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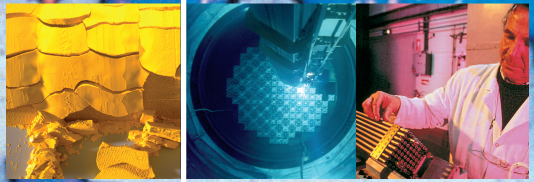
FROM RESEARCH TO INDUSTRY

→ From the uranium mine to waste disposal

7 → The nuclear fuel cycle



UPSTREAM THE REACTOR: PREPARING THE FUEL
IN THE REACTOR: FUEL CONSUMPTION
DOWNSTREAM THE REACTOR: REPROCESSING NUCLEAR WASTE
NUCLEAR WASTE

The nuclear fuel cycle

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Spent fuel is stored in a pool on the site, where it will remain for three years.

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Uranium ore is extracted from open-pit mines – such as the McClear mines in Canada seen here – or underground workings.

> **“The nuclear fuel cycle includes an array of industrial operations, from uranium mining to the disposal of radioactive waste.”**

introduction

Fuel is a material that can be burnt to provide heat. The most familiar fuels are wood, coal, natural gas and oil. By analogy, the uranium used in nuclear power plants is called “nuclear fuel”, because it gives off heat too, although, in this case, the heat is obtained through fission and not combustion.

After being used in the reactor, spent nuclear fuel can be reprocessed to extract recyclable energy material, which is why we speak of the nuclear fuel cycle. This cycle includes all the following industrial operations:

- uranium mining,
- fuel fabrication,
- use in the reactor,
- reprocessing the fuel unloaded from the reactor,
- waste treatment and disposal.

Per unit or mass (e.g. per kilo), nuclear fuel supplies far more energy than a fossil fuel (coal or oil). When used in a pressurised water reactor, a kilo of uranium generates 10,000 times more energy than a kilo of coal or oil in a conventional power station. Also, the fuel will remain in the reactor for a long time (several years), unlike conventional fuels, which are burnt up quickly. Nuclear fuel also differs from others in that uranium has to undergo many processes between the time it is mined and the time it goes into the reactor.

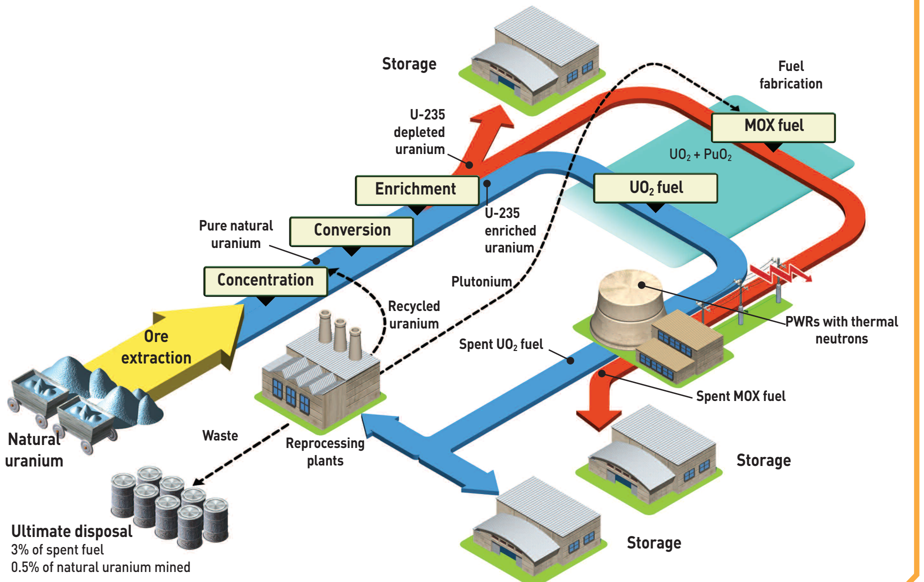
For the sake of simplicity, the following pages will only look at nuclear fuel used in pressurised water reactors (or PWRs), because nuclear power plants consisting of one or more PWRs are the most widely used around the world (see *How a nuclear reactor works* booklet).

AFTER MINING, THE URANIUM IS PURIFIED, CONCENTRATED AND ENRICHED.

Upstream the reactor: preparing the fuel

© Cogema/P. Lesage

Simplified diagram of the fuel cycle in France today



EXTRACTING URANIUM FROM THE ORE

Uranium is a relatively common metal in the Earth's crust (it is 50 times more common than mercury, for example). Like most metals, it cannot be mined directly in its pure form, because in its natural state it is found in rocks combined with other chemical elements. The rocks with the highest uranium content are known as uranium ores, which often include uraninite and pitchblende.

The nuclear fuel cycle thus begins at the open-pit mines or underground workings where the uranium ore is mined. The largest known ore deposits are in Australia, the United States, Canada, South Africa and Russia.

> **“In order to increase uranium content, ore rocks are broken up and finely ground. The resulting concentrate is called yellow cake.”**

CONCENTRATING AND REFINING URANIUM

The ore generally has a rather low uranium content. For example, in France, one tonne of ore contains between 1 and 5 kg of uranium (between 0.1 and 0.5%). This makes it essential to concentrate the uranium in these ores, a job usually carried out on the spot.

First of all, the rocks are broken up and finely crushed. Then various chemical processes are used to extract the uranium.

The resulting concentrate looks like a yellow paste and is called yellow cake. It contains about 75% uranium oxide, i.e. 750 kg per tonne.

Uranium is a metal that oxidises very quickly when it comes into contact with oxygen in the air and changes into uranium oxide.

However, this uranium concentrate cannot be used in a nuclear reactor as it is. The uranium oxide must first go through various stages of purification (or refining) to get rid of any impurities. Once it is very pure, it is converted into uranium tetrafluoride (UF_4), which is composed of four fluorine atoms and one uranium atom.

ENRICHING URANIUM

The fuel used in a PWR must contain between 3 and 5% uranium-235, because this is the only uranium isotope that can withstand energy-releasing nuclear fission (see *How a nuclear reactor works* booklet). The problem is that 100 kg of natural uranium contains 99.3 kg of uranium-238 and 0.7 kg of uranium-235, making only 0.7% of fissile uranium-235. The process of increasing the proportion of uranium-235 is called enrichment. This is a difficult operation because, like all the isotopes of the same element, uranium-235 and uranium-238 are very similar and have almost identical chemical properties (see *The Atom* booklet). They can be distinguished, however, due to their slightly different mass, uranium-235 being just a little lighter than uranium-238.

This is why the current uranium enrichment process used is based on the difference in mobility caused by this slight difference in mass. Of all the enrichment processes studied so far, only two have been developed on an industrial scale: gaseous diffusion and the ultracentrifuge process.

> **“Before it can be used as nuclear reactor fuel, natural uranium must be enriched with uranium-235.”**

ENRICHMENT METHODS

Gaseous diffusion

Before being enriched via this process, the uranium tetrafluoride obtained after extraction from the ore and refining will be transformed

Raise boring in frozen ground in the McArthur mine (Canada).

© Cogema/Cameco

COMINAL ore processing plant in Niger.

© Cogema/O. Martel

into uranium hexafluoride (UF$_6$), which becomes a gas when heated to 56°C.

The gaseous diffusion process consists in passing gaseous UF$_6$ through a long series of “barriers” formed by membranes with microscopic pores. Uranium-235 hexafluoride molecules are slightly lighter than uranium-238 hexafluoride molecules and cross each barrier a little faster, gradually enriching the uranium as they do so.

However, as the difference in mass between the two isotopes is very small, the uranium-238 travels hardly slower than the uranium-235. For this reason, the operation has to be repeated 1,400 times at the uranium enrichment plant in France (the Eurodif plant in Tricastin in the Rhone valley, which produces more than a third of the world’s enriched uranium) to obtain enough ^{235}U-enriched uranium for use in nuclear power plants.

Ultracentrifuge process

Another uranium enrichment process is used on a smaller scale by the European Urenco group (Germany, Netherlands, United Kingdom). It is known as the ultracentrifuge process.

This separation process uses a centrifuge which, acting like a high-speed salad spinner, projects the uranium-238 hexafluoride molecules to its outer edge more quickly than those of uranium-235 hexafluoride, which remain nearer the centre. The very slight difference in mass between the two molecules gradually increases the uranium-235 concentration. This process also requires many stages to obtain sufficiently enriched uranium.

© Cogema/P. Lesage

Diffusers at Eurodif’s Georges Besse plant.

FUEL IS USED IN A NUCLEAR REACTOR FOR THREE OR FOUR YEARS.

In the reactor: fuel consumption

© Médiathèque EDF/C. Pauquet

> **“In a nuclear power plant, more than 40,000 “rods” are prepared and grouped together in “bundles” with a square cross-section called fuel assemblies.”**

© CEA/M. Faugère

Each fuel assembly contains 264 “rods” that contain uranium oxide “pellets”.

PREPARING FUEL ASSEMBLIES

Following enrichment, uranium hexafluoride is transformed into a black uranium oxide powder. This is compressed, then sintered (baked in a furnace) to make “pellets”, which are small cylinders about 1 cm long and as thick as a small piece of chalk. Each pellet weighs only 7 g but can release as much energy as a tonne of coal (1 million grams).

The pellets are inserted into four metres long tubes made of zirconium alloy. These “claddings” are sealed at both ends to make fuel “rods” In a nuclear power plant, more than 40,000 of these rods are prepared and grouped together in “bundles” with a square cross-section. These are called “fuel assemblies.” There are 264 rods in each assembly. It takes 157 fuel assemblies containing a total of 11 million pellets to fuel a 900 MW nuclear reactor (1 MW = 1 million watts).

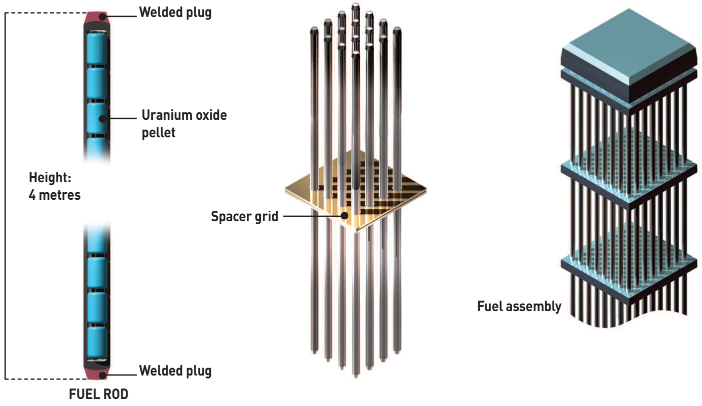
URANIUM-235 CONSUMPTION

The reactor core is made up of fuel assemblies, arranged in a precise geometrical pattern. Each one remains in the core for three or four years. During this period, uranium-235 fission provides the heat required to generate water steam, then electricity.

This is possible because uranium-235 is fissile, which means that when its nucleus collides with a neutron, it splits (hence the term fission) into radioactive fission products, releasing energy as it does so. Uranium-238, even though it represents 97% of the mass of nuclear fuel, does not split when a neutron is absorbed. However, some uranium-238 nuclei capture a neutron and are transformed into plutonium-239, which is fissile like uranium-235. That’s why we say that uranium-238 is fertile. Some of the plutonium-239 can generate energy through nuclear fission. A small fraction is also transformed into other plutonium isotopes by neutron capture mechanisms.

Atoms with unstable nuclei are said to be radioactive. These nuclei are naturally transformed into other nuclei, emitting radiation as they do so (see *Radioactivity* booklet).

Preparing fuel assemblies



FUEL DEGRADATION

Little by little, the fuel’s performance deteriorates as it undergoes a number of transformations, including:

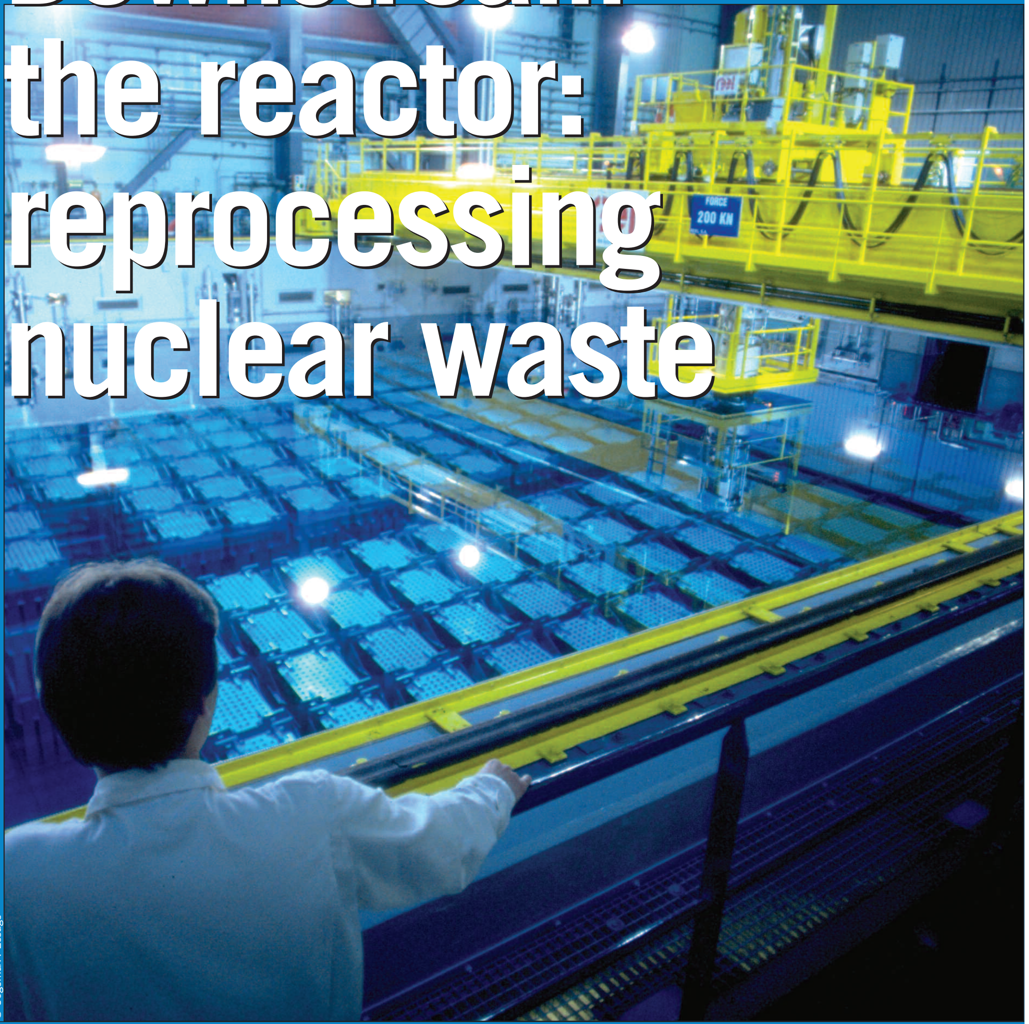
- the gradual consumption of uranium-235,
- the appearance of fission products (which absorb neutrons and disturb the chain reaction).

After a certain period of time, the fuel must therefore be removed from the reactor, even if it still contains large amounts of retrievable energy material, in particular uranium and plutonium. This spent fuel is also highly radioactive because it contains fission products. The radiation emitted by these radioactive atoms gives off a great deal of heat. For this reason, once it has been removed from the core, spent fuel is stored for three years in a special pool near the reactor to lose some of its radioactivity (see *Radioactivity* booklet).

> **“Spent fuel is stored in a pool on the site, where it will remain for three years.”**

REPROCESSING INVOLVES RETRIEVING RECYCLABLE MATERIAL – PLUTONIUM AND URANIUM – AND ISOLATING NON-RECYCLABLE RADIOACTIVE WASTE.

Downstream the reactor: reprocessing nuclear waste



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> “Some countries reprocess their spent fuel themselves, while others subcontract the job to other countries such as France.”

THE PURPOSE OF REPROCESSING

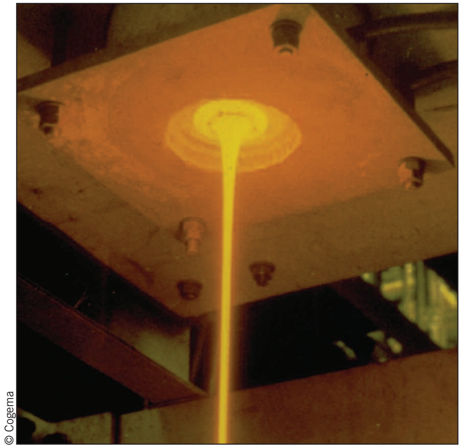
Reprocessing involves:

- retrieving material that can still be used – plutonium and uranium – to produce more electricity, in other words, recycling energy materials found in the spent fuel,
- sorting radioactive waste that cannot be recycled.

Some countries, such as Sweden and the United States, have not opted for reprocessing. In these countries, spent fuel is considered as waste and is stored after removal from the reactor awaiting direct disposal. France, the United Kingdom, Russia and Japan have chosen to build reprocessing plants. Other countries, like Germany, Switzerland and Belgium have their spent fuel reprocessed in other countries (particularly in France).

EXTRACTING FISSION PRODUCTS

When they arrive at the reprocessing plant, spent fuel assemblies are again stored in spent fuel pools. They are then cut into small pieces and placed in a chemical solution that dissolves the fuel but leaves the metal parts (cladding, etc.) intact. These are then stored as nuclear waste. The fuel solution undergoes a series of chemical processes to separate the plutonium and uranium from the fission products. The fission products are embedded in special glass (this is the vitrification process) and stored as nuclear waste. Uranium and plutonium, which account for 96% of the total, are isolated and conditioned separately.



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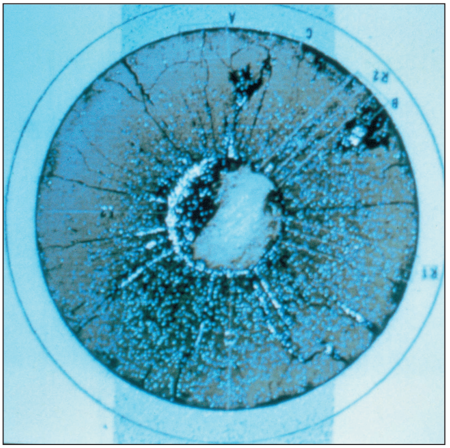
Once separated, fission products are embedded in special glass and disposed of as nuclear waste.

RECYCLING FUEL MATERIALS

How to use plutonium after reprocessing is the subject of many studies, especially at the CEA. New fuels made from a mixture of uranium oxide and plutonium oxide (called MOX from "Mixed Oxides") are already in use in some EDF reactors (PWRs). In addition, the uranium recovered during reprocessing is still slightly richer in uranium-235 than natural uranium (about 1% uranium-235), so it can be enriched again to more than 3% and follow a path similar to that of ordinary fuel.

> "Recovered uranium can be enriched to more than 3% and follow a path similar to that of ordinary fuel."



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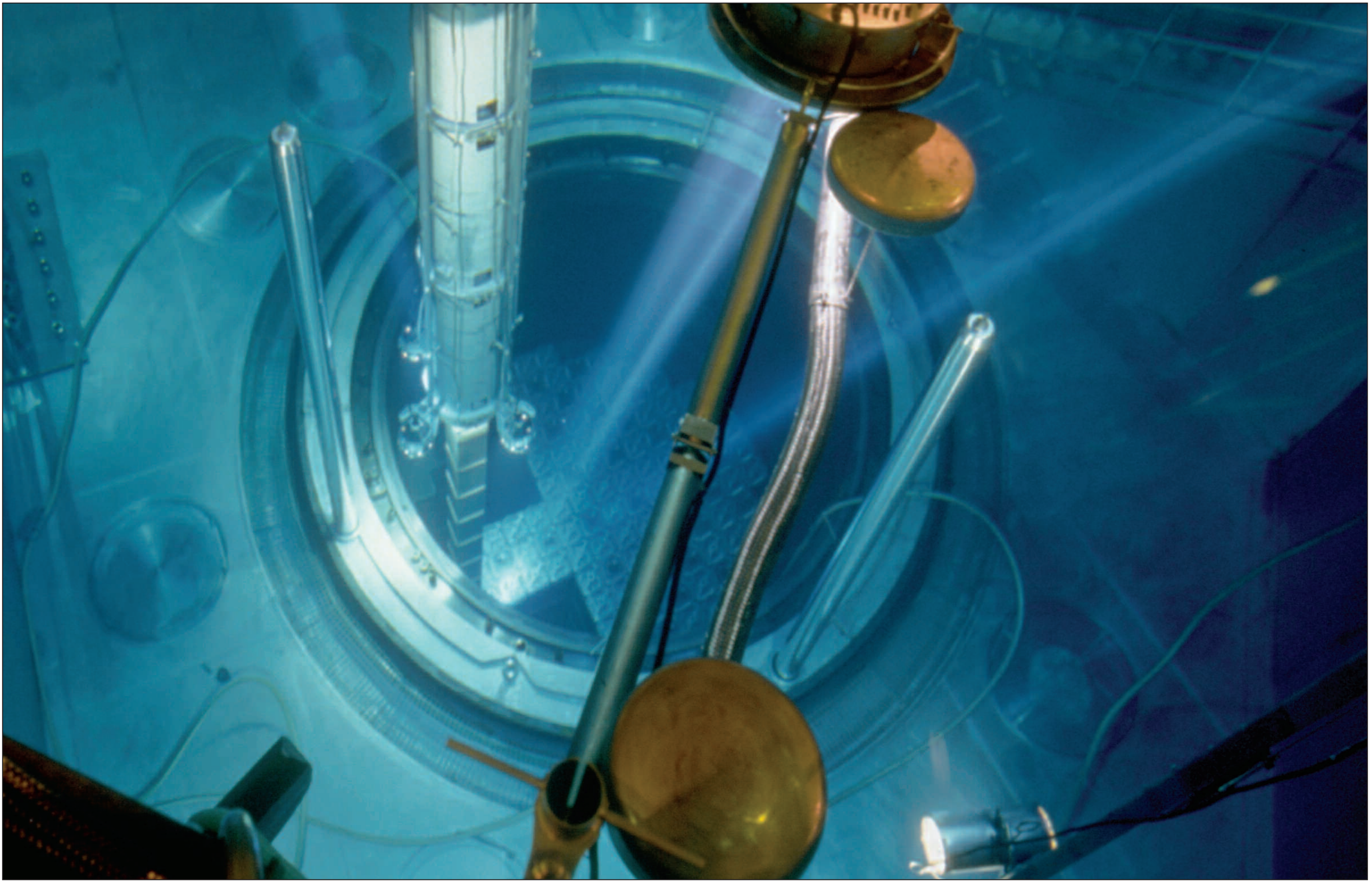
Coloured cross-section of MOX fuel.

Loading the reactor core in the Daya Bay reactor (China).



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NUCLEAR WASTE DISPOSAL METHODS DEPEND ON HOW LONG THE WASTE REMAINS RADIOACTIVE.

Nuclear waste


© CEA/E. Joly

NUCLEAR WASTE PRODUCTION IN FRANCE

All human activities generate waste. With population growth and industrial development comes an increasing volume of waste to be treated, conditioned, recycled or disposed of when recycling is impossible.

The nuclear industry is no exception to the rule. This waste, however, only represents a tiny fraction of the total amount that society produces. For the sake of comparison, France produces 2,500 kg of industrial waste per capita every year (including 100 kg of toxic waste) compared to 1 kg of nuclear waste of which only 10 g is high-level waste. Quantity is not, however, the only factor to be considered; toxicity is also very important. This is why a great deal of research focuses on waste treatment and disposal methods. Nuclear waste is produced at every stage of the nuclear fuel cycle: uranium mining

THE THREE CATEGORIES OF RADIOACTIVE WASTE

Category A

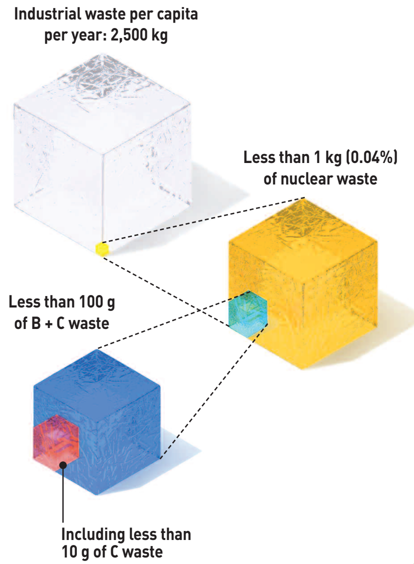
- Short-lived (half-life less than 30 years) low- and intermediate-level waste.
- – "Beta" and "gamma" radiation.
- – Radioactivity comparable with naturally occurring radioactivity after 300 years.
- > Origin: laboratories, nuclear medicine, industry (food processing, metallurgy, etc.), nuclear plants (contaminated items: gloves, filters, resins, etc.).

Category B

- Long-lived (half-life several tens of thousands of years) low- and intermediate-level waste.
- – "Alpha" radiation.

Category C

- Long-lived, high-level waste, giving off heat for several hundred years.
- – "Alpha", "beta" and "gamma" radiation.
- > Origin: reprocessing of spent fuel from nuclear power plants (combustion ashes).



“After 300 years, 90% of waste is no longer radioactive.”

and enrichment, fuel fabrication, reactor operation and reprocessing. Dismantling nuclear facilities also creates waste. Radioactive waste is also produced by research centres (such as the CEA) as well as industries and hospitals using radioactive elements.

SORTING AND DISPOSING OF RADIOACTIVE WASTE

As not all radioactive waste is the same, it is classified according to two criteria for disposal purposes:

- activity level, i.e. the radiation intensity, which determines the degree of radiological protection required,
- radioactive half-life, which determines how long the waste may be harmful.

Waste is therefore distinguished according to its lifetime and activity as follows.

Radioactive half-life of a radioelement: the time required for half the atoms initially found in the radioelement to disappear due to a disintegration process.

¥ Short-lived low- and intermediate-level waste. This accounts for 90% of radioactive waste produced in France. After 300 years, it has lost almost all its activity (see *Radioactivity* booklet). It is compacted in steel or concrete containers that are disposed of in surface repositories. There are two of these in France, one in La Hague (Manche), the other in Soulaines (Aube). They are managed by Andra, the French national agency for radioactive waste management.

¥ Long-lived and/or high-level waste (10% of the total volume). The radioactive decay of this waste spans thousands, or even hundreds of thousands, of years. It is embedded in bitumen, cement or glass. In France, a law was passed in 1991 to determine what should be done about this type of waste. Deep geological disposal is one option considered. One underground laboratory has been built to study this option. Other options are transformation into shorter-lived waste in a nuclear reactor (this is known as transmutation), studies of new conditioning processes and long-term, surface or sub-surface storage (sub-surface means several tens of metres below the surface). Until a final decision is reached, this waste is being held in surface facilities in La Hague and Marcoule.

© CEA

Conditioning waste in a concrete matrix.

RESEARCH ON LONG-LIVED WASTE

Reducing the volume and activity of solid and liquid waste is among the top priorities of current research and development work, which includes:

- CEA research on the separation and transmutation of long-lived radioactive elements contained in this waste,
- the CEA's study of conditioning and long-term, surface and sub-surface storage processes,
- the study of reversible or irreversible disposal options in deep geological formations, work that is largely supported by the underground laboratory built by Andra.

Safeguarding humans and their environment is a prominent part of the work of CEA researchers and engineers, who take special care to develop processes and technologies aimed at constantly reducing risks relating to radioactivity. On a day-to-day basis, they take the same care in managing the waste produced by their own research work.

“In 2006, the French parliament will announce its decision concerning the prefered management scheme for long-lived nuclear waste.”

Shielded vitrification line for fission products.

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