Nuclear Reactors for the Generation of Energy

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The principle of operation of a nuclear power plant does not fundamentally differ from that of a fossil fuel power plant. Only the way of producing heat changes. Nuclear power plants use the fission of uranium atoms as a heat source in a reactor, while so-called "conventional" power plants produce heat by burning natural gas, coal or oil. In both cases, the production of heat makes it possible to transform water into steam. This steam can then be used to produce electricity by means of a turbine or be used as a source of heat for a non-electrical industrial application. A huge difference consists in the energy density: while burning 1 kg of coal produces 8 kWh of heat, the fission of 1 kg of uranium 235 produces 24.000.000 kWh[1]. The amount of waste generated by nuclear energy is therefore extremely low compared to the energy produced.

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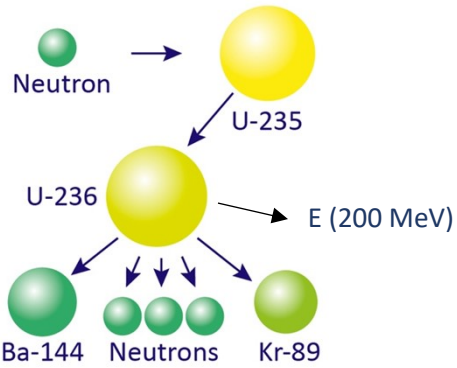
[1] https://www.euronuclear.org/glossary/fuel-comparison/

1 Main Principles

1.1 Fission energy and chain reactions

In a nuclear fission reactor, energy is obtained when a heavy atomic nucleus (such as uranium 235) captures a neutron and then splits into two lighter nuclei. Besides these two fission products, fission releases some neutrons, alpha, beta particles and gamma radiations.



There are about 2000 fission products which constitute the isotopes of about thirty chemical elements. Most of these products are radioactive and they evolve by successive disintegrations towards a stable state. The mass of the particles obtained and of the fission products is slightly lower than the initial mass consisting of the heavy atomic nucleus and the neutron that broke it. The missing mass has not disappeared, however: it has been transformed into energy, according to Einstein's law $E = mc^2$, in the form of heat. The thermal energy released results mainly from the kinetic energy of the pieces of the nucleus of the original uranium atom. Per atom of split uranium 235, the release of energy is equal to 200 million electron volts (MeV). The fission of around ten atoms of uranium 235 releases an average of 23 neutrons. These neutrons tend to be captured by the vessel internals and by absorbing materials (boron, cadmium, gadolinium) introduced in purpose, or to escape from the medium where fission occurs. In order to obtain a chain reaction at equilibrium, it is necessary to recover one neutron per atom of split uranium to produce a new fission. For comparison, it is worth noting that the energy released during chemical combustion reactions (such as those involving gas or coal) is typically on the order of 10 eV per molecule. This is approximately 20 million times smaller than the energy released by the fission of a Uranium-235 nucleus.

In thermal[2] reactors such as Pressurized Water Reactors (PWRs, like the Belgian reactors), it is necessary to "slow down" the released neutrons so that they are absorbed by the uranium 235 (and split them) rather than being absorbed by the uranium 238. This role is played by the moderator, which is water in PWRs but which can also be graphite or heavy water in other reactor types. Neutrons from fission of U-235 and slowed down by the moderator will strike other U-235 nuclei which in turn will undergo fission, thus producing heat as well as radiations and releasing other neutrons. When each fission is followed by

[2] As opposed to fast reactors (see section 2).

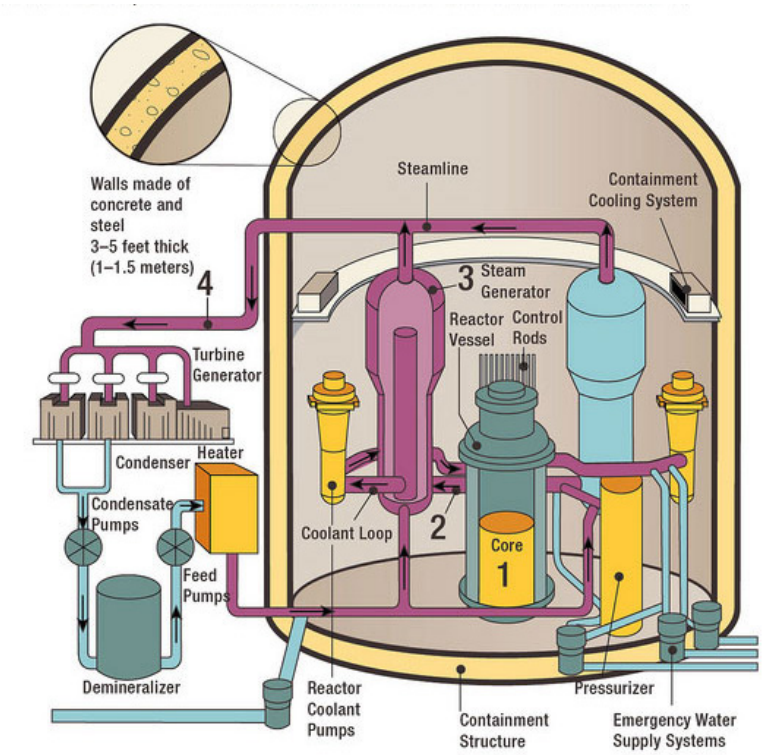
a new fission, the chain reaction is self-sustaining and it provides a considerable and constant amount of heat, the reactor is said to be "critical".

1.2 Converting the nuclear heat to electricity

In PWRs (see figure 1.1), the fission products, contained in the fuel rods, transform their kinetic energy into heat and heat the water in the primary circuit, which reaches an average temperature of 300°C. Thanks to the pressurizer, the water is kept under pressure (155 bars) to avoid boiling. Beyond playing a moderator role, this water also serves as a coolant (heat carrier): it extracts the heat from the reactor core and transfers it to the water in the secondary circuit through the steam generators (large heat exchangers made up of thousands of tubes in the shape of an inverted U). This secondary water is then transformed into steam. The two circuits are hermetically separated from each other.

The steam produced in the steam generators then expands through several turbine bodies which drive an alternator. It is the latter that transforms mechanical energy into electricity, which will supply the high-voltage network.

Figure 1.1
Main systems of a Pressurized Water Reactor
(Image from US Nuclear Regulatory Commission)



After activating the turbines, the steam is "sucked in" by the depression created in the condenser. In contact with the thousands of tubes of the condenser, the steam is condensed thanks to the cooling water from a tertiary circuit. The water from the secondary circuit is then rerouted to the steam generators.

In most cases, the cooling water is simply pumped from a large river or the sea before being released. In some cases, in order to reduce the heat released to the environment, a cooling tower is used to cool the tertiary water thanks to evaporation. Only 1.5% of this non-radioactive water escapes from the cooling tower in the form of vapor: this is what is commonly called the plume. The remaining water can be released to the environment or reused to cool the condenser again in a “closed circuit” .

It is also sometimes possible to avoid the use of cooling water by using air-cooled condensers, but this case is rather rare for nuclear power plants.

1.3 Reactivity control and decay heat removal

Reactivity[3] in a PWR is controlled by two means: control rods and boric acid. Control rods are made of materials that absorb neutrons and are used to control reactivity in a fast way. They are moved inside the fuel assemblies to maintain the reactivity at the desired level and, in case of an anomaly, they drop by gravity and instantaneously stop the chain reaction. That’s the emergency stop.

Boric acid, which is a good neutron absorber, is used to control the reactivity in the longer term. Indeed, during the operation of the plant between two refueling outages (12 to 24 months), the fuel burns out and the reactivity decreases slightly. To compensate for this decrease of reactivity, the concentration of boric acid dissolved in the primary water is regularly decreased. The concentration of boric acid is also adapted for load variations. Moreover, in case of accident, boric acid may be injected as a second way of stopping the chain reaction and to be sure that the reaction cannot restart.

Even when a reactor has been stopped, it must be cooled down because of the decay heat. Indeed, fission products contained in the fuel continue to emit radiations which heat the fuel. Directly after shutdown, the decay heat is about 6% of the nominal heat produced by a reactor in operation. It decreases with time ~~and is~~ to around 0,6% one day after shutdown. This decay heat can be removed by different ways.

In case of normal shutdown (e.g. for outage), the heat will be removed by the steam generators. They will be cooled by the secondary water in the beginning of the shutdown, then by the auxiliary water. Once the temperature and pressure in the primary circuit have been sufficiently lowered, the shutdown cooling system will be activated. It will cool permanently the reactor fuel until it is displaced to the spent fuel pool.

In case of accident, the same cooling procedure applies, except if cooling by the steam generators is impossible or in case of a breach in the primary circuit. In these cases, the safety injection system will be used to inject cold water and boron into the reactor.

[3] A term expressing the departure of a reactor system from criticality. A positive reactivity addition indicates a move toward supercriticality (power increase). A negative reactivity addition indicates a move toward subcriticality (power decrease).

2 Fast Reactors compared to Thermal Reactors

A fast-neutron reactor (FNR) or fast-spectrum reactor is a category of nuclear reactor which uses fast neutrons to sustain the chain reaction, as opposed to slow or thermal neutrons used in thermal-neutron reactors. Such a fast reactor doesn't need a neutron moderator, but requires fuel that is relatively rich in fissile material when compared to that required for a thermal-neutron reactor.

FNRs designs must therefore rely on coolants that do not contain light elements to avoid moderation effects on the neutrons. Water (which has a high content of hydrogen, the lightest of all elements) is thus prohibited, and other coolants such as liquid sodium or lead must be used instead.

In thermal reactors, most fission reactions involve U-235. U-238, which constitute about 95% of the fuel, produces heavier elements by neutron capture. Some of them are fissile (Pu-239 for example) but others are difficult to fission in thermal reactors and they thus accumulate. These minor actinides such as curium, neptunium and americium ultimately stay within the generated radioactive waste. Some of them have very long half-life and are responsible of the long-term (~100.000 years) radiotoxicity of the waste.

In fast reactors, Pu-239 is the fissile element which is used in a matrix of U-238. The heavier elements are also more prone to fission in fast reactors, which means that minor actinides do not accumulate. While it is beneficial from a waste perspective, the major advantage of fast reactors is a better use of the uranium. While a thermal reactor uses only about 1% of the uranium (mainly isotope 235), fast reactors can virtually consume all the uranium converted in Pu-239, through multi-recycling, leaving as final waste almost only fission products. The resulting waste is then reduced in volume and has a lower time of toxicity[4] compared to waste from thermal reactors.

Fast reactors can be designed to be "breeders", producing more fuel than they consume and so feeding other thermal reactors. Recycling spent fuel and relying on fast reactors would provide for thousands of years of fuel without the need to mine new resources. They can also be designed to "burn" the minor actinides produced by thermal reactors in a process called transmutation. This is what the Belgian MYRRHA project is intended for, and it will be described in another chapter.

3 Current Existing NPPs

3.1 The reactor families

In November 2023, there were 412 reactors in operation worldwide (see Figure 3.1), spread over 31 countries and representing an installed capacity of 370170 Megawatts, as well as 58 facilities under

[4] A few hundred years.

construction[5]. Nuclear energy provides about 10% of the total world electricity consumption. The operational reactors belong to different families.

A family is characterized by the techniques used to produce electricity in a nuclear reactor. Three constituents define it: the fuel, the moderator and the coolant.

The **PWR** (Pressurized Water Reactor) is the most important family of reactors in operation worldwide. Its coolant and moderator are water under pressure. Another important family is the **BWR** (Boiling Water Reactor), where the coolant and the moderator are boiling water. Then there are other reactor families:

- the **Gas Cooled Reactor**, cooled by carbon dioxide and moderated by graphite,
- the **High Temperature Gas-cooled Reactor**, cooled by helium and moderated by graphite,
- the **Pressurized Heavy Water Reactor** (also called CANDU), cooled and moderated by heavy water under pressure,
- the **Fast Neutron Reactor**, without moderator and cooled by liquid metal (generally sodium),
- and the **Light Water Graphite Reactor** (LWGR or RBMK in Russian).

All families are thermal reactors, except the FNR. The CANDU is the only family using natural uranium. The other families use enriched uranium and in some cases plutonium.

Figure 3.1

Number and capacities of the different reactor families
(Source IAEA PRIS - November 2023)

Reactor type	Description	Total MWe	Number
BWR	Boiling Light-Water Cooled and Moderated Reactor	43071	41
FNR	Fast Neutron Reactor	1380	2
GCR	Gas Cooled, Graphite Moderated Reactor	4685	8
HTGR	High Temperature Gas Cooled Reactor	200	1
LWGR	Light-Water Cooled, Graphite Moderated Reactor	7433	11
PHWR	Pressurized Heavy-Water Moderated and Cooled Reactor	24093	46
PWR	Pressurized Light-Water Moderated and Cooled Reactor	289308	303
Total		370170	412

[5] https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByRegion.aspx

3.2 European situation

The 100 nuclear power reactors (97 GWe) operating in 12 of the 27 EU member states account for about one-quarter of the electricity consumed in the whole of the EU, and for 40% of the EU's carbon-free electricity (see figures 3.2 and 3.3). Two reactors are currently under construction (France, Slovakia), seven are planned (Bulgaria, Czech Republic, Finland, Hungary, Romania) and 25 are proposed. To these current and future reactors, we can add those in operation in Russia (37), Belarus (2), Switzerland (4), Ukraine (15) and UK (9). In these countries, 11 reactors are in construction if we include the 4 in Türkiye[6].

Other countries are considering the option of nuclear energy, such as Italy, Estonia, Lithuania, Croatia. We should also mention the EU Nuclear Alliance, composed of 14 EU countries (plus UK, and Belgium as observer at the end of 2023) which promotes reaching 150 GW of nuclear capacity in the EU by 2050.

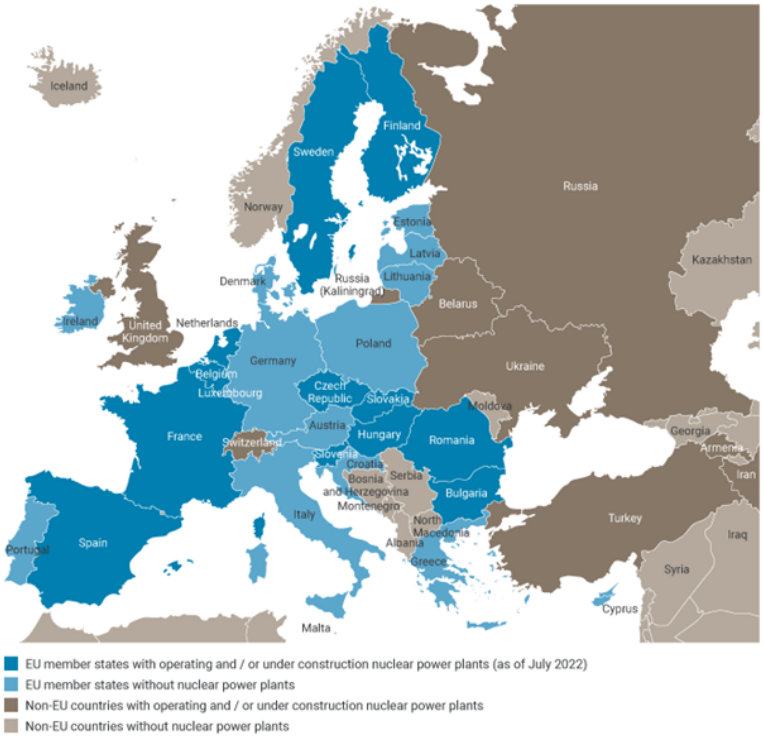
On the other hand, there are also countries that are fundamentally against nuclear energy. Among them, Germany, Luxemburg, Austria and Spain (which still operates 7 units).

The European reactors belong mainly to the PWR family. Indeed, on the 157 reactors currently in operation, only 8 are BWRs (Spain, Sweden, Switzerland, Finland), 8 are GCRs (UK), and 2 are CANDUs (Romania)[7].

Figure 3.2

Status of nuclear energy utilization in European countries

(Image from World Nuclear Association)



[6] https://world-nuclear.org/information-library/country-profiles/others/european-union.aspx

Figure 3.3

Status of nuclear energy utilization in the European Union

(Source World Nuclear Association)

Reactors in the European Union	Nuclear electricity generation		Reactors operable		Reactors under construction		Reactors planned		Reactors proposed	
	2021		April 2023		April 2023		April 2023		April 2023	
	TWh	% e	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross
Belgium	48.0	50.8	5	3928	0	0	0	0	0	0
Bulgaria	15.8	34.6	2	2006	0	0	1	1000	3	3000
Czech Republic	29.0	36.6	6	4212	0	0	1	1200	3	3600
Finland	22.6	32.8	5	4394	0	0	1	1170	0	0
France	363.4	69.0	56	61,37	1	1650	0	0	6	9900
Germany	65.4	11.9	0	0	0	0	0	0	0	0
Hungary	15.1	46.8	4	1916	0	0	2	2400	0	0
Lithuania	0	0	0	0	0	0	0	0	2	2700
Netherlands	3.6	3.1	1	482	0	0	0	0	2	2000
Poland	0	0	0	0	0	0	0	0	6	6000
Romania	10.4	18.5	2	1300	0	0	2	1440	1	720
Slovakia	14.6	52.3	5	2308	1	471	0	0	1	1200
Slovenia	5.4	36.9	1	688	0	0	0	0	1	1000
Spain	54.2	20.8	7	7123	0	0	0	0	0	0
Sweden	51.4	30.8	6	6885	0	0	0	0	0	0

3.3 Belgian nuclear history and current situation

The first Belgian power reactor, commissioned at the Mol research center, was the BR3 (Belgian Reactor nr 3). The original intention was to install it on the World Exhibition 1958 site in Brussels, but this idea was finally abandoned. With a gross power of 11.2 MWe, it was connected to the network in October 1962. This first European PWR (first outside the United States), whose operation was firstly ensured by electricity producers, among other things, allowed originally to train the personnel of the future Doel and Tihange power stations. From 1963, it was also used to test MOX fuel (mixture of oxides of uranium and plutonium) and other innovative fuel types under real conditions. It was permanently shut down in 1987, after 11 operating cycles. The BR3 has not, however, fallen into oblivion; it has been designated as a pilot facility and project for research on the dismantling of reactors by the European Commission. A large part has already been dismantled including several world premieres.

At the time of the start-up of the first reactors, electricity production in Belgium was provided for three quarters by coal, a large part of which came from Belgian mines. But the decline of the coal mines was already beginning and at the same time the consumption of electricity continued to grow. From 1950 to today, global electricity consumption has increased twelvefold. This growth was rapid until 1973 (first oil shock), after which it slowed to a more moderate pace. Keystone of industrial development in Europe in

the nineteenth century and during the first half of the twentieth, coal was gradually replaced by other energy sources from the 1960s.

However, to produce electricity, uranium quickly appeared in the eyes of officials as an alternative to national coal. The quantities of electricity that nuclear power is likely to produce made it possible to envisage the future with serenity. The first commercial nuclear power plant built by the Belgians in collaboration with the French is located in the boot of Givet, in Chooz, on the banks of the Meuse River. This PWR plant, whose reactor was the most powerful in the world at the time (242 MWe), began to supply electricity to the grid in 1967. It was definitely shut down in 1991.

The Chooz power plant, called Chooz A, has enabled the Belgians and the French to acquire know-how and experience both in the manufacture of equipment intended to equip future nuclear installations, but also in the management of a nuclear power plant. After the commissioning of Chooz A, the Belgians decided to launch their nuclear power program. Two sites were selected: Doel on the left bank of the Scheldt downstream from Antwerp and the industrial estate of Tihange on the right bank of the Meuse, upstream from Liège.

In 1968, Doel 1 and 2 were ordered. The work started by creating 80 hectares of reclaimed polder area. The dikes were increased in height to 11 meters above sea level. Construction started in 1969 and in 1970 the first staff were recruited. The Doel 1 reactor was commissioned in early 1975 and later that year Doel 2 also followed. Doel 3 went online in 1982 and in mid-1985 Doel 4 was fully operational.

Doel 1 and 2 are fully owned by Electrabel. Doel 3 and 4 are largely owned by Electrabel (89.8%) and partly by EDF.

In accordance with the law on the nuclear phase out, unit 3 (1006 MW) of the Doel nuclear power plant was definitively disconnected from the electricity grid on Friday September 23, 2022, after 40 years of operation. Doel 3 is therefore the first Belgian nuclear power plant to definitively stop producing electricity.

Figure 3.4

The 4 Doel units

	Doel 1	Doel 2	Doel 3	Doel 4
Capacity (MWe)	445	445	In decommissioning	1039
In service date	15/02/175	01/12/1975	01/10/1982	01/07/1985
Closure date	15/02/2025	01/12/2025	01/10/2022	1/11/2035
Share Electrabel/EDF (%)	100/0	100/0	90/10	90/10

In 1968, Tihange 1 was ordered. The power station was commissioned in 1975, just in time to reduce Belgium's dependence on oil. Tihange 2 went online in mid-1983 and Tihange 3 followed in 1985.

Tihange 1 is owned 50/50 by EDF and Electrabel. This cooperation between France and Belgium started with the construction of the Chooz nuclear power plant in France. Tihange 2 and 3 are largely owned by Electrabel (89.8%) and partly by EDF.

On January 31, 2023, Tihange 2 (1008 MW) was shut down in accordance with the law on nuclear exit.

Figure 3.5

The 3 Tihange units

	Tihange 1	Tihange 2	Tihange 3
Capacity (MWe)	962	In decommissioning	1038
In service since	01/10/1975	01/02/1983	01/09/1985
Closure date	01/10/2025	01/02/2023	*1/9/2035*
Share Electrabel/EDF (%)	50/50	90/10	90/10

In 2023, the 5 Belgian nuclear power plants in operation together produce about a third of the country's total electricity consumption, with little CO_2 emissions. Nuclear energy is important for Belgium, for guaranteeing the electricity supply 7 days a week and 24 hours a day, for achieving the climate objectives, for the competitiveness of electricity prices and for local employment.

In December 2023, an agreement was signed between the Belgian Government and ENGIE Electrabel for the lifetime extension of Doel 4 and Tihange 3, which will now operate until 2035. Both parties also agreed to form a 50/50 joint venture, BE-NUC. The joint venture will take ownership of the units, while ENGIE Electrabel remains the nuclear operator of Doel 4 and Tihange 3.

3.4 Technical characteristics of the Belgian units

All the Belgian units are PWRs designed Westinghouse (Doel 1-2, Doel 4, Tihange 1 and Tihange 3) and Framatome (Tihange 2 and Doel 3). They all have a double wall confinement and an internal steel liner, with an aim to reduce radiological releases in case of accident and make it robust against external hazards such as explosions or airplane crashes.

Doel 1-2 are twin units, with each two loops and shared circuits (safety and non-safety) between the units. Tihange 1 is a three-loop unit with two safety trains while the other units have three loops with three safety trains.

The most recent units (Doel 3 and 4, Tihange 2 and 3) have the particularity to be designed, from the origin, with two levels safety systems. The first level is intended to cope with accidents from internal origin. The second level, totally independent from the first one, is designed to automatically maintain the reactor in a safe state after an external event (explosion, flooding, tornado, airplane crash, …).

For the oldest units, a partial second level was added after the first periodic safety review (10 years of operation) and was improved after the 10-year lifetime extension decided by the government in 2012-14. By doing this, they reached the same level of safety than the most modern Belgian units.

Thanks to this concept, the Belgian plants can be considered as among the safest plants of their generation.

Safety has also been improved after the Fukushima accident. Indeed, the stress tests organized at the European level have led to improvements of the nuclear safety of the units to make them resistant against the most extreme situations. These improvements are the following:

- All reactor buildings are equipped with a special filtering system, which – in the very unlikely event of a severe accident – reduces the possible emission of radioactive particles to an absolute minimum.
- The plants have additional protections against flooding. Specifically in Tihange, a wall has been built to protect the entire site from flooding during an exceptionally high water level of the Meuse River. The complex structure is 2.3 meters high and 1.8 kilometers long and is equipped with locks, drains and pumps.
- The fire safety infrastructure has been expanded.
- New earthquake-resistant buildings with additional safety features for exceptional external conditions have been constructed, consisting of both mobile (diesel generators, pumps, firefighting equipment and vehicles, etc.) and fixed equipment (e.g., additional control room in bunker).
- The earthquake resistance of key safety systems has been improved.
- Certain safety systems have been expanded, for example, those that ensure the cooling of the reactor core in accident conditions.
- At both sites, staff training programs and emergency planning organization were strengthened to manage events at several units simultaneously.

3.5 Gen III reactors

The nuclear sector is characterized by proposals for the short term and projects for the long term. For the new types of reactors, a distinction is made between evolutionary reactors and revolutionary reactors. The first are reactors derived from the reactors currently in operation, designed according to the same principles and capitalizing on the experience acquired over several decades on a number of large reactors. These so-called evolutionary reactors are also referred to as Generation III reactors. On the contrary, the second, the so-called revolutionary or Generation IV reactors, are designed as a major technical evolution with respect to the current reactors. They are planned to be commissioned from around 2035, as discussed in the next chapter.

Generation III reactors are an improvement on the previous generation and are optimized according to the most recent regulations. In addition to improved safety, post-accidental conditions following core meltdown are explicitly considered in the design of these reactors, which therefore have the means to limit the consequences of such situations. These plants integrate as design-basis the lessons learnt from the Fukushima accident, while the previous generation of plants have had to make design modifications after the post-Fukushima stress tests.

These designs include the EPR from Electricité de France, the VVER-1200 from Rosatom, the APR1400 from Korea Hydro and Nuclear Plant, the HPR1000 from China General Nuclear Power Corporation and the Chinese National Nuclear Company, the ABWR from General Electric Hitachi and the AP1000 from Westinghouse which are all operational in one or more locations around the world. To this list, we can

also add the Chinese CAP1000 and CAP1400 which are derivatives of the AP1000 and are under construction in China.

The first Generation III reactors were put into operation between 2010 and 2022 (Belarus, China, Finland, Japan, Pakistan, Russia, South Korea, United Arab Emirates). In 2023, more than 40 were under construction worldwide (USA, United Kingdom, France, Hungary, Türkiye, etc.).

Figure 3.6

The two AP1000 units of the Vogtle Nuclear Power Plant

(Image from Georgia Power Company)

Figure 3.7

The Olkiluoto-3 Nuclear Power Plant

(Image from Teollisuuden Voima Oyj)

4 Generation IV Reactors

With a medium-term outlook, the reactors currently under study share the characteristic that they are not yet operational, except in a few countries. They require extensive research, development, and testing—initially on a reduced scale and later on an industrial scale. For this reason, these projects are collectively referred to as Generation IV.

To ensure their success, the reactors of the future will have to open to new markets, thanks to new applications such as the production of process heat, hydrogen or for the desalination of seawater for large urban agglomerations. They will also have to be part of a sustainable development perspective by consuming fuel more efficiently than current reactors while producing less waste.

A wave of projects was launched at the initiative of the Department of Energy (DOE) of the United States in 2001, entitled Generation IV Nuclear Energy Systems Initiative, which succeeded in federating around itself a set of research organizations of 10 countries in an informal cooperation structure called the GIF (Generation IV International Forum). Six reactor-fuel systems have been selected by the GIF; to put it simply, we can say that there is a light water reactor, a (very) high temperature (up to 1000°C) gas-cooled reactor, three fast neutron reactors which save a factor of 100 available resources and a molten salt reactor which is very economical in fuel consumption (thorium or uranium).

Two sodium-cooled fast reactors are already in operation in Russia and one lead-cooled fast reactor is under construction. China has recently built a demonstrator of high temperature gas-cooled reactor and is building an experimental molten salt reactor. Japan is also operating a research high temperature gas-cooled reactor.

In Belgium, SCK CEN wishes to contribute to the development towards a sustainable use of nuclear energy by building a new research facility, which will be used, among other things, in research on materials and fuel for future reactors. This innovative system, called MYRRHA, is based on a lead-cooled fast reactor and involves a particle accelerator. This project will also demonstrate the industrialization of Generation IV technology and the possibility of transmuting minor actinides on large scale.

Figure 4.1

The 6 Generation IV Systems

(Source Generation IV International Forum)

System	Neutron spectrum	Coolant	Outlet Temperature °C
VHTR (Very-high-temperature reactor)	Thermal	Helium	900-1000
SFR (Sodium-cooled fast reactor)	Fast	Sodium	500-550
SCWR (Supercritical-water-cooled reactor)	Thermal / fast	Water	510-625
GFR (Gas-cooled fast reactor)	Fast	Helium	850
LFR (Lead-cooled fast reactor)	Fast	Lead	480-570
MSR (Molten salt reactor)	Thermal / fast	Fluoride / chloride salts	700-800

5 Small Modular Reactors

In the short and medium term, the future of nuclear energy could partly rest on Small Modular Reactors. This is a concept, not a technology, which implies small, standardized and manufactory-built nuclear reactors be deployed at large scale in several countries. This concept looks at series effect rather than scale effect as with traditional large reactors. But for this to appear, an “harmonization” of the licensing regimes in the interested countries will be necessary, at least in Europe, in order to avoid duplicating the licensing work and be able to use the same design for each project.

Beginning 2023, the IAEA counted about 80 SMR designs under development, at different design stages, and with different technologies. The OECD NEA has developed a dashboard to follow the progress in the development of these SMRs. While a large part of the SMR designs are based on light water reactor technology, all Generation IV technologies are present within the 80 designs.

The most mature projects are those based on light water and high temperature gas-cooled technologies (one is already operational in China), but developers of lead- or sodium-cooled fast reactors and molten salt reactors are aiming to operate their first-of-a-kind reactors by early 2030s.

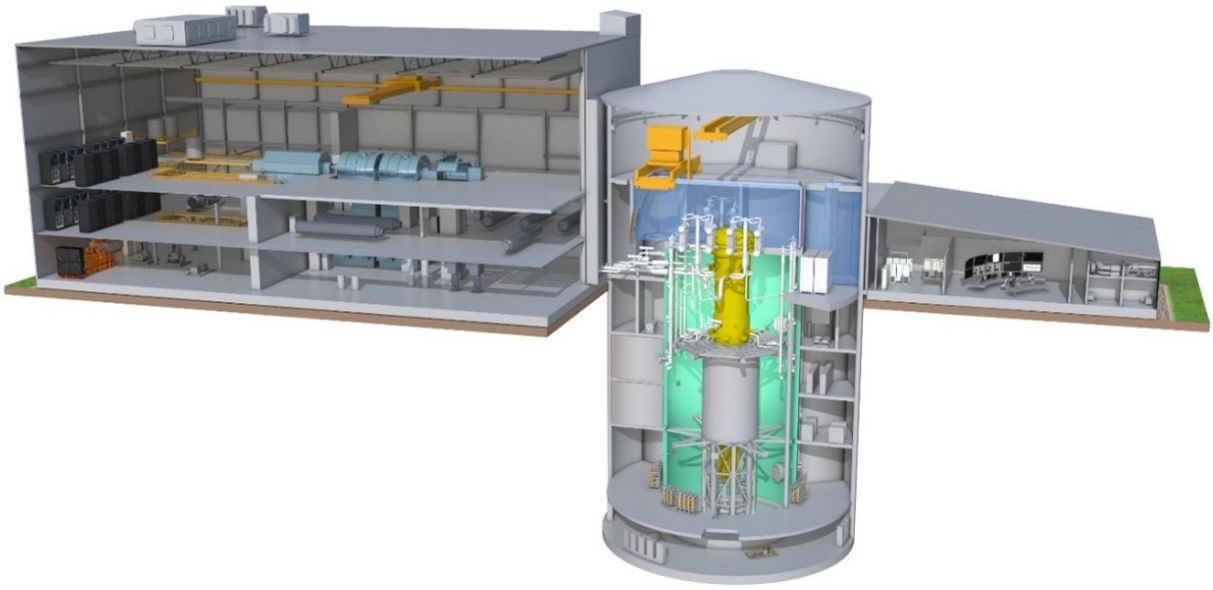
The most advanced countries are Russia and China, with each one SMR in operation and several projects in development.

In Canada, the most advanced projects are those led by Ontario Power Generation. According to their plan, a Micro-Modular™ Reactor developed by Ultra Safe Nuclear Corporation should be operational at Chalk River Laboratories by 2027 and a BWRX300™, developed by GE-Hitachi Nuclear Power, by 2028 at Darlington.

Figure 5.1

The BWRX-300™[7]

(Image from GE Hitachi Nuclear Energy © 2023)

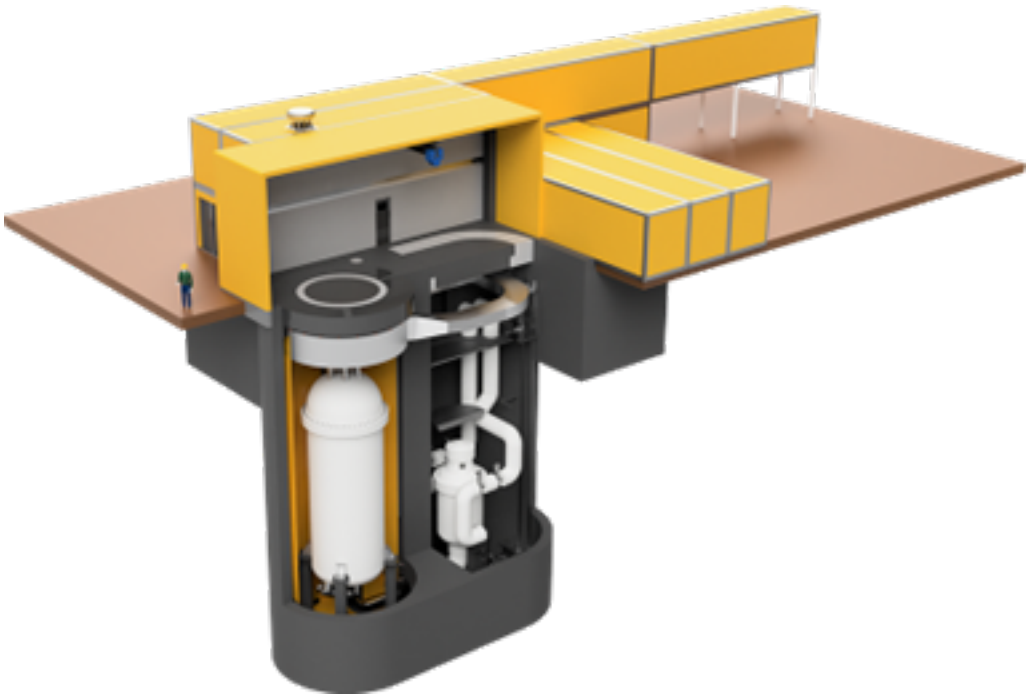


[7] The BWRX-300™ is a boiling water reactor producing 300 MW of electricity.

Figure 5.2

The Micro-Modular™ Reactor[8]

(Image from Ultra Safe Nuclear Corporation © 2023)



In the US, the most advanced project is the one of NuScale Power, with 4 to 12 VOYGR™ modules (77 MWe each) installed in a common pool. The NuScale technology (a previous version of 60 MWe) is the only western technology already certified by a regulator, the Nuclear Regulatory Commission.

In Europe, the two main developers are the NUWARD™ consortium, led by Electricité de France, and Rolls Royce SMR. There are also several projects involving US technologies. Moreover, the SCK CEN has partnered with Italian (ENEA Ansaldo) and Romanian (Raten) companies to develop a lead-cooled SMR.

[8] The Micro-Modular™ Reactor (MMR®) is a flexible high-temperature gas-cooled micro reactor capable of producing up to 45 MWt heat and up to 15 MWe electric power.

Figure 5.3

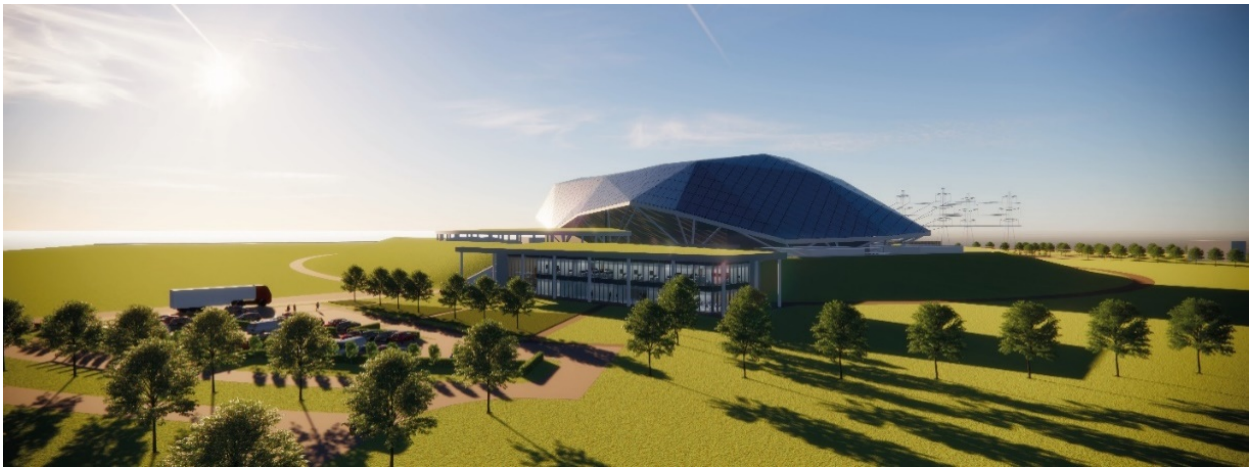
The NUWARD[9]

(Image from NUWARD © 2023)

Figure 5.4

The Rolls Royce SMR[10]

(Image from Rolls Royce plc © 2023)



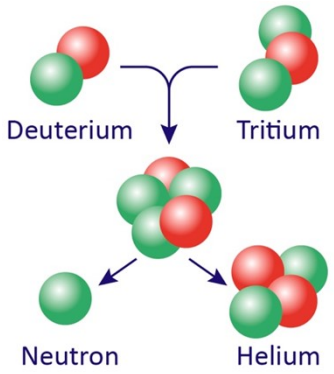
[9] The NUWARD Reactor is a twin pressurized water reactor (2*170 MWe)

[10] The Rolls Royce SMR is a pressurized water reactor (470 MWe)

6 Fusion reactors

The fusion of two light nuclei into a heavier nucleus is a source of (nuclear) energy like the fission of a heavy nucleus. It is even the most widespread source of energy in the universe since it is the basis of the immense production of energy created within the sun and the stars. Unlike fission, which involves a neutral particle, fusion involves charged particles of the same sign exerting repulsion forces between them. To overcome these forces and put the nuclei concerned "in presence", at distances such that the fusion mechanism is triggered, it is necessary to raise the temperature of the medium (called plasma) to very high values: a few tens of millions of degrees. Different possibilities exist to "confine" the plasma: either the use of intense magnetic fields, or the use of laser beams which, in addition to confinement, have the effect of compressing the plasma, to trigger the fusion process. In the first case we speak of magnetic confinement; in the second, of inertial confinement. A simple statement of the principle makes it possible to glimpse the (technological) difficulties of carrying out the process. If this were perfectly mastered, humanity would have an almost inexhaustible source of energy.

The most common[11] reaction applied to fusion reactors is called the D-T reaction: a deuterium nucleus (hydrogen with 1 neutron) and a tritium nucleus (hydrogen with 2 neutrons) are transformed into a helium nucleus, energy, and a neutron.



As for the fuel, deuterium is very abundant, in particular in seawater, while tritium can be produced in fusion reactors, by using lithium. Both can guarantee energy production for millions of years. In addition, there is no long half-life radioactive waste produced. Unfortunately, it is impossible to predict the price of fusion power today. In particular, the economic competitiveness of fusion in the future will depend closely on the cost of other means of electricity production.

Fusion has been the subject of advanced research since the early 1950s, particularly in Europe; combined with feedback from the JET20 project and other experimental reactors, these efforts have enabled the design of an experimental reactor of the Tokamak type, bearing the name of ITER (International Thermonuclear Experimental Reactor). The objective of this international project supported by the

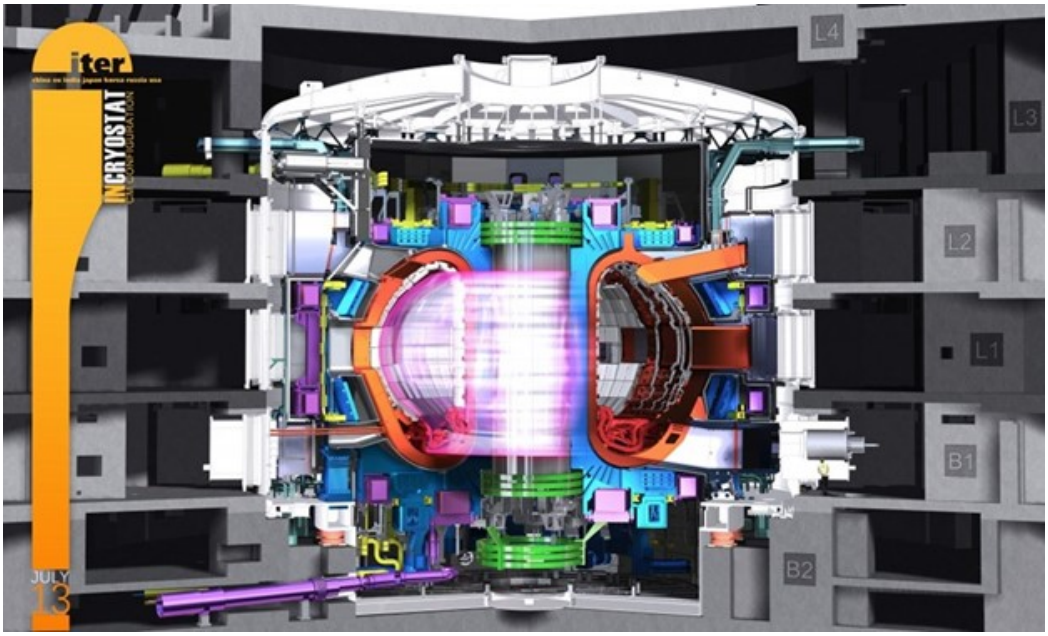
[11] Other reactions are possible : deuterium – deuterium, deuterium – helium 3 (helium with a missing neutron, which can be found on the moon or produced), and hydrogen – boron 11 (one of the natural isotope of boron).

European Community is to demonstrate experimentally that nuclear fusion is credible as an energy source. ITER is currently being built at Cadarache in the south of France, with the participation of Belgium (Tractebel). First fusion experiments should start around 2035 and a commercialization of fusion reactors based on ITER could be envisaged by 2050.

Figure 6.1

The ITER Tokamak

(Image from ITER Organization)



For several years, many private companies are developing fusion reactors with an aim to have a reactor operational in the 2030s. Although they are attracting a lot of private funding and some of them have made interesting achievements so far, it is difficult to predict if and when they will reach their goal.

Fusion, which has many advantages both in terms of safety and in terms of environmental impact, is undoubtedly a means of energy production of the future in the perspective of continued sustainable development.