium and plutonium oxide; this source will send neutrons into a surrounding thorium blanket.

Indian atomic energy officials are confident that this exotic fuel system can be scaled up from a smaller, 40-megawatt Fast Breeder Test Reactor (FBTR) that has been running in Kalpakkam without major problems since 1985. This reactor and other research projects at the Indira Gandhi Center for Atomic Research in Kalpakkam have demonstrated, IGCAR officials say, that India has mastered the new technology. In a "bold step forward," says Anil Kakodkar, chair of the Atomic Energy Commission (AEC) in Mumbai, researchers at IGCAR in May of this year successfully extracted plutonium in high purity from the unique plutonium-rich mixed carbide fuel discharged from FBTR.

AEC anticipates that the fast breeder at Kalpakkam will cost about \$700 million and produce 500 MWe. The long-term goal, according to Kakodkar, is to increase nuclear electric output from 3360 MW today to "around 275 gigawatts" by the middle of this century.



**Proof of principle.** Researchers at Kalpakkam used thorium fuels in a 40-megawatt test reactor.

"everything they have reported to date indicates they are on track."

India cannot go it entirely alone, however. It still requires uranium, including for two boiling water reactors it bought from General Electric in the 1960s, and that may be one reason it is interested in opening nuclear trade with other countries. At a meeting last month with Prime Minister Manmohan Singh, President George W. Bush called India "a responsible state" with "advanced nuclear technology." The opening could lead to future exchanges of personnel and technology—and possibly fuel. Singh reassured Parliament, however, that the deal would not undermine India's nuclear self-sufficiency.

—PALLAVA BAGLA

Despite this, few believe the United States should embark on fuel reprocessing anytime soon because that would open a Pandora's box that the public is just not ready for. An influential 2003 report on the future of nuclear power, co-chaired by former CIA director John Deutch, concluded that for the

next 50 years, a once-through fuel cycle was the best option for the United States. "Once-through will dominate for many years," says Regis Matzie, chief technology officer at Westinghouse Electric. "Reprocessing is very costly in comparison, and utilities always take the least-cost route."

Few, however, believe that this situation can continue forever. "I don't see how we can expand nuclear with the way we are doing it today. We have to clean up the fuel cycle, and [reprocessing] may be the only way to do it," says Campbell. "It's a 100-year problem, not a 10-year problem." Farther down the road than the NGNP, 25 or more years from now, a new breed of reactor will be needed that can destroy much of its own waste. DOE has begun looking for such designs through a program called Generation IV and has enlisted a handful of other countries to collaborate. Beginning in 2000, a panel of more than 100 international nuclear experts sifted through many proposed designs and whittled them down to six generic types worthy of further study. Some of these are quite exotic,

including one cooled by molten lead and another in which the fuel itself is a circulating mixture of molten salts.

All but one of the six Generation IV designs have the ability to burn up the more long-lived products of the fission reaction. Nevertheless, industry experts seemed underwhelmed by the prospect of such futuristic reactors. "They're too far out, too speculative, and I can't see the advantage," says Matzie. But France's AREVA, which already has experience of building fast neutron reactors for destroying waste, is looking that far ahead. "AREVA must be ready to produce plants with fast neutrons. We know how to do it, but we have 20 or 30 years to develop better, cheaper, safer technology," says Garderet.

U.S. reactor makers appear more focused on the near term, waiting for that spark that will set their industry burning again. "The Bush Administration is clearly supportive of nuclear power. This provides a window of opportunity: If steps are not taken by 2008, the opportunity will be lost," says GE's Wells. Matzie agrees: "A big banner will go up when U.S. utilities start buying again. Once the U.S. starts building and establishes a track record, it will be time for others to do the same."

—DANIEL CLERY

With reporting by Gong Yidong of *China Features* in Beijing.



**Gentle giant.** Westinghouse's AP1000 design now has passive safety systems using gravity and natural circulation.

CREDITS (TOP TO BOTTOM): PALLAVA BAGLA/WESTINGHOUSE