

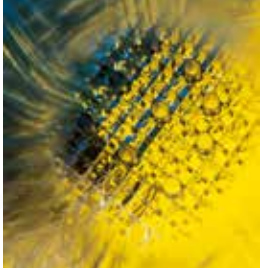
FROM RESEARCH TO INDUSTRY



EDUCATIONAL BOOKLET

NUCLEAR REACTORS

- Nuclear fission
- Components of a nuclear reactor
- From one generation to the next
- Fourth generation of reactors



Summary



Introduction 03



Nuclear fission 04-06

Fissile atoms that...	05
... release energy	05
Neutrons and chain reaction	06



Components of a nuclear reactor 07-11

Fuel	09
Control rods to trap neutrons	09
A moderator to slow down neutrons	09
A coolant to transport heat	09
A steam generator to exchange heat	10
Reactor containment	11



From one generation to the next 12-17

Generation and technology: two separate notions	13
Four generations of nuclear reactors	13
Nuclear reactor technologies	16



Fourth generation of reactors 18-23

Why choose the fast reactor technology?	19
Why focus on sodium-cooled fast reactors?	21
The Astrid integrated technology demonstrator project	21

Introduction



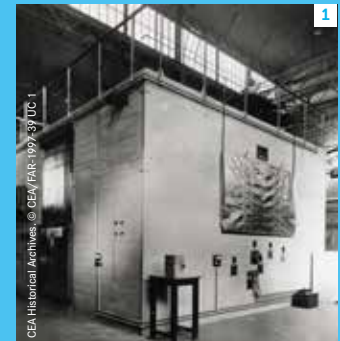
Managing energy supplies is a key issue for the world's future. Various power generation systems exploiting different sources of energy already operate side by side today, i.e. renewable energy (hydraulic, wind, solar, etc.), thermal combustion (coal, gas, oil) and nuclear. These generation systems (excepting photovoltaics) cannot function without power plants, which all follow the same principle based on the operation of a turbine coupled to an alternator to generate electricity. These power plants differ by the way the turbine is driven.

It is the water from a dam that drives the turbine in a hydraulic power plant. It is the steam produced when the fossil fuel (coal, natural gas or oil) is burned that drives the turbine in a conventional thermal power plant. In a nuclear power plant, it is the heat produced when uranium atoms split that is used to transform water into steam, which in turn drives the turbine.

The French Alternative Energies & Atomic Energy Commission (CEA), which was created in 1945, is behind the development of the French nuclear power industry. Nuclear power currently provides 75% of the total power generated in France. The nuclear fleet operated by EDF comprises 58 nuclear reactors rated between 900 and 1,450 MWe. The French Energy Transition Act signed in August 2015 has recently secured the long-term contribution of nuclear energy to the French energy mix at 50%.

As early as 1945, the CEA was behind the development of the French nuclear power industry.

- 1- The first French nuclear reactor called Zoé.
- 2- Cruas-Meysses nuclear power plant.



Front cover and top of page 2: Fuel assembly grid © D.Sarraute/CEA -
Reduced-size image of the cover page: Fuel from the Civaux nuclear power plant. © EDF - Production: Agence Gimmik - April 2016



NUCLEAR FISSION

When an atom undergoes fission, it releases a large amount of energy which is transformed into heat. In a nuclear reactor, this heat is recovered to generate electricity.



© S.Le Coustier/CEA

↑ Selective extraction of uranium in a laboratory.

FISSILE ATOMS THAT...

The nucleus of certain large atoms will split into two smaller nuclei when it collides with a neutron. In this case, the nucleus is considered to be “fissile” and the reaction is referred to as “fission”.

As particles with no electric charge, neutrons are able to get sufficiently close to the positively charged nucleus without being repelled by the electric forces.

In this manner, they can collide with the nucleus to split it into two parts, called fission products, which are most often **radioactive**¹. The only natural fissile nucleus is uranium-235.

... RELEASE ENERGY

When a nucleus undergoes fission, a considerable amount of energy is released.

The energy carried by the neutrons represents a small fraction of the total energy released.

Most of this energy is carried by the fission products in the form of **kinetic energy**². Expelled at a velocity of about 8,000 km/s, these fission products push their way through the other atoms by knocking against them. During these collisions, they rapidly lose their speed (and thus energy) by heating up the surrounding environment, before stopping in the bulk of the uranium. Their initial energy is finally transformed into heat and the local temperature in the uranium increases.

In a nuclear reactor, this heat is recovered to generate electricity.

1- Atoms with unstable nuclei are called radioactive. They naturally transform into other atoms by emitting radiation (see booklet called “The radioactivity”).

2- The kinetic energy refers to the energy of a body in movement. It increases with the mass and velocity of the body. A car travelling at very high speed has more kinetic energy than the same car travelling at low speed. The damage will be greater in the case where the first car hits an object than if it were the second car. Likewise, a car has less energy than a truck travelling at the same speed.

DID YOU KNOW?



↑ The team waiting for the Zoé reactor to diverge.

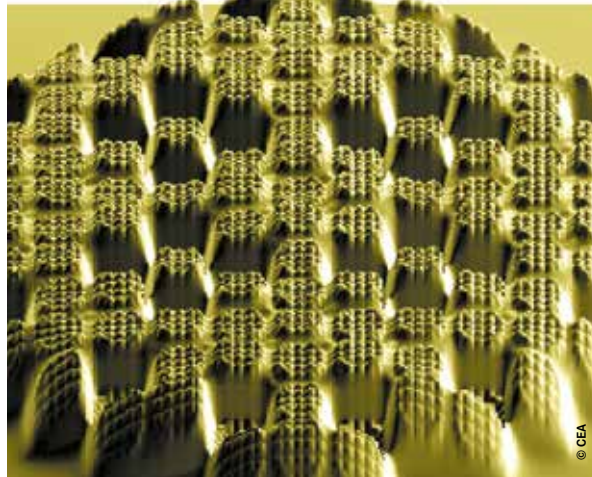
When the first chain reactions occur inside a nuclear reactor, the reactor is said to have diverged.

The first nuclear reactor built by Enrico Fermi diverged in 1942 in the US.

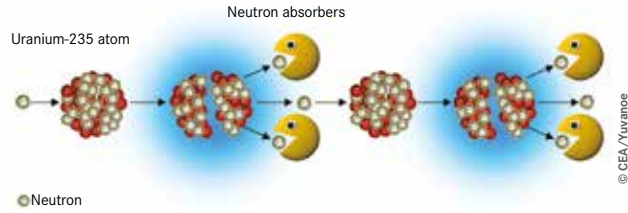
In France, the first reactor called Zoé (French abbreviation for zero power, uranium oxide, heavy water) was built on the CEA Fontenay-aux-Roses centre and diverged on 15 December 1948. ■

The chain reaction is controlled in a nuclear reactor so as to maintain a constant number of fissions.

Neutronic simulation. →



Controlled chain reaction in nuclear reactors



NEUTRONS AND CHAIN REACTION

Each fission produces an average of two to three high-energy neutrons which travel at very high speed (20,000 km/s) among the uranium atoms. These projectiles are small, light and electrically neutral compared with fission products, which means they can travel relatively far before interacting with another nucleus. In turn, they trigger new fission reactions, releasing more neutrons and so forth: this is known as a chain reaction.

This phenomenon is controlled in a nuclear reactor. Most of the neutrons are captured to maintain a stable number of fission reactions.

Only one neutron from each fission provokes a new fission reaction to release energy in a regular manner. This is how the amount of heat released every second from the mass of uranium is controlled.

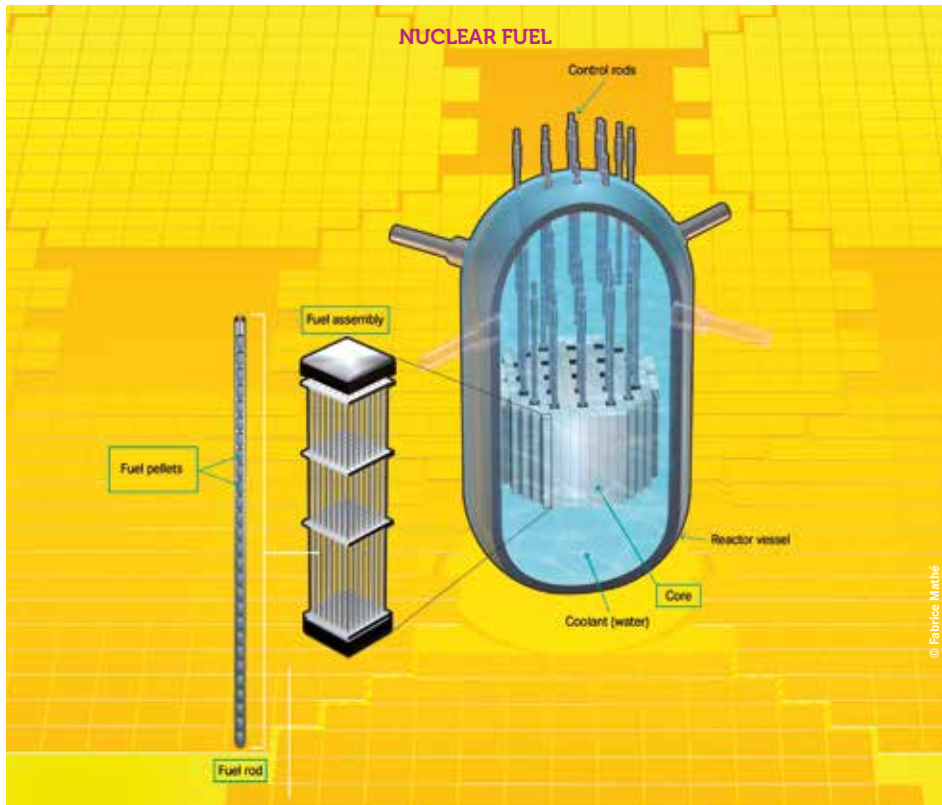
COMPONENTS OF A NUCLEAR REACTOR

There are various types of reactor technologies. Nonetheless, these nuclear reactors all have several components in common such as the fuel, control rods, moderator and coolant.

While the control rods manage the chain reaction, the coolant removes the heat from the reactor.

The 58 reactors in service in France are for generating electricity.

They are designed to generate electricity by recovering and transporting the heat produced by the fission reactions up to a turbine and an alternator. The main components specific to a reactor are located in the nuclear island. This is where the fission reactions take place and includes the nuclear boiler and systems for the fuel, as well as the equipment required to operate and guarantee the safety of the entire facility. The other part of the nuclear power plant is called the conventional island and includes, among others, the turbine, the alternator and the condenser.



FUEL

The fuel used in a nuclear power plant contains fissionable atoms whose energy is extracted by fission. Uranium-235 is more than often used as the fuel. Pressed into pellets, the fuel is inserted into leaktight cladding called "fuel rods". These rods are then bundled together to form a fuel assembly which is placed in the core of the reactor. (See booklet called "The nuclear fuel cycle").

CONTROL RODS TO TRAP NEUTRONS

In a nuclear reactor, the chain reaction is constantly managed by means of control rods which are made from a material capable of absorbing neutrons. These rods are mobile in the reactor core: they can be dropped down to reduce the fission rate or pulled up to either maintain or increase the rate. In the case of an incident, the rods are dropped into the fuel which almost immediately stops the chain reaction.

A MODERATOR TO SLOW DOWN NEUTRONS

Most reactors are equipped with a moderator. Its role is to slow down the neutrons released during the fission reaction which can otherwise be too energetic to efficiently provoke other fission reaction.

Neutrons are slowed down when they go through matter that is composed of atoms with light nuclei which does not absorb, like water or graphite. The moderator slows the neutrons down from their initial speed of around 20,000 km/s to a speed of about 2 km/s.

A COOLANT TO TRANSPORT HEAT

The energy released as heat during the fission of uranium-235 nuclei must be transferred from the reactor core to the systems designed to transform heat into electricity, i.e. the turbine and alternator. This role is guaranteed by the coolant, the fluid used to remove the heat generated by the nuclear fuel.

The coolant can be water, a liquid metal (sodium or lead) or a gas (carbon dioxide or helium). The coolant is also used to maintain the fuel temperature at its nominal temperature that is compatible with the resistance of the materials.



Control room in a nuclear power plant.

The moderator slows down the neutrons so they can collide with the atoms and provoke fission reactions.

A STEAM GENERATOR TO EXCHANGE HEAT

A heat exchanger is designed to transfer thermal power from one system to another. In the case of pressurised water reactors (PWRs), for instance, the primary coolant is water which exits the reactor core at a high temperature of about 330°C and is kept a high pressure of about 150 bar to prevent it from transforming into steam. This water then flows through a steam generator that is used to transfer the thermal power between the primary and secondary systems. They are

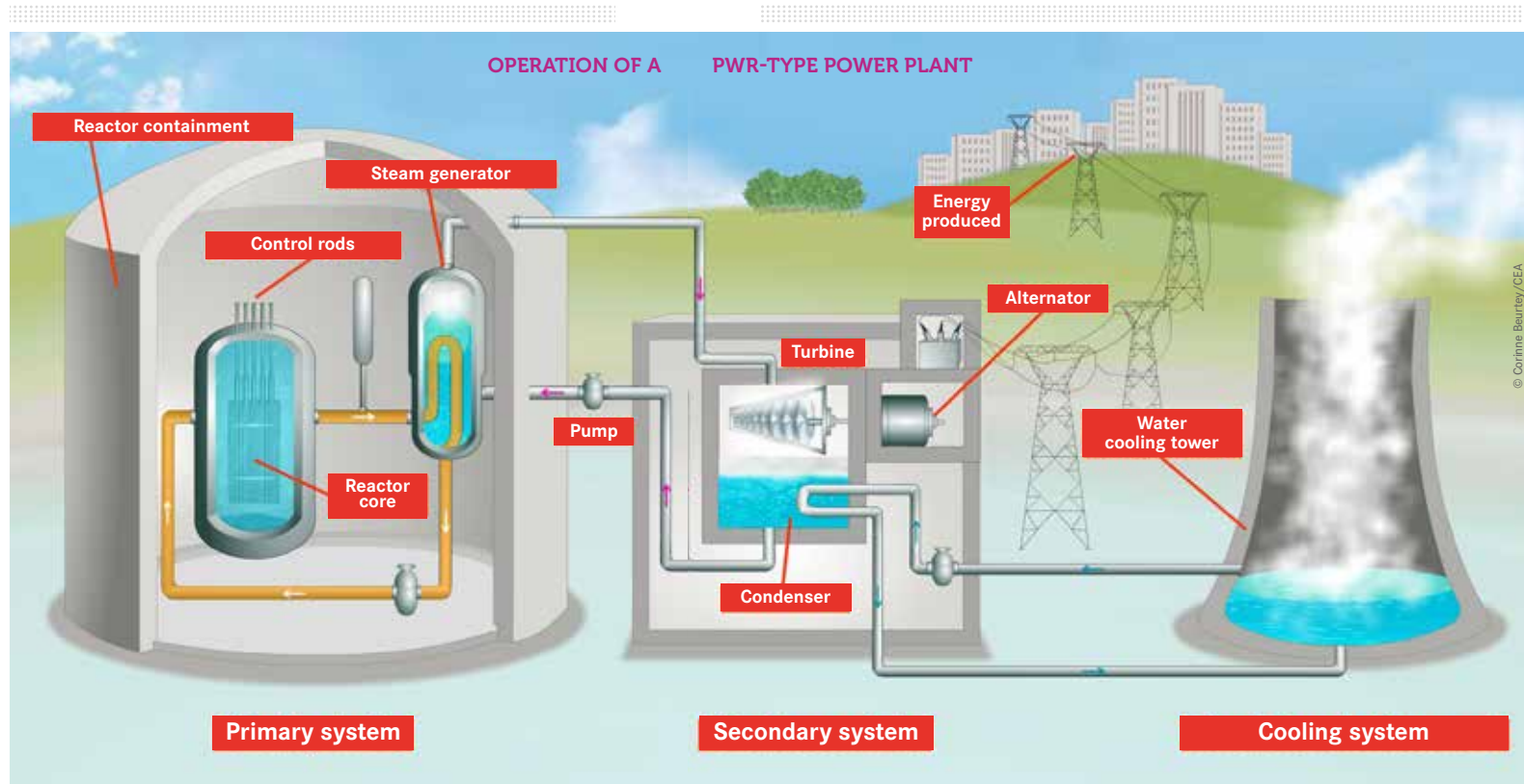
designed so that the water in the secondary system boils and generates steam. When the steam expands, it drives a turbine that is coupled to an alternator which produces electricity. This system is also known as a power conversion system; thermal energy is converted into mechanical and then electrical energy. A third system is designed to cool and then condense steam.

In the case of sodium-cooled fast reactors (SFRs), the primary coolant is sodium, which is a liquid metal that exits the core at about 550°C

and at low pressure (several bar). The power conversion system is based on the same principle as that of a PWR: a steam generator produces steam which expands in a turbine coupled to an alternator. The key difference is an additional system interposed between the primary system containing low-pressure sodium and the water-to-steam power conversion system at high pressure. The objective of this intermediary system is to take into account the risk of interaction between sodium and water by dissociating the radiological risk in the primary system from other risks. Two heat exchangers are therefore required between the primary system and the power conversion system.

REACTOR CONTAINMENT

The reactor containment is made of steel and/or reinforced concrete. It contains the reactor vessel, the primary system, the steam generators, and the main components important to reactor safety. It is leaktight and designed to prevent leaks from radioactive fuel elements into the environment, particularly in the case of a severe accident like a core meltdown (strong rise in the temperature causing the fuel to melt).





Core of a nuclear power reactor. © EDF



FROM ONE GENERATION TO THE NEXT

Each generation of reactors brings significant improvements in response to the major issues of their time.



© EDF / Châtael Saas sp

← Cruas-Meysse nuclear power plant.

The first nuclear power plants were built throughout the 1950s in the US, the Soviet Union and France. Several reactor generations have since been developed across the world; there are currently four generations today.

Each generation integrates major progress in terms of operational safety, security, fuel economy and economic competitiveness.

GENERATION AND TECHNOLOGY: TWO SEPARATE NOTIONS

In the nuclear industry, the notion of “generation” is distinctly different from that of “reactor technology”. A generation can comprise several types of reactor technologies. The differences between generations correspond to specific requirement criteria at each period of time.

FOUR GENERATIONS OF NUCLEAR REACTORS

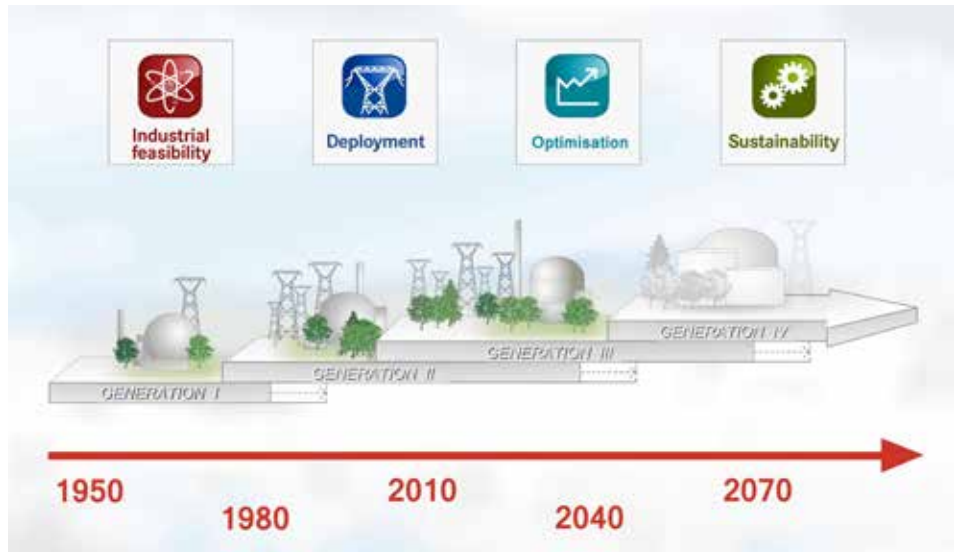
The Generation IV International Forum launched in 2001 is dedicated to research on “reactors of the future” and as a result, has defined four generations of nuclear fission reactors. Each generation was assigned a set of specific objectives to resolve the issues relevant at the time of their design. Considering the operating lifetimes of such facilities, reactors belonging to different generations can be found in service or under construction. For instance, most of the reactors currently in service are second generation, while the third generation is only just starting to be deployed, and the fourth generation has just reached design phase.

The first generation includes the prototypes and the first industrial-scale reactors used for commercial purposes that were developed in the 1950s and 1960s before being commissioned in the 1970s. During this period, France developed a reactor technology using natural uranium for the fuel since it did not have access to uranium enrichment technologies.

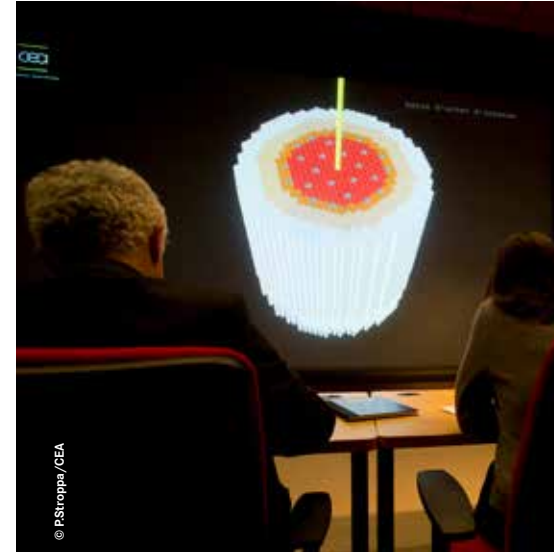
The second generation of nuclear reactors was commissioned from early 1970 onwards. This generation was designed with objectives of improved competitiveness and energy independence at a time when tensions were running high due to the price of fossil fuels (oil crisis). Most of the reactors in service throughout the world today are second generation. In France, this generation is composed of pressurised water reactors (PWRs) adapted from the American technology by EDF.

The third generation focuses on safety and security requirements: consolidated resistance to external hazards such as plane crashes. These reactors have incorporated operating experience from second-generation reactors, from the Three Mile Island and Chernobyl

↓ The different generations of nuclear reactors.



© Corinne Beaursey/CEA



← Simulating the behaviour of fuel in a second-generation reactor.

accidents, and from the September 11 attacks. An example of this type of reactor is the European Pressurised Reactor (EPR), with four currently under construction (one in Finland and two in China) and others planned, particularly in the UK.

The fourth generation refers to reactors currently in design phase which could be deployed on an industrial scale by around 2050. Their design incorporates a number of technological breakthroughs with respect to what has been built so far. Research on these future systems is being carried out under the Generation IV International Forum which has defined the criteria to be met: sustainability, nuclear safety, economic competitiveness and resistance to nuclear proliferation.

FOCUSON

GENERATION IV INTERNATIONAL FORUM

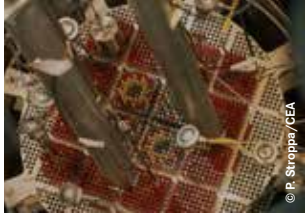
The partners* of the Generation IV International Forum signed an official charter in 2001 which launched cooperation in R&D aiming to establish the feasibility and performance of future nuclear reactor systems.

Objective: develop reactors with improved safety, sustainability (e.g. more efficient use of uranium) and economic viability with respect to other energy sources, while fighting nuclear proliferation, being resistant against terrorist attacks, and generating less ultimate waste.

In late 2002, six reactor concepts were selected. Three of these concepts are based on fast neutrons: sodium-cooled fast reactors (SFRs), gas-cooled fast reactors (GFRs) and lead-cooled fast reactors (LFRs). The others are supercritical water reactors (SCWRs), very high temperature water reactors (VHTRs) and molten salt reactors (MSRs).

* There are currently 14 today: South Africa, Argentina, Australia, Brazil, Canada, South Korea, China, the US, France, Japan, the UK, Russia, Switzerland and Euratom.

DID YOU KNOW?



Core of a research reactor used for neutronic studies of thermal neutron reactors.

Some reactors are intended for research and do not generate electricity. They are used, for instance, to measure the neutronic properties of reactors, to study the behaviour of materials and fuels under irradiation, to gauge the impact of accident conditions, and to validate new concepts and prototypes. Research reactors are also used to produce radioelements used in the medical industry for diagnostics and radiotherapy purposes. ■

NUCLEAR REACTOR TECHNOLOGIES

Since the inception of the nuclear power industry, several reactor technologies have been developed across the globe. These technologies differ by their choice of technological options. Among them, three key characteristics are used to classify the reactors into different technologies:

- The type of fissile material used as nuclear fuel, e.g. natural uranium, enriched uranium, plutonium;
- The coolant used to recover the heat produced in the core and to transport it, e.g. ordinary pressurised or boiling water, heavy water, carbon dioxide, sodium, helium;
- The moderator, which determines the average energy of the neutrons in the reactor core, e.g. ordinary water, heavy water, graphite.

A combination of these three components produces reactors with different characteristics which do not meet the selection criteria of a reactor technology in the same way.

These technical or economic criteria change over time. For instance, the first technologies developed were required to operate with natural uranium as the fuel, thereby limiting the choice of moderator. With the development of uranium enrichment technologies, new reactor technologies operating with enriched uranium were deployed.

TECHNOLOGY	FUEL	MODERATOR	COOLANT
UNGG reactor (Natural uranium graphite-gas) First technology developed in France. The last reactor of this generation was shut down in 1994.	Natural uranium (0.7% uranium-235)	Solid carbon (graphite)	Carbon dioxide
CANDU reactor Technology developed in Canada.	Natural uranium	Heavy water*	Heavy water under pressure
RBMK reactor (<i>Bolchoe Molchnastie Kipiachie reactor</i> which means "high power boiling water reactor"). These reactors make up 40% of the nuclear fleet in the ex-USSR.	Enriched uranium with 1.8% uranium-235	Carbon (graphite)	Boiling water
Boiling water reactor (BWR) Technology developed in the US, Japan and Sweden.	Enriched uranium with 3% uranium-235	Ordinary water boiling in the core	
Pressurised water reactor (PWR) The most conventional technology in the Western world. It was developed in ex-USSR under the name of VVER.	Enriched uranium with 3% uranium-235	Pressurised water maintained in liquid form	Pressurised water acting as both moderator and coolant
Fast reactor The French Phenix (250 MWe), prototype reactor operated from 1973 to 2009.	Enriched uranium or plutonium	None : neutrons remain fast	Liquid sodium Does not slow down neutrons

*Heavy water: composed of water molecules whose hydrogen atom is deuterium, a heavy isotope of hydrogen (see the booklet called "The atom").



FOURTH GENERATION OF REACTORS

France is continuing its technology watch and R&D programmes on systems for the fourth generation. It is leading the design studies on an integrated technology demonstrator of a sodium-cooled fast reactor.



© A. Gomin/CEA

↑ Shielded line of hot cells for recycling spent fuels.

WHY CHOOSE THE FAST REACTOR TECHNOLOGY?

In terms of the physics, fourth generation fast reactors have the advantage of saving on uranium resources and recycling recoverable materials, plutonium in particular.

In the current water reactors (PWRs) comprising the French fleet, only a small fraction of the raw material, i.e. uranium-235 (minor isotope of natural uranium) is

exploited to produce energy. The 8,000 tonnes of natural uranium imported each year by France are used to produce 1,000 tonnes of enriched uranium to supply the power plants. The remainder, i.e. 7,000 tonnes of depleted uranium, is stored in view of its future use in fourth generation reactors.

These stocks currently amount to more than 270,000 tonnes and cannot be used in the current reactor fleet.

Additionally, materials (uranium and plutonium) that can be recovered from spent fuel produced by the current fleet are treated and then can be recycled into fuel called MOX, i.e. mixed uranium and plutonium oxide. This kind of fuel can only be used efficiently once in the water reactors currently in operation.



© A. Goiny / CEA

↑ Hall of the Phenix reactor at Marcoule where the first experiments on transmutation were performed.

1- Transmutation involves breaking down elements that are heavier than uranium and which are also the largest contributors to the long-term radiotoxicity of waste.

This reaction leads to the formation of new elements that often have shorter half-lives or are even non-radioactive.

2- Toxicity of a radioactive nature to which any body can be exposed either by injection or inhalation.

Fast reactors can burn all of the natural uranium (including depleted uranium) whereas today's reactors only burn less than 1%. By utilising all of the uranium in the ore, fast reactors multiply the energy that can be extracted from a given mass of natural uranium by a factor of about 100. They can burn without limits all the plutonium produced by both the current reactor fleet and by themselves, which makes it possible to manage stocks in a rational and sustainable manner via multiple recycling.

Fast reactors also offer the possibility of **transmuting**¹ some of the most radiotoxic elements contained in the ultimate waste. It would therefore be possible to reduce the storage space required for long-lived high-level waste by a factor of 10 with a reduction in its **radiotoxicity**² by up to a factor of 100 after 300 years.

Fast reactors are therefore a key feature of a closed fuel cycle strategy making it possible to efficiently manage recoverable materials in spent fuel, firstly from the current fleet of reactors and then subsequently from a homogeneous fleet of fast reactors. They could thus operate for several thousand years dispensing entirely with natural uranium.

WHY FOCUS ON SODIUM-COOLED FAST REACTORS?

The sodium-cooled fast reactor (SFR) concept has become the reference technology for fourth generation systems across the world. Its international scope and its technology readiness lead us to believe that its industrial-scale deployment is feasible sometime around 2050. This requires first qualifying the various technological advances on a representative scale to check the viability of the performance targets set for the fourth generation of nuclear reactors.

THE ASTRID INTEGRATED TECHNOLOGY DEMONSTRATOR PROJECT

In France, studies on fourth generation systems are led by the CEA under the integrated technology demonstrator project called **Astrid**³. It will benefit from the experience accumulated from fast reactors having already operated in the world, while incorporating new technological breakthroughs. The reactor's power has been defined to achieve a sufficient degree of flexibility while maintaining a level of representativeness in line with the main industrial issues.

The Astrid project is currently in design phase. It is being led in collaboration with industrial partners, which opens the door to particularly advanced technological choices, chiefly in the fields of nuclear safety and operability.

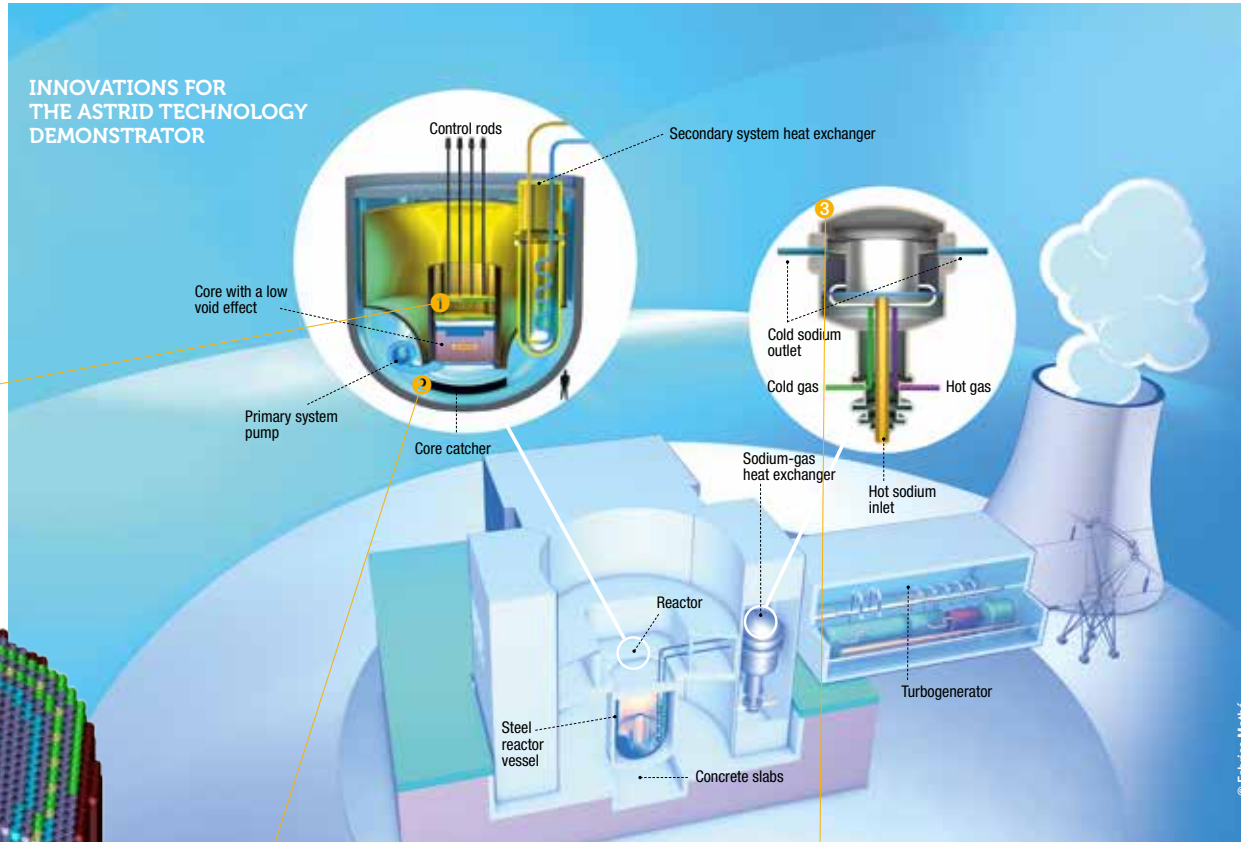
↓ Test platform to support the design of fourth generation reactors.



PF Grosjean / CEA

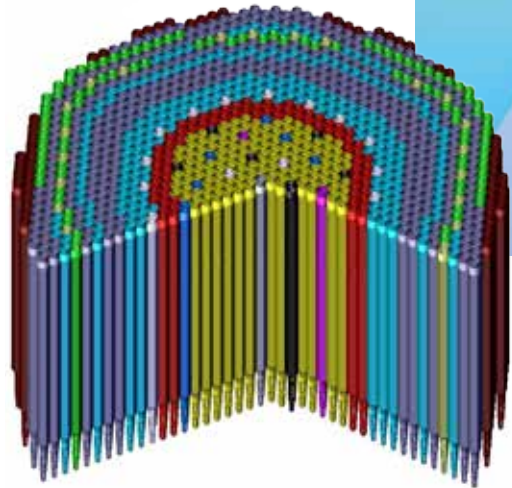
3- Advanced Sodium Technological Reactor for Industrial Demonstration.

INNOVATIONS FOR
THE ASTRID TECHNOLOGY
DEMONSTRATOR



Among the decisive breakthroughs, it is worth mentioning:

- 1 An innovative core that is naturally resistant to accident conditions, which is a significant step forward in the field of nuclear safety and a world first. It is designed to reduce the core's reactivity in the case of a loss-of-coolant causing the sodium temperature to increase.



© CEA

↑
Astrid innovative and enhanced-safety core.

- 2 A core catcher integrated into the reactor vessel, which prevents radioactivity from escaping into the environment in the case of a severe accident with core meltdown.

- 3 A power conversion system that uses gas instead of water, thereby preventing any risk of chemical reaction between water and sodium.

- **Inerting⁴** and early leak detection devices to prevent the risk of sodium fires.
- Multiple, redundant decay heat removal systems. The reactor can use the ambient air as a means of cooling, even in the case where the power supplies and heat sink are lost.
- The possibility of carrying out inspections and maintenance while the reactor is operating.
- Measures making it possible to increase the burn-up and the cycle duration, while reducing outage times for fuel reloading.

© Fabrice Mathé

⁴- Utilisation of an inert gas like nitrogen to eliminate the risk of sodium reacting with air.



THE COLLECTION

- 1 > The atom
- 2 > Radioactivity
- 3 > Radiation and Man
- 4 > Energy
- 5 > DNA
- 6 > Nuclear reactors
- 7 > The nuclear fuel cycle
- 8 > Microelectronics
- 9 > The laser: a concentrate of light
- 10 > Medical imaging
- 11 > Nuclear astrophysics
- 12 > Hydrogen
- 13 > The Sun
- 14 > Radioactive waste
- 15 > The climate
- 16 > Numerical simulation
- 17 > Earthquakes
- 18 > The nanoworld
- 19 > Energies for the 21st century
- 20 > Chemistry for energy

FROM RESEARCH TO INDUSTRY



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Direction de la communication
Bâtiment Siège
91191 Gif sur Yvette cedex - www.cea.fr

ISSN 1637-5408.