# France's nuclear power program continues in force

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Until the disaster at the tsunami-struck Fukushima I nuclear plant in Japan, nuclear power looked poised for a worldwide expansion. Now the picture is far less clear. But perhaps the message that ought to be taken from the Japanese crisis, and indeed from the 25th anniversary of the Chernobyl disaster in Ukraine, is not so much that nuclear energy—hailed even by many environmentalists as the most realistic way to ensure low-carbon energy security—is too dangerous, but that it urgently needs an upgrade. After all, the shutdown procedure at the newer Fukushima II plant worked as planned: whatever questions remain about the location of the plants in vulnerable positions, there is reason to believe that newer technologies are safer ones. And safety—not just against leaks and earthquakes, but in terms of waste and nuclear proliferation—is one of the key factors driving innovations in reactor design.

Yet the construction times and operational lives of reactors are long, so that today's technical innovations may not be implemented for decades. Reactors currently under construction (so-called Generation III [Gen-III]) are still rooted in decades-old approaches, and when the Gen-IV designs now being planned are finally realized around 2030, it will be in a very different and not entirely predictable climate of political governance and energy priorities.

But even (perhaps especially) if the future is hazy, it is worth learning the lessons of the past. And there is nowhere better for gleaning those lessons than France, which—like Japan, but mercifully much less exposed to known seismic hazards—has long pursued a vigorous program of nuclear power.

The decision to rapidly expand the country's nuclear energy resources was made in 1974, just after the first oil shock, in the light of the fact that France has a lot of engineering expertise but few local energy resources (mostly coal, but the coal mining industry, overwhelmed by cheap imports, was finally shut down in 2004). The government-owned electricity utility Électricité de France (EdF) now runs 58 reactors and supplies about 75% of the country's electricity through nuclear power. As a result, France now has almost the lowest electricity prices in Europe and among the lowest per capita $CO_2$ emissions from electricity generation; it is the biggest national exporter of electricity worldwide.

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France is now pressing forward with Gen-III reactors while planning for Gen-IV. Most Gen-IV designs are so-called fast neutron reactors, in which fission is sustained by high-energy neutrons. This uses fuel much more efficiently and should generate less waste than today's reactors. With coolants of liquid sodium or lead, inert gases, or supercritical water, these reactors can operate at much higher temperatures than today's water-cooled designs—500°C to over 1000°C, as opposed to around 350°C. This improves the thermal efficiency, typically boosting the total energy output by about one-third relative to current models. Some of this new breed of reactors will use the heat of fission to drive chemical conversions rather than turbines for electricity—for example, making hydrogen by thermochemical splitting of water. These designs should be capable of meeting the specified safety and economy targets faster and at less cost than existing technologies. Three Gen-IV designs are being pursued in France: gas- and sodium-cooled fast reactors, and gas-cooled very-high-temperature reactors.

Since these reactors will be fundamentally different from those of today, realizing them is a daunting task that compels international collaboration. Several initiatives aim to assist this, such as the Generation IV International Forum, the International Atomic Energy Agency's Project on Innovative Nuclear Reactors (INPRO), and the European F-Bridge project, which aims to harness the best understanding and ideas in nuclear fuel design. The days when countries go it alone are past. For this reason, said Pascal Yvon of the French Atomic Energy and Alternative Energies Commission (CEA)'s Nuclear Energy Division in Gif-sur-Yvette, it is hard to speak about nation-specific challenges and solutions. "We interact a lot with our foreign opposite numbers," he said.

Nonetheless, the French experience has fostered a formidable reserve of expertise, much of it within the CEA. France chose early in the development of its nuclear program in the 1970s to focus on water-cooled pressurized water reactors (PWRs), which proved to be highly effective and now constitute all of France's working reactors. Its first Gen-III reactor was approved in 2006 and is due to start operating next year. France has also developed the expertise and infrastructure for designing and operating sodium-cooled fast-neutron reactors, including the Rapsodie (1967–1983), Phénix (1974–2009), and Super-Phénix (1986–1996). CEA's site at Marcoule in the south of France—the "cradle of the French nuclear industry" according to its director of research Étienne

Vernaz—hosted the Phénix reactor, an early attempt to move beyond Gen-II in a small-scale prototype. Its full-scale successor Super-Phénix at Creys-Malville on the Rhône was controversial with antinuclear groups from the outset and was closed for political reasons.

As the new reactor designs take over, old ones must be decommissioned. Currently, 13 French reactors are being decommissioned, although this process awaits plans for disposing of the wastes. Dismantling a reactor is costly, but EdF puts aside a small proportion of the income from current power generation to cover this, and it considers that it has accrued enough capital now to cover future costs.

## Clad in steel

Many of the challenges posed by advanced and Gen-IV reactor designs are at root materials problems. These can, broadly speaking, be placed in three categories: reactor design, fuel cycle, and waste disposal.

Phénix Reactor in Marcoule. Photo provided by CEA Marcoule.

The various coolants (gas, liquid sodium and lead, and superheated water) present a wide range of demands on heat and corrosion resistance. Moreover, the reactor materials must cope with extensive radiation damage to the crystal structures and with pressures generated by evolution of gaseous fission products. Much of this is true also for the current Gen-II water-cooled reactors, except that the new reactor designs will have operating temperatures considerably greater than these. As a result, many of the components will need to be made from entirely new materials, said Yvon. “We can’t just try to optimize the existing ones,” he said.

The fuel cladding and most of the structural components in today’s Gen-II and III reactors are made from metal alloys, primarily steels, which experience creep (slow, permanent deformation) and swelling under intense radiation damage. The radiation damage in the fuel cladding may limit the maximum energy that can be extracted from the given quantity of fuel to only a tenth of its full potential. Under intense irradiation, atoms in the metal lattice can be knocked out of position, creating point defects that migrate and cluster into voids, expanding the material like tiny bubbles. The metals may need to withstand conditions in which every single atom has, on average, been displaced dozens of times. Typically, swelling begins to cause problems in these alloys for radiation doses, causing an average of around 70 displacements per atom. Titanium has been found to combat swelling of steels by trapping defects; but one of the most promising approaches for future reactors is to disperse small particles of metal oxides within the alloy, which strengthen at the same time as trapping defects. So-called oxide-dispersion-strengthened alloys are still under development. CEA is running a pilot project to test them in reactor conditions and has conducted some tests in Phénix.

But the ideal structural materials will have to find a compromise between the need for strength, resistance to swelling, creep and corrosion, and other factors. For example, the chromium content of ferritic/martensitic steels can change this balance. High chromium content (18%) resists corrosion and mechanical stresses, but lower levels improve the resistance to swelling because of a change of crystal structure from face-centered to body-centered cubic packing. At present, steels with just 9–12% chromium are shaping up as some of the most promising candidates for use in sodium- or lead-cooled reactors. Yvon said that largely because of the difficulties of testing new materials over long timescales and extreme conditions, modeling is becoming increasingly vital. These models need to span a wide range of time and length scales, since processes stretching from individual atoms to whole grains and lasting from picoseconds to years are important to the material’s behavior.

## Fuel for the furnace

The fuels of fission reactors are radioactive materials: primarily alloys or compounds of uranium and plutonium, but also thorium. The irradiated fuel also contains other radionuclides produced in fission. These generate heat by radioactive decay in reactions that are self-sustaining because of their production of fission-inducing neutrons. All of today's reactors use either uranium oxides (enriched relative to the raw mineral oxide in the fissile isotope $^{235}$U) or a mixture of uranium and plutonium oxides (mixed-oxide or MOX). While relying on uranium imports for the basic fuel, France is fully self-sufficient in fuel fabrication and enrichment.

But there is far more to nuclear fuel than chunks of the radioactive material. In general, this material is surrounded by cladding. The fissile oxide itself is sintered from powder, and the resulting material must have good, uniform thermal conductivity to minimize heat cracking. The microstructure is also compromised by radiation damage. Extensive cracking of the fuel and cladding can lead to the movement of radionuclides toward and into the cladding.

Various other fuel formulations are being considered. Inert-matrix fuels, for example, are designed to burn excess plutonium and other actinides extracted from spent fuel, as well as plutonium from weapons disassembly, mixed with other metal oxides, in current-generation reactors. Other fuel innovations are aimed at Gen-IV reactors. Very-high-temperature gas-cooled reactors, for instance, might use grains of fuel encased in multilayer coats. Such fuels have been extensively studied for the past four decades. Typically they have a kernel of uranium surrounded by layers of carbon and silicon carbide, the latter providing an impermeable barrier to gas escape and a strong "pressure vessel" to contain it. These coated particles are pressed into small cylinders or spheres called "pebbles," which are used in so-called pebble-bed reactors.

Another fuel currently being explored is thorium, which can be transmuted by neutron irradiation, either *in situ* inside a reactor or from a particle accelerator, to the fissile isotope $^{233}$U. One of the key advantages of thorium-based reactors is that the spent fuel contains lower quality plutonium, which is not really suitable for use in weapons—this reduces concerns about proliferation. What's more, thorium reactors produce much less long-lived minor actinides compared to reactors based on low-enriched uranium or a mixture of plutonium and depleted uranium.

Locations of nuclear power plants in France, as of January 2011.

Ray Sollychin of the Canadian Neopanora Institute, which promotes new energy technologies, said that, in principle, use of thorium "could start today in the current generation of nuclear energy systems with some redesign," but is not yet economical. Several of the advanced reactor types under development, including liquid-metal- and gas-cooled fast reactors and molten-salt reactors, could use thorium in a closed cycle, which would involve reprocessing of the spent fuel. But the current lack of thorium fuel reprocessing and fabrication infrastructure presents a chicken-and-egg problem.

## Waste not

The French government elected from the outset to reprocess used fuel to recover uranium and plutonium, thereby reducing the amount of high-level waste that needs disposal. About 20% of the electricity produced by EdF comes from recycled fuel. But nuclear waste management has not had a smooth ride even in France. Despite the generally positive public attitude toward nuclear energy, controversies about how and where to dispose of the waste emerged in the 1980s. These led the French government to draw up the 1991 Bataille Act, which imposed a moratorium on the selection of a site for deep geological disposal and instead instigated a 15-year research program for how long-lived waste should be handled. In the interim, it is stored at sites at La

Hague, Marcoule, and the CEA’s facility at Cadarache in southeastern France.

In 2006, the French government elected to store high-level waste in a deep geological repository, which has yet to be identified. The French National Radioactive Waste Management Agency (ANDRA) is planning to operate a prototype experimental repository in the clay deposits beneath its Meuse/Haute Marne laboratory in Bure, eastern France. The final site for long-term storage, which may be within this same geological formation, is due to be licensed in 2015 and to become operational in 2025, at an anticipated cost of around €15–30 billion.

Public perception still constitutes one of the main hurdles to waste management. “The principal difficulties encountered during the last 20 years, in France as elsewhere,” said Vernaz, “were more societal than technical.” The French government has been proactive in creating a visitor and educational center at Marcoule called Visiatome, which opened in 2005. “The main targets are elected officials, teachers, and doctors,” said Vernaz—but the center attracts all citizens, including children. Vernaz considers this a useful start to the process of public engagement, but adds that “there is so much still to do.”

High-level waste in France is vitrified—transformed to a glassy rock-like solid—for storage and ultimately for disposal. The standard specification used is a borosilicate developed in the late 1980s, called R7T7, comprised of oxides of boron, silicon, aluminium, and sodium. But various other formulations are being studied, such as glasses based on rare earth oxides, in which some of the fission products are more soluble. The trick, said Vernaz, is to find a compromise between a glass that is suitably dense, in which the radionuclides are sufficiently soluble, that has good thermal conductivity to reduce localized heating, that resists crystallization (devitrification) and corrosion, and that meets obvious constraints of processing and cost. The glass matrices currently used are expected to contain waste for more than 300,000 years in a geological repository, even under somewhat pessimistic forecasts of the environmental conditions.

Waste glass is currently formed at high temperatures (around 1150°C) at a treatment plant in La Hague, where the packaged waste is then stored in canisters inserted into the floor of a purpose-built hall. But the Marcoule laboratories have been developing a method of using high-frequency electromagnetic radiation to cause melting of the glass components through the Joule effect. Because the reaction vessel is water-cooled, a solidified glass layer forms on the inner wall that protects it from corrosion. Another possible disposal strategy aims to transmute long-lived radionuclides by neutron bombardment in fast reactors or particle accelerators to shorten the hazardous lifetime of the waste.

Intermediate and low-level wastes can be immobilized in cements, which are simpler and cheaper to make than glasses—these are typically standard Portland-type calcium silicates. There is plenty of optimization to be done even here, however. Gases such as hydrogen produced by radiolysis of the matrix have to be able to escape through the porous material to avoid risk of explosions, but the cement should not retain large amounts of water that could leach out slowly, carrying dangerous solutes with it. The Marcoule center has also been experimenting with a combined process of vitrification and incineration for intermediate-level waste, which uses an oxygen plasma to burnup some of the material, such as ion-exchange resins, slurries, and sludges, and thus reduce its volume.

## Keep it safe

At the start of 2011, nuclear power looked set to enjoy considerable global expansion in the coming years, with more than 50 countries considering nuclear programs and, in some cases, planning their first plants. “Several countries, such as China, South Korea, Finland, India, and South Africa, have already decided to make huge investments in developing nuclear energy,” said Bernard Bigot, French High Commissioner for Atomic Energy. “Others are very close to taking this step, in particular, Great Britain and the United States.” But that was before Fukushima. Moreover, with a growth in nuclear energy would come inevitable fears of weapons proliferation and waste handling. The Global Nuclear Energy Partnership, a U.S.-driven initiative, hopes to combat these problems, for example with a global system of fuel leasing and return by particular licensed states.

The safety requirements for nuclear power are evolving continuously because of both regulatory changes and the knowledge gained from operating experience. Complying with these changes requires advances in assessment methods, state-of-the-art numerical and experimental simulations, investigation of the consequences of design changes, comprehensive exploration of severe accident scenarios, and inspection and repair technologies that work while a plant is operating. Achieving all of this is truly challenging but crucial for securing public acceptance.

Fukushima has now made that task considerably harder. While the French President Nicolas Sarkozy restated the country’s commitment to nuclear energy shortly after the Japanese accident, EdF has vowed to learn lessons from it, for example by creating a rapid-reaction taskforce to be deployed in cases of emergency. Yet there has been complacency and over-confidence about worst-case risks, according to Laurent Stricker, chair of the World Association of Nuclear Operators. It is important to ensure “the right emergency procedures and equipment, and regular emergency drills,” he said. “Some countries do this very well; others do it much less, or not at all.” But as Fukushima shows, “an accident in one country has consequences for all nuclear operators elsewhere.” ☐

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