



*Since the 1950s, nuclear reactor designs have continued to evolve, from the earliest Generation I prototype designs to the Generation II designs that have operated safely over the past 40 years. The latest Generation III designs recently introduced, e.g. the European Pressurised Reactor (EPR), incorporate the lessons learned from earlier designs and reduce plant costs while enhancing safety and security. Today's research on the next Generation IV focuses on additional goals of passive safety, proliferation resistance and nuclear waste minimisation, as well as broader goals such as cogeneration for process heat applications.*

## Nuclear Energy Factsheets

### Successive Generations of Nuclear Fission Technology

#### • Continuous development

The early Generation I prototypes evaluated the basic design features and commercial power potential of nuclear reactors from the safety, operability and fuel cycle viewpoints. Reactor concepts differed in their design of the nuclear fuel, the neutron moderator, which determines the neutron energy spectrum, and the core coolant. The first reactors for commercial electricity production, such as the Calder Hall (UK) gas-cooled Magnox reactor, the Shippingport pressurised water reactor (PWR) in the US, the BR3 PWR in Belgium and the EDF1 graphite moderated, gas-cooled reactor in France, demonstrated the economic viability of nuclear power and confirmed the design concepts.

The commercialisation of nuclear power was achieved with Generation II reactors that are dominated by Light Water Reactor (LWR) technologies (pressurised and boiling water), with once-through, slightly enriched uranium fuel cycles. Generation II reactors have an original design lifetime of 40 years, which in many cases has been extended to 60 years through plant upgrade modifications. Reactors have also achieved increased power output by as much as 20% through the use of new fuel technologies and system upgrades.

Generation III reactors incorporate evolutionary (and in some cases innovative) improvements in design with common goals of simplification, larger margins to limit system challenges, longer grace periods for response to emergency situations, high availability, competitive economics and compliance with internationally-recognised safety objectives.

The lessons learned from the nuclear accidents of Chernobyl and Three Mile Island have been applied since the first stages of the Generation III plants design, with the main objective to reduce the likelihood of accidents as well as mitigate their consequences in the event that they occur. One of the most significant improvements is the incorporation of passive safety features in some designs, which do not require active controls or operator intervention, but instead rely on gravity or natural convection to mitigate the impact of abnormal events and are less vulnerable to electrical, mechanical and human failures.

The design of new reactors also incorporates features to meet more stringent safety objectives, by both improving the prevention of severe accidents involving core damage and mitigating their consequences. New plants planned throughout the world, in particular in China and India, include

Generation III design features, facilitated through cooperation with countries that have established nuclear energy programmes. In Europe, two Gen III reactors are under construction (in Finland and France). Examples of Generation III reactors include advanced Pressurised Water Reactor designs, such as the EPR, AP1000, and APWR and Boiling Water Reactor designs, such as the ABWR and ESBWR.

#### • Generation IV

R&D of the next generation of reactor types was officially started by the Generation IV International Forum (GIF) with a focus on meeting tomorrow's need for reliable and more sustainable electricity and non-electricity applications of nuclear energy. Primary goals include passive nuclear safety, proliferation resistance, minimal natural resource utilisation and nuclear waste generation, and affordable capital and operating costs.

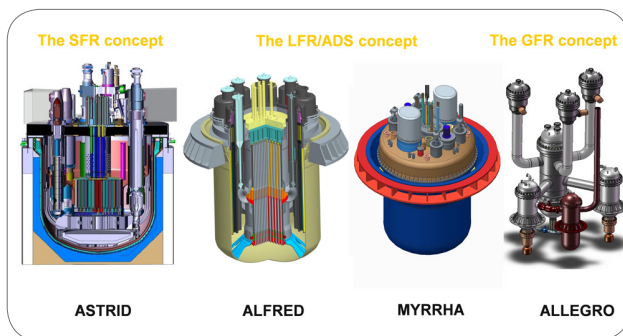
The six most promising Gen IV technologies were selected for further R&D, each with their own unique advantages and challenges. The main differences of these technologies in terms of design mainly concern the type of moderator (graphite, supercritical water) and coolant (liquid metal, molten salt, helium). The characteristics of these designs are the operating temperature (impacting the thermodynamic efficiency), the neutron energy spectrum (fast, epithermal, or thermal), and the fuel conversion processes (open or closed fuel cycle).

Three designs within the GIF are based on Fast Neutron Reactor (FNR) technology:

- Sodium-cooled Fast Reactor (SFR)
- Lead-cooled Fast Reactor (LFR)
- Gas-cooled Fast Reactor (GFR)

They are characterised by the type of fuel and coolant incorporated into the reactor design, which impacts the amount of breeding and actinide burning potential as well as operating temperatures.

FNRs can extract at least 50 times more energy than current LWRs for a given quantity of uranium. In addition, the fast neutron spectrum of FNRs is well-suited to convert the long-lived radiotoxic higher actinides in high-level nuclear waste to shorter-lived isotopes. They have the advantage of fuel breeding within a closed fuel cycle [1], with minimal production of high level waste.



The 3 reactor designs based on the Fast Neutron Reactor technology promoted by GIF, with the 4 corresponding prototypes planned in Europe

In Europe, the European Sustainable Nuclear Industrial Initiative (ESNII) in SNETP covers the different FNR technologies. At the end of 2012, a prioritisation exercise was performed by ESNII. With respect to the 2010 evaluation of technologies, sodium is still considered to be the reference technology since it has more substantial technological and reactor operations feedback. The Lead(-bismuth) Fast Reactor technology has significantly extended its technological base and can be considered as the shorter-term complementary technology, whereas the Gas Fast Reactor technology has to be considered as a longer-term alternative option. The main goal of ESNII is to design, license and build in the next 10-15 years the Sodium Fast Reactor prototype called ASTRID and the flexible fast spectrum research facility MYRRHA. For the development of the Lead-cooled Fast Reactor, maximum synergy of activities will be sought with the MYRRHA development to optimise resources and planning.

For the LFR demonstrator ALFRED, the main focus will be to qualify and integrate technologically-ready solutions into the design to keep a short time schedule for the construction of the demonstrator. ALFRED has a representative size scalable to an LFR FOAK (First Of A Kind) of commercial interest, in the range of Small Modular Reactors. R&D activities on the lead coolant addressing the specific characteristics that differ from lead bismuth, and an innovation programme aimed at increasing the economic performances of the technology will be run in parallel, exploiting the demonstrator itself as a test-bed for the qualification of improved design options. Design activities and support R&D shall be performed in the next years to the maximum extent, compatibly with available resources and taking full advantage of feedbacks, where applicable, from the ongoing design of MYRRHA and related R&D programmes.

The viability of the Gas Fast Reactor is essentially based on two main challenges driving the envisaged time schedule. First, the development and qualification of an innovative fuel type that can withstand the irradiation, temperature and pressure conditions put forward for the GFR concept. Secondly, a high intrinsic safety level will need to be demonstrated for this GFR concept. This will imply dedicated design activities followed probably by out-of-pile demonstration experiments. These high priority R&D activities should be embedded into an overall R&D roadmap that supports the development of the Gas Fast Reactor concept. For the development, guidance and implementation of this R&D effort, a GFR centre of excellence will be created. This centre could develop the technical capability to launch the ALLEGRO gas cooled reactor.

The other GIF reactor designs focus on either the thermal or epithermal neutron spectrum. These include the:

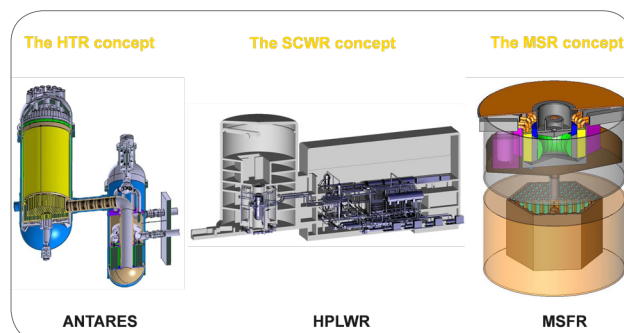
- Graphite-moderated, helium-cooled Very High Temperature Reactor (VHTR)
- Supercritical Water (moderated and cooled) Reactor (SCWR)
- Molten Salt Reactor (MSR)

The VHTR that is studied within the Nuclear Cogeneration Industrial Initiative (NC2I) in SNETP has a ceramic core that can withstand very high temperatures, and a strongly negative temperature feedback. Nuclear safety requirements are therefore met more easily in a passive way. The VHTR has a once through fuel cycle, and can operate at 700-800°C with the current technology for high efficiency electricity and steam production cogeneration. VHTR R&D focuses on achieving temperatures of 1000°C and beyond, for even higher efficiency and to support hydrogen production processes.

The SCWR is a direct cycle LWR at a temperature and pressure above the thermodynamic critical point of water; it has advantages for significantly higher operating efficiency than existing LWRs, but unavailability of materials in these harsh conditions (high temperature, high pressure and irradiation) hamper its development.

The MSR is based on the concept of a circulating molten salt coolant and fuel mixture - the coolant and the fuel are therefore combined. Through online processing and large flexibility in the fuel composition that can be adopted, a large amount of different applications can be imagined for this reactor system, from a breeder reactor using Thorium and depleted Uranium, to an actinide burner to reduce the lifetime of high level radioactive waste, and all options in between. Relatively high operation temperatures can be achieved for enhanced efficiency. The combination of a low pressure primary system and fuel in fluid form can offer high levels of passive safety, while a circulating fuel introduces specific safety challenges.

All of these reactor designs are in the scope of the European nuclear fission R&D agenda as covered in the Strategic Research and Innovation Agenda and Deployment Strategy released by the Sustainable Nuclear Energy Technology Platform (SNETP).



The HTR, SCWR, and MSR reactor systems, with the corresponding European designs

**REFERENCES** [1] In a closed fuel cycle, highly exposed nuclear fuel is reprocessed and reinserted into the reactor for further use in periodic cycles.

- <http://www.gen-4.org>
- <http://www.iaea.org>
- <http://www.oecd-nea.org>
- <http://www.world-nuclear.org>
- <http://www.snetp.eu/strategic-research-and-innovation-agenda>
- <http://www.snetp.eu/deployment-strategy>