New nuclear reactor designs

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Developing new types of nuclear reactors to replace existing ones is a long-term process. Many new designs are under study but, since 2000, an international forum has been encouraging research which focusses on a few promising systems which meet the new criteria of fourth generation reactors. In France, the systems studied in this context are sodium-cooled fast neutron reactors and molten salt reactors. Accelerator-driven reactors, as part of a waste-incineration strategy in dedicated facilities, have also been studied over the past twenty years.

Why study new systems?

In a nuclear reactor core, the reactions at work that ultimately lead to the production of thermal energy, and in particular fission, are well known and common to all reactors. However, the ways of exploiting the chain reaction, controlling it, consuming the fuel, or extracting heat from the reactor can be achieved in different ways that meet various priority criteria that we will see later.

However, a new design, different from those previously in use or currently in operation, takes time to demonstrate and be approved; it requires modelling and, at some point, model experiments and then the construction of prototypes to support its feasibility. It often takes several decades of research, design, development and experimentation to arrive at a system ready for scaling-up to industrial level, which often exceeds the length of an individual's professional career.

This time scale is the main reason why scientific and technological research organizations try to anticipate future needs. In the case of nuclear power, this involves revisiting old reactor concepts or proposing new ones in the light of the latest knowledge and advances. France is a country with strong expertise in nuclear sciences and reactor-related technologies, and therefore has a melting pot favorable to this type of research. The objective is to have solutions that have demonstrated their feasibility beyond 2030 (or even 2040 or 2050 for the most innovative ones). This research explores possible solutions and does not predict future choices to be made by politicians and society. Nevertheless, for the same reasons of temporal inertia, the choices of research directions are somewhat binding for the future.

What is "Generation IV"?

The nuclear reactors currently operating in France are part of what is called the second generation. Improved versions under construction, such as the EPR, are considered to be third generation. In many countries, prospective research is being carried out to imagine future-oriented fourth-generation reactors. At the instigation of the United States Department of Energy, an international forum, the Generation IV International Forum (GIF), bringing together a dozen countries including France, was formed in 2000. Its objective is to encourage international research on a few reactor designs that will meet specific criteria with possible implementation by 2030-2040. These criteria are defined as targets for the economic, environmental and social improvements needed if nuclear energy is to make a significant contribution to meeting the global energy demand of the twenty-first century. They cover four main areas:

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- Sustainability: the aim is to be able to place nuclear energy on a long-term footing by optimizing both fuel supplies and waste generation, with a view to their long-term management. Existing systems are essentially based on the use of enriched uranium 235, which requires the processing of large quantities of uranium from which this isotope can be extracted; it takes about 200 tons of uranium each year to operate a 1 GW pressurized water reactor core that will fission only one ton of material. In the future, it is hoped to be able to use a system that allows the full potential of the ore extracted to be used and thereby enable energy production on a global scale for several centuries.
- Safety and reliability: the aim here is, on the one hand, to minimize the risk of nuclear accidents leading to disasters such as Chernobyl or Fukushima and, on the other hand, in the event of an accident, to minimize the impact on people and the environment. To this end, the emphasis is placed on the passive safety of the systems and in particular the withdrawal of residual power in the event of a core shutdown.
- Economic competitiveness: a new system must be able to compete in a free energy market where sources of energy generation are increasingly diverse.
- Proliferation-resistance and physical protection: the diversion of civil nuclear facilities and materials for military purposes has long been a risk that has been under international scrutiny. This risk is now compounded by the risk of malicious or even terrorist acts. It is therefore proposed that protection against theft of radioactive materials and acts of sabotage which could occur in facilities or in the transport of materials should be built into the design of new systems.

Which systems are available to meet these criteria?

A nuclear reactor is defined in terms of its three main components: the fuel, not only the type but also its geometry, composition and chemical form; the moderator, a material present in the core that optimizes the use of the fuel by slowing down the neutrons to a greater or lesser extent; and the coolant, which is used to transfer thermal power from the core to the heat exchangers to convert it into electricity. For most reactors currently in operation, water acts as both moderator and coolant. There are a very large number of possible combinations of these three elements, and thus many potential nuclear reactor variants. Throughout the history of nuclear power, a few hundred have been studied theoretically, but in total, fewer than 20 have been built to provide power. There are still many possible options for meeting the new requirements. The GIF has decided to concentrate research on six of what are considered the most promising designs.

Three of them are so-called "fast" neutron systems, i.e. those that conserve as much of the original neutron energy as possible. This has several advantages with respect to the sustainability requirements. In order to optimize the use of uranium ore, it is conceivable to regenerate the fuel by transforming the so-called "fertile" uranium-238 nuclei into "fissile" plutonium-239 nuclei(a). If each uranium-238 nucleus produces a plutonium-239 nucleus by neutron capture, the full energy potential of the uranium ore, 99.3% uranium-238, is used. Fast neutrons minimize parasitic neutron capture and thus maintain the criticality of the system and the regeneration of the plutonium.

These fast neutron reactors can use different moderating and heat transfer fluids; the three models studied are the Sodium Fast Reactor (SFR), the Lead Fast Reactor (LFR) and the Gas Fast Reactor (GFR). They all have good thermal efficiency. Sodium combines a low melting temperature with a very high boiling point, providing good thermal inertia to the primary circuit. However, the SFR and LFR have to cope with the chemical properties of a liquid metal: reactivity with water and air for sodium, corrosion for lead. The third model has the advantage of using a chemically inert gas, helium, but its relatively low thermal inertia during a forced circulation shutdown is not optimal for safety, and requires the development of a very specific fuel.

The Very High Temperature Reactor (VHTR) would operate between 800 and 1,000 °C. It uses slower neutrons, known as "thermal" neutrons. It is also cooled with helium, but moderated with graphite. Its main advantage is that the gas can be used directly in a turbine on the primary circuit. The heat produced by these systems can also be used in different ways on an industrial level, in particular for the production of hydrogen.

A type of water reactor model, the SuperCritical Water-cooled Reactor (SCWR), is also being explored. It operates at a temperature and pressure above the critical point of water (374 °C, 221 bars), hence its name. It can be designed for either thermal or fast neutrons. The extremely hot steam produced can be sent directly to the turbine and, after condensation, the water is returned to the core. This process benefits from the long experience of fossil-fueled thermal power plants using supercritical water. It has an economic efficiency advantage as its thermal efficiency can be as high as 44%, compared to 33% for today's pressurized water reactors. However, technological challenges remain to be addressed, such as: modelling heat transfer during accidents, depressurization and loss of supercritical conditions, qualification of materials for high temperatures, especially steels for fuel cladding; and demonstration of the passive safety of the system.

The sixth concept, one of the most innovative, uses molten salts (Molten Salt Reactor, MSR). It is presented later on.

Fourth-generation systems studied in France

On the basis of estimated finite uranium resources and significant use of nuclear power worldwide, France had already devised a strategy in the 1960s that began with the development of thermal reactors using enriched uranium. The idea was to build up a stockpile of plutonium (nuclei produced during operation), which could then be used to power fast neutrons breeder reactors and ensure sustainable energy production. France thus very early on concentrated its research efforts on fast neutron reactors, and opted for liquid sodium as a coolant, bringing the idea to fruition. However, only two liquid sodium units were built on an industrial scale in France: Phénix (1973-2010), then Superphénix, which was prematurely shut down in 1997 for industrial, economic and political reasons, linked to the post-Chernobyl context. This type of reactor is again the subject of research for the fourth generation because of its clear advantages with regard to fuel and waste requirements and the added benefit of being based on a technology already implemented in several countries. Thus the CEA, EDF and Framatome have devoted major research efforts to revisiting this concept, notably with the 600 MW pilot sodium reactor project ASTRID.

The molten salt reactor (MSR) concept was studied in the United States from the 1950s and abandoned in the 1970s. In this system, the fuel is dissolved in a molten fluoride salt, which also acts as a coolant and can flow directly through the heat exchangers. A reactor moderated by graphite in its early versions, it was recently revisited as a fast neutron reactor by French academic research teams, in particular to make it regenerative with simplified in-line reprocessing, using thorium and uranium fuel. The molten salt fuel has many advantages. On the one hand, the salt has favorable thermodynamic properties: high boiling temperature, good calorific capacity and thermal conductivity. On the other hand, in the event of a system malfunction, the liquid salt can be passively reconfigured, for example, dispersed in a network of tanks designed to withstand high temperatures, allowing different options for dissipating its residual power. On-line reprocessing of the salt makes it possible to maintain a neutron balance in the core that is conducive to using different fuels. In a complete technological break with existing and well-tested reactors, it requires a reappraisal of the safety approach and a considerable research effort to remove the scientific and technological barriers, firstly with regard to salt and materials (corrosion, reprocessing, physico-chemistry, etc.), and the neutronics of a liquid fuel (fuel-coolant, criticality control), all steps needed before an industrial prototype can be built. The natural inertia of nuclear processes is a hindrance to the deployment of these highly innovative technologies, even if they potentially represent interesting solutions for the future.

Accelerator-driven reactors

Although not part of the fourth generation systems studied by the GIF, Accelerator Driven Systems (ADS) are still the focus of major feasibility studies because of their potential to incinerate some of the nuclear waste produced through existing processes, making it possible to reduce radiotoxicity and residual heat and consequently the storage space the waste requires. These reactors are said to be "subcritical", i.e. the chain reaction can neither start nor maintain itself spontaneously without the contribution of external neutrons. In most designs, an accelerator provides high-energy protons, which strike a target made of a heavy metal (e.g. lead) located in the reactor core. This produces nuclear reactions that release large numbers of neutrons. These neutrons will cause fissions in the core and thus generate power that can be reduced to zero on demand by shutting down the accelerator. This control of power by the accelerator enables somewhat exotic fuels to be used such as minor actinides(b) whose properties do not allow them to be used in critical reactors. The ADS is then operated in a fast version, with liquid lead as moderator-coolant. The main challenge to the use of these systems (apart from the chemistry of liquid lead, a feature common with the LFR) is to reach a level of particle beam reliability never before achieved. These reactors have been studied for more than twenty years, particularly in Europe and France, with intense R&D on linear accelerators. The construction in Belgium of a demonstration reactor of about 100 MW, MYRRHA, is currently scheduled in two phases: one for the accelerator in 2026 and the other for the reactor in 2033.

Conclusion

Research on new nuclear energy production systems is not currently limited to research carried out within the framework of the GIF, whose initiative has had the merit of setting ever more demanding requirements for the development of designs, particularly with regard to nuclear safety and the issue of waste, and of reviving collaborative R&D between countries with a nuclear industry. It can be noted that the greatest misgivings expressed by society towards nuclear power have to some extent been taken into account by research. However, developing new reactors up to an industrial scale in the face of the progress made by other energy sources, particularly renewable ones, is not without its economic implications. This is why, apart from developing these new concepts, great efforts are also being made, particularly by French industry, to study third-generation reactors based on the optimization of existing water reactors.

In summary, the options for the future of nuclear power are numerous. But the research effort, which must be anticipated over decades, cannot be carried out with equal emphasis on every system. The challenge is to conduct R&D that will lead to an industrial model without refraining from investigating more ambitious avenues for the future.

To find out more

- *Les réacteurs nucléaires à caloporteur sodium*, CEA, Monographie de la DEN, Éditions Le Moniteur (2014).
- *Les réacteurs nucléaires à caloporteur gaz*, CEA, Monographie de la DEN, Éditions Le Moniteur (2006).
- "Technology Roadmap Update for Generation IV Nuclear Energy Systems", Gen. IV International Forum, January 2014, NEA/OECD.
- Gen.IV International Forum, www.gen-4.org/gif/jcms/c_9260/public
- « Vers un cycle du combustible nucléaires durable: Évolution et tendances », NEA/OECD (2012) No. 6981. www.oecd-nea.org/ndd/reports/2012/6981-trends-sustainability-fuel-cycle-fr.pdf
- "Perspective on the use of Thorium in the Nuclear Fuel Cycle", NEA/OECD (2015) No 7224. www.oecd-nea.org/science/pubs/2015/7224-thorium.pdf

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a. A nucleus of uranium-238 that captures a neutron gives a nucleus of uranium-239, a radioactive nucleus, which decays into a nucleus of plutonium-239.

b. Highly radiotoxic heavy nuclei created by neutron capture in reactors.