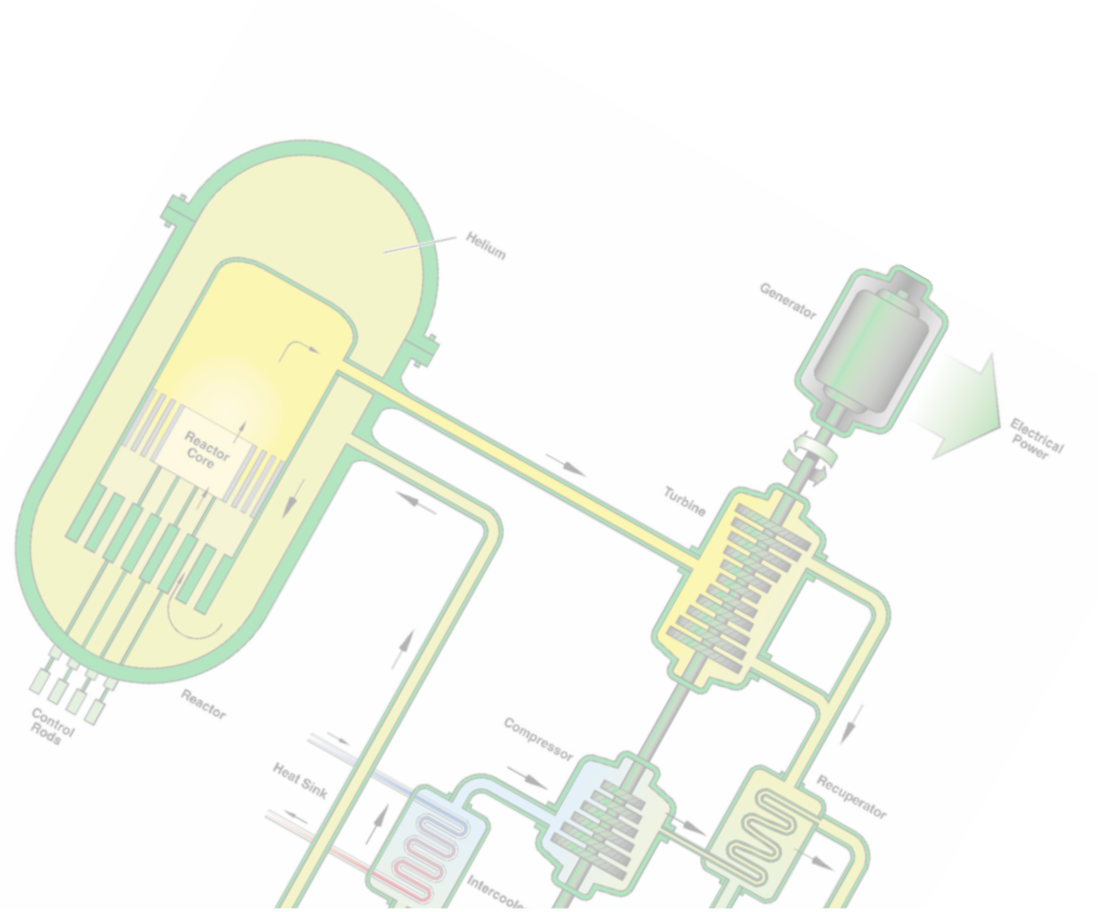
Foro **Nuclear**
Foro de la Industria Nuclear Española
MONOGRAPH

www.foronuclear.org/en/

Advanced Nuclear Technology

New Reactor Designs



Innovation is the driving force behind the ongoing development of nuclear technology, a process which results in new reactor designs with superior capabilities than current reactors. These advances comprise power stations and hybrid facilities for high-temperature industrial heat generation, heating, hydrogen production and seawater desalination.

Why are new fission reactor designs being developed?

- Because of their high energy density: The fission of 1 g of U-235 releases about 24 MWh, a power equivalent to the burning of 2.5 t of coal or 2 t of oil.
- Because they help to bring down greenhouse gases emissions and develop an energy matrix with competitive prices.
- Because of the importance of preserving scientific and technological know-how.
- Because it is strategically wise to maintain and develop state-of-the-art nuclear power-specific technologies, which has an important driving effect on various economic sectors while strengthening energy independence.

> **Researchers are currently working on developing nuclear reactors that will allow hydrogen to be produced and seawater desalinated**

NUCLEAR ENERGY IN THE FUTURE

Characteristics of new designs

The U.S. power industry's first report on the requirements new advanced LWRs should meet, entitled *Utility Requirements Document* (URD), was released in 1990. Likewise, European utilities drafted a similar document (*European Utility Requirements* - EUR) addressing the realities of the European electricity market, European technological capabilities, the possibility of licensing throughout Europe and the experience accumulated in the continent.

Simplifying the facilities or reducing building times are some of the requirements placed on new reactors

Requirements:

- To optimize safety by utilizing natural phenomena.
- To maintain competitiveness in relation to other energy sources.
- To prevent the improper use of radioactive materials by developing and enhancing current non-proliferation measures.
- To simplify nuclear facilities and reduce building times.
- To study and apply human factors.
- To render emergency plans in the area surrounding stations unnecessary by eliminating the likelihood of radioactive emissions.
- To take the management of spent fuel and the dismantling of facilities into account from the very beginning of design so as to minimize the generation of waste.

Objectives:

- To have plants that can operate for 60 years.
- To have safe, flexible operation with a high-degree of overall availability.
- To increase automation and improve human factors, giving operators more time to make decisions and thus decrease the likelihood of making mistakes.
- To reduce the core damage frequency to less than 1:100,000 per reactor and year and the accumulated frequency of emissions after the core is damaged to less than 1:1,000,000 per reactor and year.
- To incorporate designs for dealing with severe accidents.
- To limit the protective measures needed in the surrounding area in the hypothetical case of an on-site emergency by including further measures in the design of the plants.
- To take measures for preventing nuclear proliferation and terrorist attacks.

Generations of nuclear reactors

GENERATION I

Shippingport N.P.P.

First Prototypes

Calder Hall (GCR/MAGNOX)
Douglas Point (PHWR/CANDU)
Dresden-1 (BWR)
Fermi-1 (FBR/SFR)
Peach Bottom 1 (HTGR)
Shippingport (PWR)
Obninsk (LWGR)

1950 1960

GENERATION II

Diablo Canyon N.P.P.

Commercial Production of Electricity

Bruce (PHWR/CANDU)
Calvert Cliffs (PWR)
Flamanville 1-2 (PWR)
Grand Gulf (BWR)
Kalinin (PWR/VVER)
Kursk-1 (LWGR/RBMK)
Palo Verde (PWR)

1970 1980

GENERATION III / III+

Kashiwazaki N.P.P.O Ikiluoto N.P.P.

Advanced and Evolutionary Reactors

ABWR (GE-Hitachi; Toshiba BWR)
ACR 1000 (AECL CANDU PHWR)
AP1000 (Westinghouse-Toshiba PWR)
APR-1400 (KHNP PWR)
APWR (Mitsubishi PWR)
Atmea-1 (Areva NP-Mitsubishi PWR)
CANDU 6 (AECL PHWR)
EPR (AREVA NP PWR)

ESBWR (GE/Hitachi BWR)
Small Modular Reactors
- B&W mPower PWR
- CNEA CAREM PWR
- India DAE AHWR
- KAERI SMART PWR
- NuScale PWR
- OKBM KLT-405 PWR

VVER-1200 (Gidopress PWR)

1990 2000 2010 2020

GENERATION IV

Future

Innovative Designs

GFR	Gas-Cooled Fast Reactor
LFR	Lead-Cooled Fast Reactor
MSR	Molten Salt Reactor
SFR	Sodium-Cooled Fast Reactor
SCWR	Supercritical Water Reactor
VHTR	Very High Temperature Reactor

2030 2040

The approximately 450 nuclear reactors which are currently in operation are Generation II and III designs. On the other hand, the 50+ units which are currently being built belong to Generation III/III+.

Source: GEN IV International Forum & Foro Nuclear

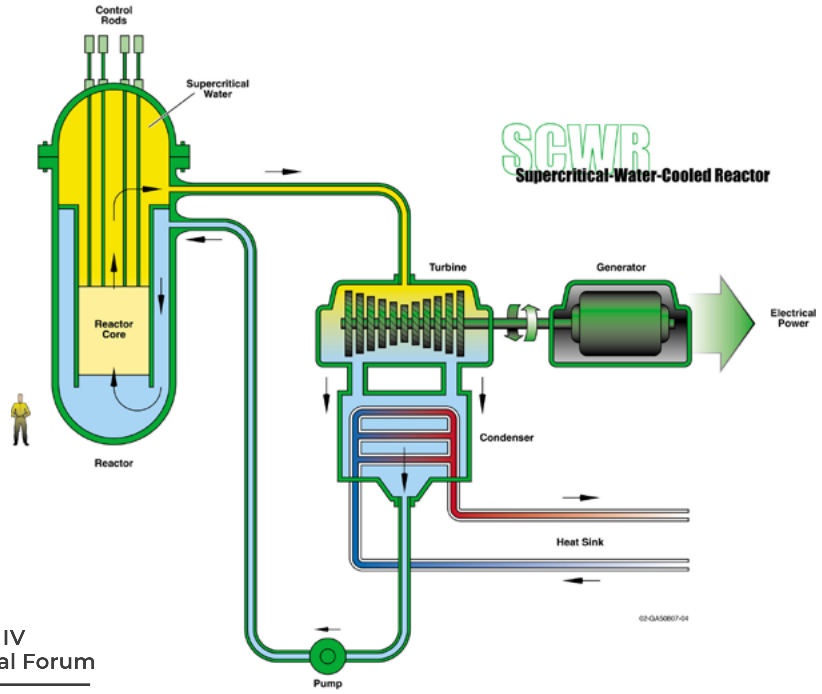
GENERATION IV NUCLEAR REACTORS

Gen. IV reactors are a collection of designs that have been developed by the *Generation IV International Forum* (GIF) with the objective of being used in commercial applications and have technology levels ranging from those requiring a demonstration project to those which are already available and are deemed competitive from a financial standpoint. **The main feature of these designs is they have a closed fuel cycle. They are expected to come into service throughout the 2030s and 2040s**.

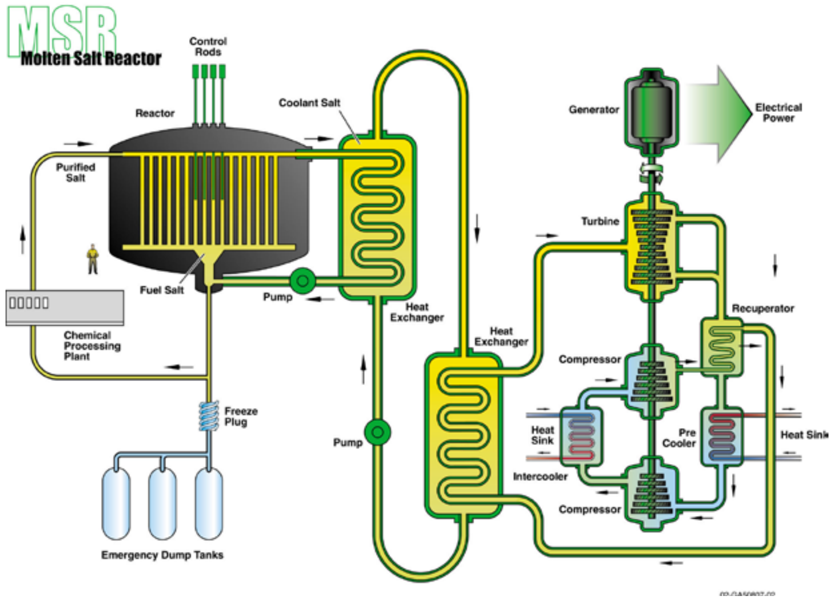
The *Generation IV International Forum* was launched by the U.S. Department of Energy (DOE) in 2001 and later opened to other countries. Spain takes part in it via the EU. The *International Project on Innovative Nuclear Reactors and Fuel Cycles* (INPRO), which is sponsored by the International Atomic Energy Agency (IAEA), is also worth mentioning.

Six nuclear systems based on a variety of designs with cores that use thermal and fast neutrons, diverse technologies for converting energy and a fuel cycle which is generally closed, whereby the reprocessed irradiated fuel from older generation reactors can be reused, were selected on the basis of the abovementioned requirements and objectives—which were adopted by GIF and INPRO.

Their unit powers range widely, from very low (≤ 300 MWe) to very high (> 1,000 MWe).



Source:
Generation IV International Forum



Source:
Generation IV International Forum

Gas-Cooled Fast Reactor (GFR)

It consists in a high temperature helium-cooled fast reactor with a closed fuel cycle. It marries the advantages of fast neutron spectrum systems and the long-term sustainability of uranium resources. It minimizes the generation of waste by means of multiple reprocessing phases and the fission of long-lived actinides and reaps the performance-wise benefits of high temperature cycles. In addition, the generated heat could be used for industrial purposes e.g. to produce hydrogen.

Lead-Cooled Fast Reactor (LFR)

It is a type of reactor that runs on fast neutrons and at a high temperature and is cooled with molten lead or a homogeneous mix of lead and bismuth that has a point of fusion below those of its constituents (eutectic), which allows it to operate at low loads, has very good thermodynamic properties and is relatively inert as regards interactions with air or water.

It has excellent material management capabilities since it runs on fast neutrons and uses a closed fuel cycle to achieve an efficient conversion of fertile uranium. It can also be used to burn actinides, and as a *burner/breeder reactor* with uranium or thorium cycles. These reactors use fast neutrons that do not need to be moderated for the fusion process to take place.

The Generation IV International Forum has chosen six nuclear systems based on a variety of designs

Molten Salt Fast Reactor (MSFR)

Its main characteristic is that the fuel in the core is dissolved in molten fluoride salts. This technology was developed over 50 years ago at the *Oak Ridge National Laboratory* in the U.S. and subsequently developed in Russia. This type of reactor has the additional attractions of burning actinides in the irradiated fuel removed from LWRs and of potentially being used as a *burner/breeder reactor* with hypothetical thorium cycles.

It does not have a solid moderator, such as graphite, owing to its high negative temperature coefficient and void reactivity coefficient, which is a unique safety feature that other solid-fuel fast reactors lack.

It is notable because the use of molten salts as the coolant makes it easier to know better the heat transfer for applications such as hydrogen production.

Supercritical Water Reactor (SCWR)

It is a high pressure and temperature LWR that operates above the critical thermodynamic point of water (374 °C and 22.1 MPa / 218.1 atm).

The reactor core can be designed for a fast- or thermal-neutron spectrum or can be integrated in a pressure vessel or in pressure tubing in the reactor, which necessitates the use of light or heavy water, with deuterium instead of hydrogen as the moderator.

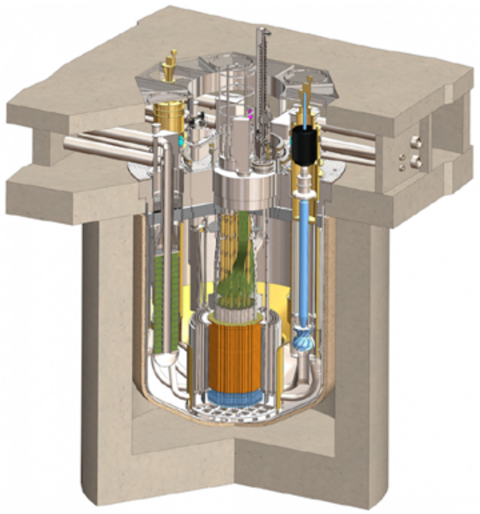
As a result of the above, this kind of reactor has a greater thermal efficiency (up to 44%), does away with the steam generators of PWRs and steam separators and driers of BWRs and with recirculation pumps altogether, and the reactor pressure suppression and turbine buildings are smaller.

Sodium-Cooled Fast Reactor (SFR)

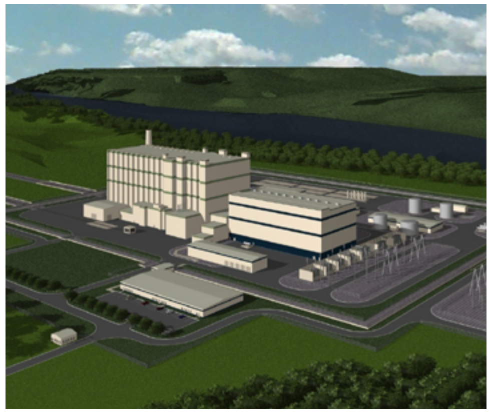
It employs liquid sodium as the coolant and allows a high power density to be married with a low coolant volume fraction and low pressure operation. Although corrosion is prevented by having an oxygen-free atmosphere, the violent reaction of sodium with air and water requires the system through which the former flows to be hermetically sealed. The reactor's fuel cycle allows the fissionable fuel to be regenerated and makes it easier to manage the minor actinides that are generated, which can be split thanks to the efficiency of the high energy neutrons.

The range of powers under consideration is wide —from 300 to 1,500 MWe, whereas operating temperatures range from 500 to 550 °C.

General Electric-Hitachi (GEH) and TerraPower are working together on a program —commissioned by the U.S. DOE— which is currently in its conceptual phase. The end result so far is the Natrium design, which hybridizes electrical generation with a molten sodium salt reactor of the traveling wave type (*Traveling Wave Reactor* – TWR), which stores heat in molten salts, which allows the reactor's output to be increased from the rated 345 MWe to around 500 MWe in times of high demand.



Conceptual TWR design
Source: TerraPower

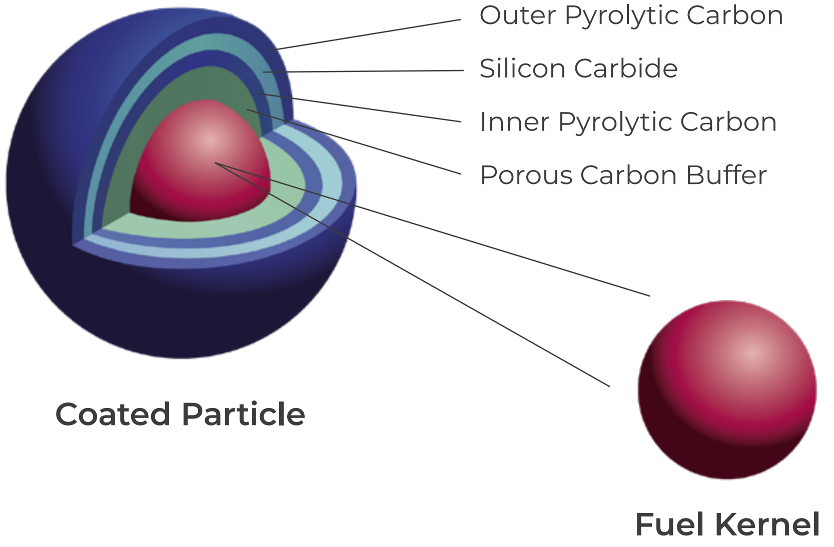


Natrium concept
Source: TerraPower

Very High Temperature Reactor (VHTR)

This design is mainly intended for cogeneration of electricity and hydrogen, which can be gleaned from water by means of thermochemical (reforming), electrochemical or hybrid processes thanks to its high outlet temperature (1,000 °C).

The fuel *kernel* is made up of very small particles of uranium, carbon and oxygen, which are encapsulated inside three layers of carbon and a ceramic material, making them highly resistant to operational transients, and embedded in a graphite matrix. Technically they are known as tristructural-isotropic —or TRISO— fuel particles. They can be manufactured as cylindrical capsules or small spherical balls (*pebbles*). They are helium-cooled.



VHTRs are highly versatile and can use alternate fuel cycles based on uranium-plutonium, plutonium, mixed oxides and uranium-thorium.

SMALL MODULAR REACTORS (SMRs)

At the outset of the 2010s, as part of the *International Project on Innovative Nuclear Reactors and Fuel Cycles* (INPRO) program and under the auspices of the U.S. DOE, a new family of nuclear reactors called **Small Modular Reactors (SMRs), with electrical powers of around 300 MWe**, began to be developed and might come on line over the next two decades.

The nuclear industry is very keen on producing electricity and process steam using small unit power, modular-design nuclear power plants in order to bring down direct investment costs, simplify the licensing process, shorten construction times and make it possible for units to be sited far away from large power grids.

SMRs have small power, a modular design and shorter licensing and building times and can be sited in remote locations

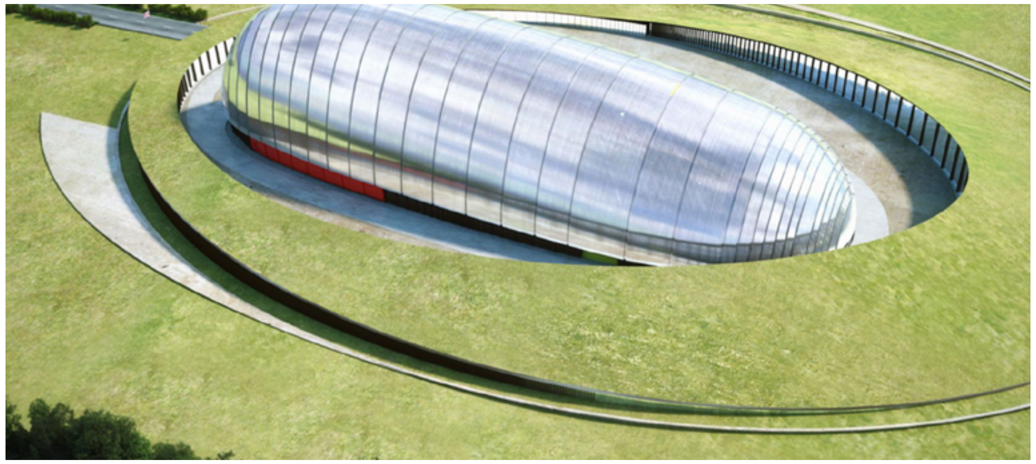
An additional factor driving the development of SMRs is that, thanks to their small capacity and modularity, they can be made in factories, with all the advantages this would entail as regards manufacturing quality, ease of licensing and standardization, cost and time savings, and doing away with mistakes and making changes during installation. They could be sent to the site already assembled and ready to reach the desired power by just adding additional modules, which could be reloaded and serviced independently of each other. The advantages of modularity could also be applied to desalination plants and remote locations.

They inherently have a high safety level and use passive means, such as gravity, to actuate the safety systems, or convection to transmit heat.

Some of them are also designed to be installed in part or in whole underground to reduce the risk of terrorist attacks.

There are several examples of SMRs which are in an advanced design phase:

- The pictures show the Rolls Royce design in a possible semi-buried facility, like the ones the U.K. is considering building. It is based on 220 MW modules that can be coupled to attain the desired power levels and would cut construction times down to less than five years.

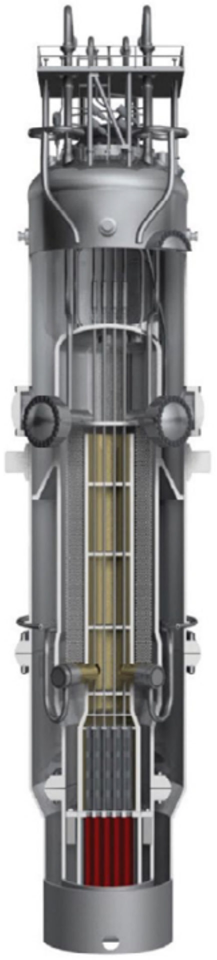


Source: Rolls Royce

- The reactor design General Electric Hitachi (GEH) has been working on is based on its evolutionary knowhow obtained designing different BWRs and, as can be seen in the figure on the left, consists of a highly compact vessel, which can be factory-made and has a power of 300 MWe.

- Nuscale's design is based on 60 MW modules in which the reactor, the steam generator and the pressurizer are housed inside a pressure vessel. Each module is submerged in a water pool. Its passive safety features include the circulation of coolant by convection, which provides for indefinite cooling without operator intervention or the need for outside power or makeup water.

GEH BWR X 300



NUSCALE SMR

The first floating, energy-producing nuclear power station in the world was put in service in May 2020 in Russia

Source: Rosatom

An example of an SMR that is remotely located and already in operation is **the low power mobile unit that was commissioned in May 2020 in the east Siberian town of Pevek, which consists in a barge carrying two 35 MW Rosatom KLT-40C modular reactors** and two steam turbine generators.

Akademic Lomonosov is the first floating nuclear power station intended for electricity production the world has ever seen. It could also be converted into a desalination plant capable of producing 240,000 m^3 of water per day.