Electronuclear technology in France today

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Existing French nuclear power stations are pressurized water reactors. Before being put in the reactor, the uranium-containing fuel source has been through a lengthy process starting at the mine. It passes through a series of enrichment steps before being processed into fuel rods. After being irradiated in the reactor the spent fuel is separated and treated for disposal. Additional processing steps are required if the plutonium is to be recycled and used as fuel, as is the case in France.

Nuclear Fuel

The energy density of nuclear fuel

The fission of a uranium atom releases a considerable amount of energy per unit of mass, 100,000 times more than the most concentrated fossil fuels. Thus, in our current nuclear reactors, a single uranium fuel pellet of a few grammes can provide as much thermal energy as five barrels of oil[(a)] (fig. 1). This accounts for two advantages of nuclear power: it uses only small quantities of natural resources and consequently its price does not fluctuate greatly.

However, whilst air combustion of hydrocarbons is relatively simple, the use of nuclear power requires sophisticated technical skills. Radioactive elements must be controlled throughout the nuclear fuel chain to prevent them from having any harmful effects on either humans or the environment. Care is needed especially when the spent nuclear fuel is unloaded from the reactor due to the presence of highly radioactive elements, albeit in small quantities.

The raw material uranium

Uranium is a 'heavy' chemical element, i.e. it has a large nucleus. It is relatively abundant in the earth's crust, about the same as tin[(b)]. Uranium deposits are found throughout the world. Some deposits are very rich, with high-grade ores containing more than 20% uranium, for example Cigar Lake in Canada. Uranium is obtained by mining, using extraction techniques similar to those for other metals, but which allow for the fact that radioactivity from the radon is released into the atmosphere.

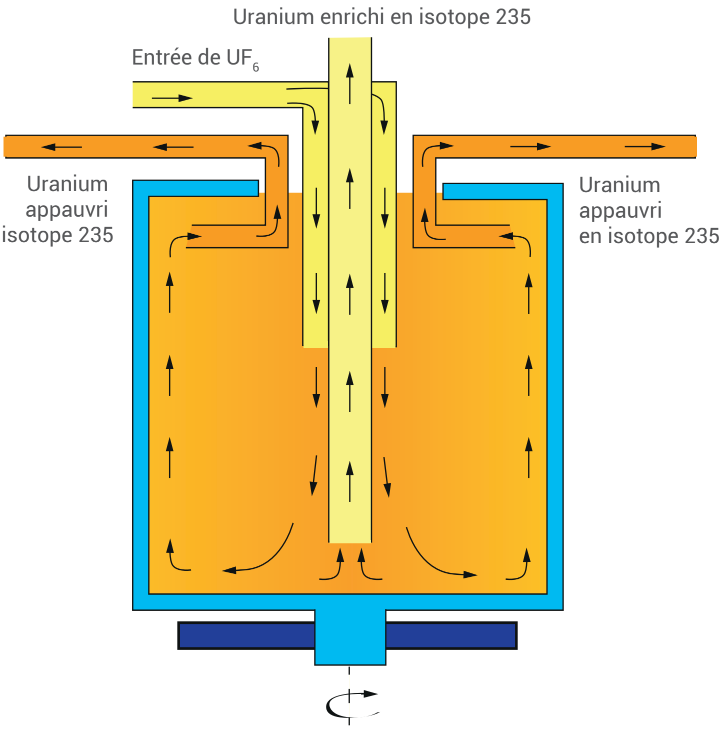
As the current contribution of nuclear power to electricity generation and more broadly to global energy output is small,

1. Image showing the size of an enriched uranium oxide pellet used in the production of nuclear fuel in a pressurized water reactor. For a given amount of energy, nuclear power uses 100,000 times less raw material than fossil fuels (oil, gas or coal).

2. The uranium ore extracted from the mine is milled and chemically-processed to produce 'yellowcake'.

uranium doesn't yet pose a significant supply problem[c]. The amount of uranium extracted from the earth, typically 60,000 tons per year, is low compared to other minerals or energy resources, which are usually in the billions of tons.

In theory, all the uranium ore required to supply the reactors in France annually could be extracted from French soil[d]. It could even be extracted from seawater, the practical limitations being the economic and energy costs. In the mines currently in operation around the world, uranium is cheap (less than 100€ per kg) and accounts for less than 3% of the cost of nuclear power per MWh[e]. Thus, unlike fossil fuels, what determines energy independence is not access to the raw material, but rather access to the specific technologies (reactors and power plants) which enable its exploitation.



3. Scheme of a centrifuge for uranium enrichment.

'Upstream' of the reactor (conversion, enrichment, fuel production)

Natural uranium is made up of three isotopes: uranium-234, present at ultra-trace levels, uranium-235, naturally present at 0.7%, and uranium-238, the most abundant form of uranium[f]. However, only isotope U-235 is fissile, i.e. can split into two parts following the absorption of a neutron into the atomic nucleus, releasing energy. It is the only fissile atom on the planet; although radioactive, it has been around since the formation of the earth due to its long half-life of 700 million years[g]. Uranium is said to be "enriched" when the proportion of its fissile atoms is increased. It is necessary to reach 4% fissile atoms in the fuel in order to maintain a chain reaction in a light water reactor.

In order to do that, the uranium must first be converted into uranium hexafluoride (UF_6), a compound which has the advantage of readily turning into a gas: it goes directly from a solid state to a gaseous state as soon as the temperature exceeds 56.4 °C. The fluorination of uranium to convert it to UF_6 is carried out in the Comurhex plant at the Malvési (Aude) then Tricastin (Drôme) sites.

Once uranium is in the gaseous hexafluorine form, the enrichment step can be carried out using ultracentrifugation[h]. This process uses the centrifugal force acting on the gas, which is contained in a vessel rotating at high speed around an axis (fig. 3). As the magnitude of the

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4. Nuclear fuel assembly of a pressurized water reactor with control rod. The grids provide mechanical support to maintain the 264 fuel rods.

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centrifugal force is proportional to the mass of the particles, the uranium-238 atoms, being slightly heavier, move to the periphery. The gas in the center of the vessel thus becomes richer in isotope 235, whilst the gas at the walls becomes poorer. The required 4% enriched uranium is reached through a series of successive centrifugation steps, using a cascade arrangement of ten or so centrifuges[i]. Factoring in losses, it typically takes 8 kg of natural uranium to obtain 1 kg of enriched uranium.

Once enriched, the gas is converted back into a solid powder of uranium oxide in a rotary kiln with steam at around 800 °C (pyrohydrolysis). The powder is then compacted and pressed into a cylindrical pellet about 1 cm in diameter and 1.3 cm in height (fig. 1). Sintering[j] in hydrogen at 1,750 °C completes the process by achieving the necessary porosity.

These pellets are then inserted one on top of the other into a long tube, a 4-metre long zirconium alloy sheath sealed at its ends. This "fuel rod" contains about 300 pellets. A fuel assembly consists of 264 fuel rods arranged in a 17 x 17 square (Fig. 4), with 25 free slots for 24 absorber rods to control the chain reaction (and one instrumentation tube). The core of a 1,300 MW Pressurized Water Reactor (PWR) is composed of 193 such assemblies. The European Pressurized Reactor (EPR) under construction in Flamanville consists of 241 assemblies.

Reactor Operation

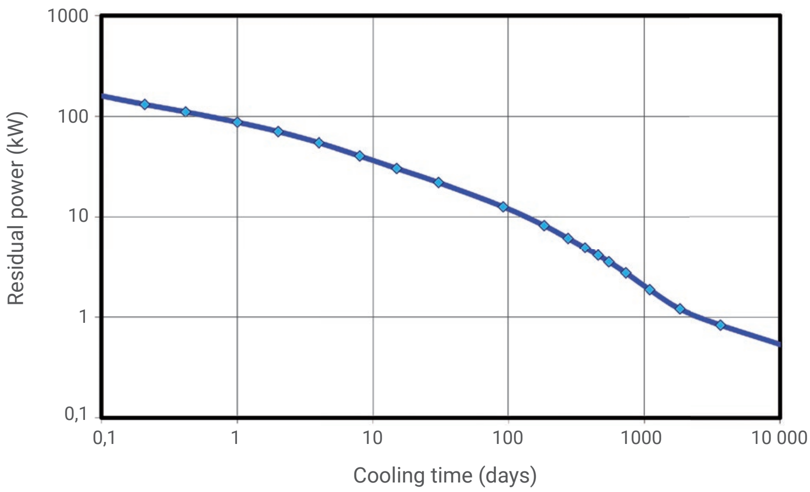
An assembly remains in the reactor core for about four years, during which time the uranium-235 nuclei fission due to an intense neutron flux produced by nuclear fission. In fact, the fission of an uranium nucleus produces an average of three neutrons. These induce the fission of other nuclei, and thus the reaction grows exponentially: it is a chain reaction.

The heat released by the nuclear reactions is carried away by a liquid, the coolant, which circulates in a closed system: this is the primary coolant system, in which the liquid becomes radioactive. To avoid contamination, this liquid passes through a heat exchanger, known as a "steam generator", which transfers the heat to a second liquid: this is the secondary coolant system. Following the same principle as in a conventional thermal power plant, because of the temperature difference between the steam generator and the source of cooling (river or sea water, or the air in the cooling towers), the coolant is able to drive a turbine that produces electricity. In the end, as in a thermal power plant, about one third of the reaction energy is actually converted into electricity; the remaining two thirds heat the atmosphere.

For electricity production, the chain reaction must be carefully regulated so that it does not run out of control. To achieve this, only one of the neutrons produced can be allowed to trigger another fission. The reactor core is then said to be "critical", a term with a positive connotation indicating that its operating regime is exactly at the desired limit. It is neither too weak nor too strong and can continue to function for as long as there is fuel remaining.

This control is ensured by fine dosing of neutron absorbing elements: either boron in the water of the primary coolant system, cadmium in the control rods, or gadolinium in the fuel. The reactor is controlled mechanically by raising or lowering the control rods in response to energy demand by the operator. This also ensures a balanced distribution of power in the core, and the absence of places where the local temperature would be too high, which could lead to boiling.

During operation of the reactor, the fissile uranium-235 gradually disappears. At the same time, because of the continuous and intense neutron radiation, a small fraction of the uranium 238, the majority isotope, is converted by neutron capture into plutonium-239, an isotope that has a high energy value since it is also fissile. When the reactor is unloaded, the spent fuel contains only 0.85% uranium-235, whereas it now contains more than 1% plutonium atoms.



5. Decrease with time of the heat released by fission products and actinides in a fuel assembly (here a 4% enriched uranium oxide irradiated at 45 GWd/t).

The high concentration of radioactive material in the core of a reactor (more than 100 tons of fuel) requires specific risk management during operation. Indeed, the most commonly considered risk in the nuclear industry is that of a major accident in a reactor during normal operation[k]. The likelihood of a possible core meltdown, although in line with estimates made at the time they were designed, 10^{-4}/year/reactor, appears in practice to be not insignificant for second-generation reactors: three major accidents in the world in 60 years, two of which caused a release of radionuclides into the atmosphere. What was considered an impossible, or at least acceptable, industrial accident in the 1970s by the proponents of nuclear power is no longer considered to be so today.

Learning from these experiences has led to improvements in safety. The Fukushima accident taught us that the loss of any cooling system and the loss of the external power supply can under certain circumstances occur simultaneously at the same facility. In the past, we guarded against either of these two events separately. Today, all operators around the world must consider the possibility of these two risks occurring simultaneously.

Therefore, the designers of the European Pressurized Reactor (EPR) focused on improving safety by reducing the probability of core meltdown by at least two orders of magnitude, at the same time doubling the construction cost (from 1,500€/kW to 3,500€/kW). If the entire current global fleet were made up of such reactors, the probability of a major accident would decrease by 100-fold from one every 20 years to one every 2000 years or more. And in the unlikely event of an accident, the radioactivity would be contained within the reactor, and therefore not require the evacuation of the surrounding population.

6. Nuclear waste container. The cylinder is made of stainless steel with a height of 1.35 m and diameter of 0.43 m. It contains about 400 kg of borosilicate glass which traps the waste. The total weight is about 500 kg.

Spent fuel

Nuclear fission and neutron irradiation generate a variety of radioactive elements inside the fuel, called "fission products", with very different half-lives. This means that when a fuel assembly is removed from a reactor core, it is highly radioactive and the fuel continues to be heated by the residual power released by this radioactivity. This heat must be removed, otherwise the assembly would melt. The assembly is immersed in a pool of water, to allow it to cool down, for 2 to 3 years, after which time the residual power of the assembly has decreased sufficiently (fig. 5) to allow it to be transported to the La Hague plant for reprocessing.

In the reprocessing plant, the spent fuel is dissolved in nitric acid. The reusable nuclear materials such as uranium and plutonium, which form the bulk of the contents, are extracted from the solution, while any remaining products, considered as the final waste of nuclear fission, are vitrified in glass and stored in containers (fig. 6).

The reprocessing of about 70% of the spent fuel in France results in the annual production of about 650 high level waste (HLW) containers of vitrified waste (see p. 21). This vitrified waste contains 98% of the total radioactivity of nuclear waste, but represents only 0.2% of its total volume[l]. Structural waste (hulls, grids, assembly tips) is compacted in similar containers and classified as long-lived intermediate-level waste. It accounts for almost all the remaining radioactivity (2%). All other waste is low-activity waste (less than 0.03% of total radioactivity).

The flow of nuclear materials

France has 58 pressurized water reactors (PWRs) (see map on p. 42), which are supplied each year with about 1,000 tons of uranium fuel enriched to 4%. The plutonium recovered from reprocessed fuel can be used as a fissile element instead of uranium-235. It is then combined with the depleted uranium to form MOX fuel (a mixture of uranium and plutonium oxides). In recent years, all of the eleven tons of plutonium produced each year have been fully recycled in the form of MOX[m] fuel. The uranium recovered at La Hague, known as reprocessed uranium (repU), now contains about as many fissile atoms as natural uranium and can therefore be re-enriched to make fuel. This re-enriched reprocessed uranium (ERU) is used to supply the four Cruas reactors in the Ardèche[n]. The general flow of nuclear materials is shown in fig. 7. ∎

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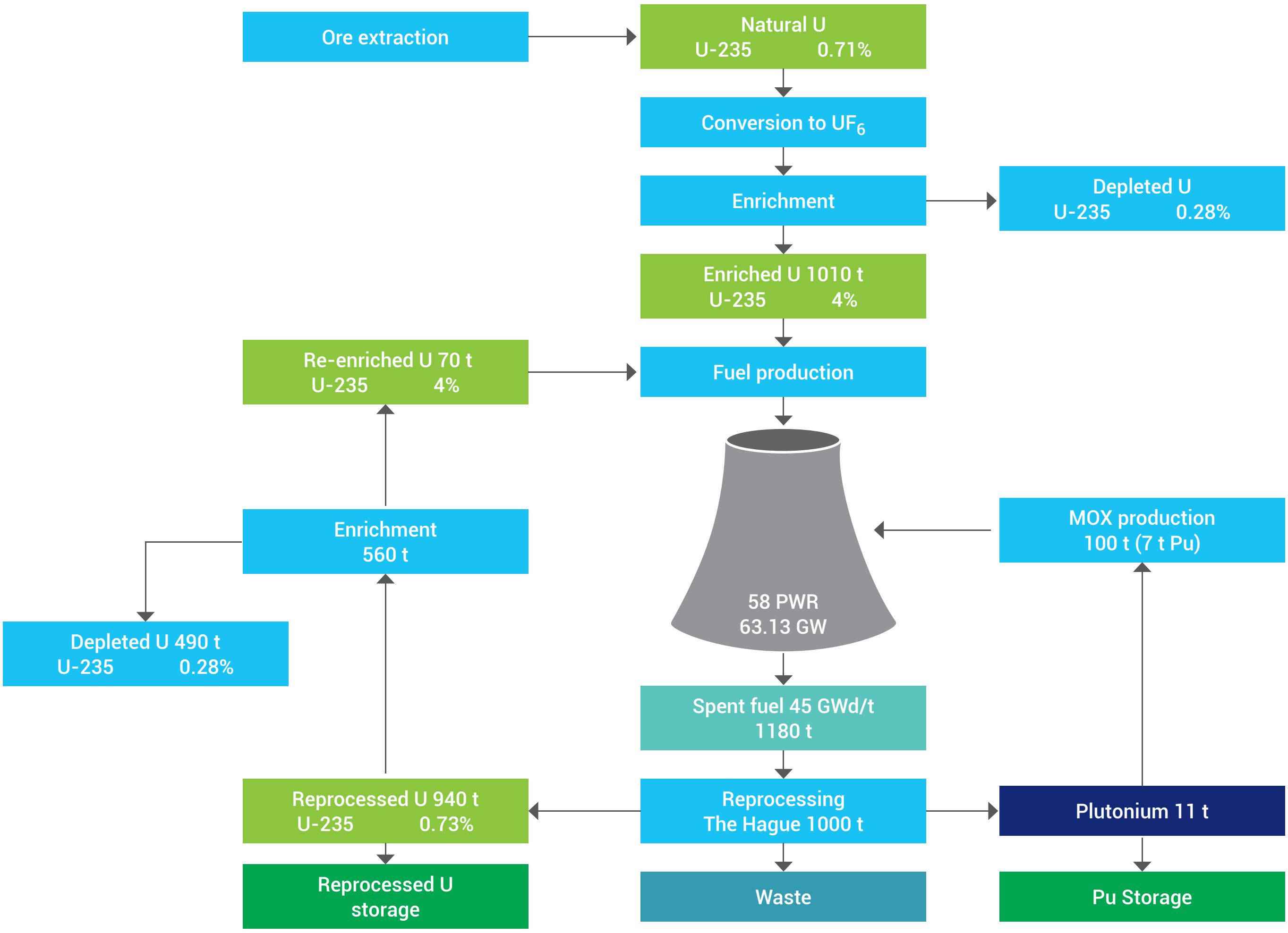

7. Annual flow of nuclear materials supplying the entire French nuclear fleet, taking 2013 as an example: from the 1000 tons of fuel in the form of uranium oxide (UOX), the recovery of plutonium enables the production of 100 tons of MOX fuel (a mixture of uranium and plutonium oxides) and 70 tons of enriched reprocessed uranium (ERU).

a. The energy density of an atomic nucleus is one billion Wh/kg. A pellet of 7.5 g of uranium enriched to 4% can provide up to 9 MWh of thermal energy, the equivalent of 5 barrels of oil or a ton of coal.

b. Uranium is present on Earth at 2 to 3 parts per million (ppm), sometimes at a concentration greater than 1000 ppm in granitic or sedimentary zones. It is 15 times less abundant than copper, as abundant as tin (but with an annual production 5 times lower), 30 times more abundant than silver, and 600 times more abundant than gold.

c. For the question of future provision, see the article by S. Bouneau (p. 46).

d. Until 2001, uranium was still mined in France. However, its production cost is not competitive on the world market because French mines have low uranium content (less than 1%).

e. See the article by A.-S. Dessillons (p. 29). Over the past 40 years, the cost per kg of uranium has fluctuated between \$5 and \$200; in 2018, it was in the range of \$40 to \$50 per kg.

f. Natural abundance: uranium-234, 0.005%, uranium-235, 0.711% and uranium-238, 99.283%.

g. Time taken for the original amount to halve. It takes at least ten half-lives for the radioactivity to decrease significantly.

h. Until 2011, enrichment was carried out at EURODIF's Pierrelatte plant by gaseous diffusion, a very energy-intensive process that has since been abandoned. Three of the four Tricastin reactors were dedicated exclusively to supplying power to the enrichment plant. Ultra-centrifugation, requiring 40 times less energy than gaseous diffusion, is now the standard technology.

i. A centrifuge enriches about 1.2 times. So ten cascade centrifuges enrich by a factor of 1.2 to the power of 10, i.e. 6 times. The proportion of uranium-235, initially 0.7%, increases to 6 times 0.7%, i.e. about 4%.

j. Heating the powder so that the grains stick together (but do not melt completely), just as in a pottery kiln.

k. The upstream stages of the fuel cycle and the transportation of either radioactive materials or nuclear waste have so far not given rise to very large accidents, except for the Mayak nuclear complex near Kyshtym (U.S.S.R.) in 1957, about which little is known.

l. The 2015 inventory of the French National Agency for Radioactive Waste Management (ANDRA) gave the following volumes at the end of 2013: 3,200 m^3 of high-level waste (HLW); 44,000 m^3 of intermediate level long-lived waste (ILW-LL); 91,000 m^3 of low level long-lived waste (LLW-LL); 880,000 m^3 of short-lived low or intermediate level waste (LILW-SL); 440,000 m^3 of very low level waste (VLLW).

m. In the past, some of the plutonium would have been retained for use as fuel in existing or future fast-neutron breeder reactors.

n. Recent trends include an increase in MOX fuel production (124 tons in 2016) and a reduction in ERU fuel to 20 tons in 2016, offset by an increase in UOX fuel to 1,070 tons. ▮

To find out more

- Presentation of the French *"Cycle du combustible"* in 2018, High Committee for Transparency and Information on Nuclear Safety (2018), www.hctisn.fr