SYNTHESIS REPORT

National Inventory of Radioactive Materials and Waste

2018

ANDRA
French national radioactive waste management agency

Liberté • Égalité • Fraternité
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01

RADIOACTIVE MATERIALS AND WASTE AND THEIR MANAGEMENT

SOURCES OF RADIOACTIVE MATERIALS AND WASTE

The National Inventory sets out the sources of radioactive materials and waste, divided into five economic sectors, as a result of which radioactive waste is produced, held or managed:

- **the nuclear power sector,** which mainly includes nuclear power plants for electricity production, as well as facilities dedicated to producing nuclear fuel (uranium ore mining and processing, chemical conversion and enrichment of uranium concentrate), reprocessing spent fuel and recycling a portion of the materials extracted from spent fuel;
- **research,** which includes civil nuclear research (in particular the French Alternative Energies and Atomic Energy Commission's (CEA) research activities), medical research, nuclear and particle physics, agronomy, chemistry, biology, etc.
- **defence,** which mainly involves deterrence, including nuclear propulsion for certain ships and submarines, as well as associated research and the activities of the armed forces.
- **industries outside the nuclear power sector,** which includes rare earth mining, the manufacture of sealed sources, and various other applications such as weld inspection, medical equipment sterilisation, food sterilisation and preservation, etc.;
- **the medical sector**, which includes diagnostic and therapeutic activities (scintigraphy, radiotherapy, etc.)

The sectors that have produced the most radioactive waste in France are the nuclear power, research and defence sectors.

In accordance with Article L. 542-1 of the French Environmental Code, radioactive waste producers are responsible for properly managing their waste until it has a final disposal solution and for managing their materials while protecting human health, safety and the environment.

ARTICLE L. 542-1 OF THE FRENCH ENVIRONMENTAL CODE

Article 542-1 of the Environmental Code stipulates that "the sustainable management of radioactive material and waste of all kinds resulting notably from the operation and dismantling of facilities using radioactive sources or materials, shall be carried out with a concern to protect human health, safety and the environment.

The means required to ensure the final safety of radioactive waste shall be developed and implemented in order to prevent or limit the burdens to be borne by future generations.

The producers of spent fuel and radioactive waste shall be responsible for these substances, without prejudice to the responsibility of their holders as those responsible for nuclear activities. Should their producers or holders fail to meet this responsibility, the State shall be responsible for these substances as a last resort if they are produced on French soil. It may task the French National Radioactive Waste Management Agency with managing the waste in accordance with Article L. 542-12".

Natural and artificial radioactivity

Radioactive substances may be of natural origin or the result of human activities. There are many sources of naturally occurring radioactivity: ores (uranium and thorium isotopes, potassium-40, or daughter elements such as radium and radon), cosmic radiation (tritium, carbon-14), etc. These natural radionuclides are dispersed throughout the entire biosphere. The concentration of radionuclides varies widely depending on the material and its origin: exposure to radionuclides of natural origin can vary by more than one order of magnitude in the various regions of the world (from an average of 2.9 mSv/year in France to more than 50 mSv/year in some parts of India or Brazil). Since the beginning of the 20th century, many uses of the properties of radioactivity have generated radioactive materials and waste. Most of the waste comes from nuclear power plants, spent fuel reprocessing plants and other civil and military nuclear facilities. Research laboratories and nuclear medicine centres also contribute to the production of radioactive waste, albeit to a lesser degree, as do certain other industries that use radioactive substances.

ARTICLE L. 542-1-1 OF THE ENVIRONMENTAL CODE

Article L. 542-1-1 of the French Environmental Code defines a certain number of concepts that it is useful to remember when consulting the National Inventory of Radioactive Materials and Waste.

Radioactive substance, material and waste

"A radioactive substance is a substance which contains natural or artificial radionuclides, the activity or concentration of which warrants radiation protection monitoring."

These radioactive substances can be classified as radioactive materials or radioactive waste:

"A radioactive material is a radioactive substance for which further use is planned or intended (after processing, if necessary)." In some cases, processing such materials for recycling purposes can generate waste.

"Radioactive waste refers to radioactive substances for which no subsequent use is planned or intended or which are reclassified as such by the administrative authority in accordance with Article L. 542-13-2. Final radioactive waste is radioactive waste that can no longer be processed by extracting recoverable materials or reducing its polluting or hazardous character under current technical and economic conditions. Radioactive waste management includes all handling, pretreatment, processing, conditioning, storage and disposal of radioactive waste, excluding offsite transport."

According to Article L. 542-13-2, a radioactive material can be reclassified as radioactive waste by the administrative authority following an opinion by the Nuclear Safety Authority (ASN) if no plans for subsequent use have been sufficiently established.

Radiation protection monitoring

In France, when a substance contains radionuclides, justification of radiation protection monitoring is not necessarily established based on an activity or concentration level per radionuclide. As a precaution, monitoring is presumed to be justified when substances come from a so-called nuclear activity and are contaminated, activated or likely to be so.

Nuclear activities (Article L. 1333-1 of the French Public Health Code) are "activities involving a risk of exposure of people to ionising radiation emanating either from an artificial source, whether substances or devices, or from a natural source, whether natural radioactive substances or materials containing natural radionuclides". With the transposition of EU Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, the concept of nuclear activity was broadened by Article L. 515-43 of the Environmental Code to include various nuclear-related measures for all natural sources of radioactivity if they warrant the use of radiation protection monitoring.

For nuclear activities conducted at regulated nuclear facilities (INB) regulated nuclear defence facilities (INBS), environmentally regulated facilities (ICPE) and for nuclear activities authorised, registered or declared under the Public Health Code, as a precaution, any contaminated or activated waste, or waste that is liable to be so must be managed as if it was radioactive. It must therefore undergo specific rigorous management, including disposal of final waste in a dedicated radioactive waste facility.

In accordance with Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, EU member states can implement general clearance levels below which the materials in question fall outside the regulated scope of radioactivity regulations. When the concept of clearance levels is used, national thresholds for a given radionuclide may either be universal (regardless of material, origin and destination) or dependent on the material, its origin and its destination.

French regulations currently do not provide for the clearance of very low-level waste.

For activities which were not considered as nuclear activities prior to the new definition established by the Order of 10 February 2016, justification of radiation protection monitoring is assessed based on the limited exposure criterion, according to which the sum of effective doses received by any exposed person due to these activities must not exceed 1 mSv/year (Article R. 1333-38 of the Public Health Code). It is also based on an acceptability study on the radiological impact of waste management, which must show that radiation protection monitoring is not justified. In this case, under certain conditions, the waste may be declassified and no longer considered radioactive. This mainly applies to waste containing naturally occurring radioactive material (NORM). When Directive 2013/59 is transposed into French legislation, these management measures will be revised so that activities which use naturally occurring radionuclides for which exposure cannot be ignored from a radiation protection standpoint will be considered as nuclear activities.

Spent fuel management in France

"A nuclear fuel is regarded as spent fuel when it has been irradiated in the core of a reactor and withdrawn definitively. Spent fuel management includes all handling, storage, reprocessing and disposal of spent fuel, excluding offsite transport."

As France has opted to reprocess spent fuel to recover the reusable materials it contains, such fuel is not considered to be radioactive waste. The purpose of spent fuel reprocessing is to extract fissile or fertile substances from spent fuel for subsequent use.

Discharges

Activities involving the use of radioactive substances can lead to controlled discharges into the environment, in gaseous or liquid form. Such discharges lie outside the scope of the National Inventory of Radioactive Materials and Waste.

Discharges from regulated nuclear facilities are described and quantified in the public reports that their operators are required to issue each year under Articles L. 125-15 and 16 of the Environmental Code. The data concerning discharges from ICPEs is gathered each year by the Ministry for the Ecological and Inclusive Transition.

CLARIFICATION

Waste producer
“Any person whose activities generate waste (original waste producer) or anyone who carries out waste-processing operations that result in a change in the nature or composition of this waste (secondary waste producer).” (Article L. 541-1-1 of the Environmental Code)

Waste holder
“Producer of waste or any other person who is in possession of waste.” (Article L. 541-1-1 of the Environmental Code)
An item of radioactive waste can have several holders between the time of its production and the time of its elimination (successively the holder-producer, then the transport entity, the operator of the storage site and the operator of the disposal site).

Waste management
“Collection, transport, recycling and elimination of waste and, more generally, all activities involved in the organisation of waste management, from production to final treatment, including trade or brokering activities and supervision of all these operations.” (Article L. 541-1-1 of the Environmental Code).

Responsibilities
“Any producer or holder of waste is required to manage it, or have it managed, in compliance with the provisions set out in this chapter.
Any producer or holder of waste is responsible for management of such waste until it is finally eliminated or recycled, even if the waste is transferred to a third party for treatment.
Any producer or holder of waste must ensure that the person to whom it passes the waste is licensed to handle it.” (Article L. 541-2 of the Environmental Code)

“Spent fuel and radioactive waste producers shall be responsible for these substances, without prejudice to the responsibility of their holders as those responsible for nuclear activities. Should their producers or holders fail to meet this responsibility, the State shall be responsible for these substances as a last resort if they are produced on French soil. It may task the French National Radioactive Waste Management Agency with managing the waste in accordance with Article L. 542-12” (Article L. 542-1 of the Environmental Code).

These provisions mean that producers are responsible for their waste and the obligations placed on them until its final elimination pursuant to Article L. 541-2 (ensuring waste management, treating it or arranging for its treatment, guaranteeing its quality and properties, and bearing the costs and responsibility for such damage as may be caused by the waste).
Holders that are not producers are solely responsible for their nuclear activities (security and safety of the facilities, activities and the radioactive waste transported, stored or disposed of).

MANDATORY DECLARATIONS TO THE NATIONAL INVENTORY

These obligations are defined in Articles R. 542-67 to R. 542-72[1] of the Environmental Code:

Article R. 542-67: "For the purpose of drawing up the National Inventory provided for under paragraph 1 of Article L. 542-12, any operator of a site hosting one or more regulated nuclear facilities, or one or more defence-related nuclear facilities, defined in Article L. 1333-15 of the French Defence Code, or one or more facilities classified for environmental protection in the case of the nuclear activities referred to in the appendix (1) to Article R. 511-9 of the French Environmental Code, or several of these categories of facilities, is required to submit annually to the French National Radioactive Waste Management Agency (Andra) an inventory of the radioactive materials and waste on that site, as at 31 December of the previous year.

"The inventory, accompanied by a brief presentation of the site and information concerning the administrative body under whose responsibility it is placed, shall include a description of the radioactive materials and waste, giving their physical characteristics and the quantities involved. The radioactive waste is grouped by waste stream.

If the site has a regulated nuclear facility showing the characteristics of a nuclear reactor, a plant for reprocessing spent nuclear fuel, or a storage or disposal facility for radioactive substances, the operator shall supplement the annual inventory with an appendix showing the breakdown of the radioactive waste on the site by producer and by waste stream.

For a defence-related nuclear facility referred to in the first paragraph of this article, the inventory shall only contain a description of the radioactive waste for said facility."

Article R. 542-68: "Any person responsible for nuclear activities that does not fall within the scope of the provisions set out in Article R. 542-67 of this Code is required to submit annually to Andra an inventory of the radioactive waste held, as at 31 December of the previous year, stating the management solution used."

Article R. 542-69: "Any operator of a site mentioned in Article R. 542-67 is required to submit a report concerning the projected quantities of radioactive materials and waste by stream for said site to the French National Radioactive Waste Management Agency once every three years. If no permanent management solution suitable for the waste has been adopted, the report shall give details of the types of storage facilities envisaged, their available capacities and their anticipated operating lifetime.

For a defence-related nuclear facility referred to in the first paragraph of Article 542-67, the triennial report shall only contain a description of the radioactive waste for that facility."

Article R. 542-72: "An order issued by the Ministers responsible for energy and nuclear safety shall set out the procedures for implementing this section. It shall indicate the type of information that must be included in the required inventories and reports, such as the concept of waste streams and reference dates to be taken into account. It shall set out the methods for communicating the documents to the French National Radioactive Waste Management Agency."

1 These articles codified the provisions of Decree 2008-875 of 29 August 2008 which implements Article 22 of Planning Act 2006-739 of 28 June 2006 on the sustainable management of radioactive materials and waste.

CLASSIFICATION OF RADIOACTIVE WASTE AND MANAGEMENT SOLUTIONS

Radioactive waste classification in France is primarily based on two parameters, which are important when determining the appropriate management method: the activity level and the radioactive half-life of the radionuclides contained in the waste.

A distinction is made between the following waste activity levels:
- very low-level waste (VLLW), with an activity level less than 100 becquerels per gram;
- vow-level waste (LLW), with an activity level between a few hundred becquerels per gram and one million becquerels per gram;
- intermediate-level waste (ILW), with an activity level from around one million to one billion becquerels per gram;
- high-level waste (HLW), with an activity level around several billion becquerels per gram.

Waste is classified according to radioactive half-life as follows:
- very short-lived waste (VSLW), which contains radionuclides with a half-life of less than 100 days;
- short-lived (SL) waste, whose radioactivity comes mainly from radionuclides with a half-life of less than or equal to 31 years;
- long-lived (LL) waste, which contains a significant quantity of radionuclides with a half-life of more than 31 years.

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The radioactive half-life is the time required for one-half of the atomic nuclei of a radionuclide to decay naturally. The radioactivity of a sample containing atoms of a single radionuclide would then be halved. After 10 such half-lives, the radioactivity would be divided by a factor of 1,000.

To manage each type of waste, it is necessary to implement or develop specific solutions that are appropriate for the hazard levels involved and their development over time.

There are therefore several categories of waste that require or will require special management.

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There are many characteristics that distinguish one type of waste from another, such as its physicochemical nature and the level and type of radioactivity. In general, radioactive waste contains a mix of radionuclides (caesium, cobalt, strontium, etc.). Depending on its composition, the waste has higher or lower levels of radioactivity lasting for varying periods of time.

HLW HIGH-LEVEL WASTE

Although this waste represents only a small volume, it accounts for most waste-related radioactivity. The activity level of HLW is several billion becquerels per gram. This type of waste comes for the most part from the nuclear power industry and related research, and, to a lesser extent, from the national defence industry. It is primarily made up of non-reusable substances from spent fuel reprocessing. Most of this waste is encapsulated in glass then conditioned in stainless steel drums. Because of its high radioactivity, this type of waste gives off heat.

CSD-V package

It contains:
- short-lived fission products such as caesium-134 and caesium-137;
- long-lived fission products such as technetium-99;
- activation products and minor actinides, some of which have half-lives of several thousand years, such as neptunium-237.

ILW-LL INTERMEDIATE-LEVEL LONG-LIVED WASTE

This waste mainly comes from spent fuel reprocessing and activities involved in the maintenance and operation of reprocessing plants. It comprises structural waste from fuel assemblies (end caps and hulls), technological waste (used tools, equipment, etc.) and waste resulting from the treatment of effluents, such as certain types of sludge. It is characterised by the presence of significant amounts of long-lived radionuclides such as nickel-63 (half-life: 100 years).

Other types of ILW-LL originate from components that have been activated while exposed to the neutron flux in a reactor.

The radioactivity of this waste ranges between one million and one billion becquerels per gram, i.e. lower than that of HLW by a factor of 10 to 100.

Hulls from the zirconium alloy cladding that covers fuel pellets

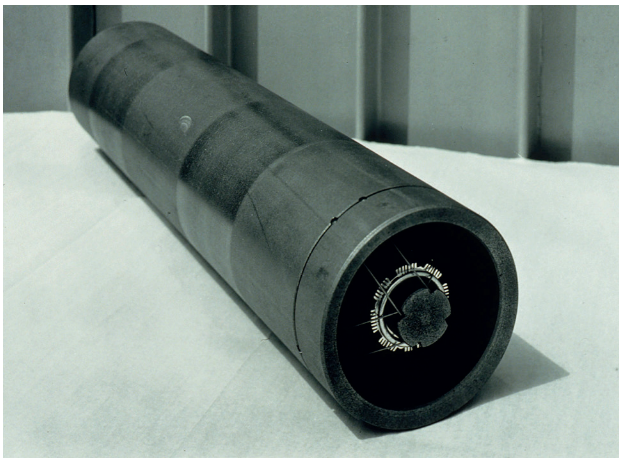
HLW and ILW-LL is currently stored pending a long-term management solution. After 15 years of research, Article L. 542-12 of the Environmental Code adopts deep geological disposal as the reference solution for this final waste and tasked Andra with conducting studies and research to select a site and design a deep reversible disposal facility for this waste. Cigeo (Industrial Centre for Geological Disposal) is the French deep geological repository project for radioactive waste (at a depth of 500 meters) (see Special Report 01).

LLW-LL LOW-LEVEL LONG-LIVED WASTE

This includes:

- radium-bearing waste mostly from non-nuclear industrial activities such as some types of research and rare earth mineral processing. Other radium-bearing waste comes from the cleanup of legacy sites contaminated with radium, which Andra is making safe as part of the activities it performs in the general interest. The radioactivity of this type of waste is generally between a few tens and a few hundreds of becquerels per gram. The radionuclides that it contains are mainly long-lived alpha emitters such as radium, uranium and thorium;
- graphite waste from the operation and dismantling of the first nuclear reactors (gas-cooled graphite-moderated reactors, GCRs) and certain experimental reactors that have been shut down. This type of waste has a radioactivity level between 10,000 and 100,000 becquerels per gram and contains mainly long-lived beta-emitting radionuclides. In the short term, the activity of graphite waste is primarily due to nickel-63, tritium and cobalt-60. Over the longer term, carbon-14 becomes the main contributor to radioactivity;
- other types of waste, such as certain legacy waste packages conditioned in bitumen, and uranium conversion residues from the Orano plant at Malvési, and waste from the operation of the La Hague reprocessing plant.

Near-surface disposal of this waste is currently being studied within the framework of Article L. 542-1-2 of the Environmental Code.



Graphite sleeve with wire locks

LOW- AND INTERMEDIATE-LEVEL SHORT-LIVED WASTE

This mainly comprises waste related to maintenance (clothing, tools, filters, etc.), operation (liquid effluent treatment or gaseous effluent filtering) or the dismantling of nuclear power plants, fuel cycle facilities and research centres.

LILW-SL mainly contains short-lived radionuclides with a maximum half-life of 31 years, such as cobalt-60 or caesium-137. It can also contain limited quantities of long-lived radionuclides.

The level of radioactivity of this waste is usually between a few hundred and one million becquerels per gram.

Low- and intermediate-level short-lived waste is disposed of in a surface facility and monitored during the time taken for its radioactivity to decay to levels with negligible impact. On the Andra disposal sites, it is generally considered that this level is reached after 300 years, which corresponds to approximately 10 half-lives and cuts the radioactivity level by a factor of 1,000. These sites will therefore be monitored for at least 300 years.

Waste from the use of radioactive products in a laboratory

There are two dedicated sites in France for the disposal of LILW-SL: the Manche Disposal Facility (CSM) and Aube Disposal Facility (CSA).

No waste has been taken to the Manche Disposal Facility since 1994, and it is currently in the closure phase. The Aube Disposal Facility has been in operation since 1992 in the municipalities of Soulaines-Dhuys, Épothémont and Ville-aux-Bois.

The category of LILW-SL includes low- and intermediate-level short-lived waste containing a significant quantity of tritium, (T-LILW-SL) Although tritium is a short-lived radionuclide, it is difficult to confine and can easily migrate into the environment where it may leave detectable traces. Most tritiated waste is solid.

The very small quantities of liquid and gaseous waste have to be treated and stabilised before storage. After about fifty years in storage, the waste is taken, depending on its level of radioactivity and the residual gas release rate, to the Industrial facility for grouping, storage and disposal (Cires), or to the Aube Disposal Facility (CSA), both operated by Andra.

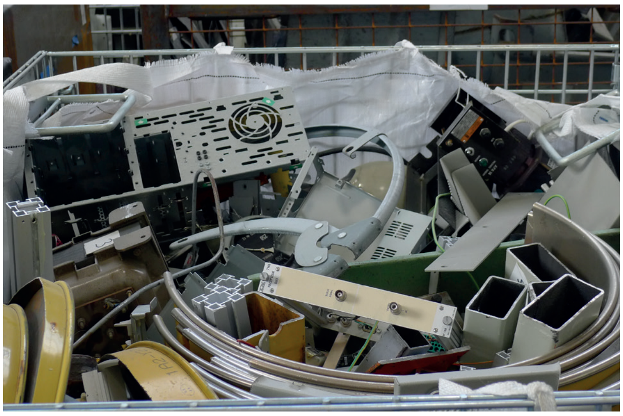
VERY LOW-LEVEL WASTE

VLLW mainly comes from the operation, maintenance and dismantling of nuclear power plants, fuel cycle facilities and research centres. It also originates from conventional industries using naturally occurring radioactive materials. It usually takes the form of inert waste (concrete, rubble and earth) or metal or plastic waste.

VLLW production will increase considerably as dismantling begins on nuclear power plants currently in operation, or on fuel cycle facilities and research centres.

The level of radioactivity of this waste is generally less than 100 becquerels per gram.

This waste is disposed of at the Industrial facility for grouping, storage and disposal (Cires), which was commissioned in August 2003 and is located in the municipalities of Morvilliers and La Chaise. As part of the National Radioactive Materials and Waste Management Plan (PNGMDR), studies are under way regarding the feasibility of creating disposal facilities on or near sites that produce VLLW, which would cater to certain types of VLLW with characteristics that would allow disposal in special facilities other than Cires, while protecting human health, safety and the environment.



VLLW

VSLW VERY SHORT-LIVED WASTE

Some waste, mainly from the medical sector or research, contains very-short-lived radionuclides (with a half-life of less than 100 days), which are used for diagnostic or therapeutic purposes. This waste is managed by allowing it to decay in situ for several days to several months until its radioactivity is low enough for it to be disposed of using conventional methods.

Medical waste may constitute liquid or gaseous effluents, or contaminated solid or liquid waste generated by the use of radionuclides in this field.

Decay tanks

Broadly speaking, with this classification, one or more management methods can be assigned to each waste category (see Special Report 1).

It does not, however, take into consideration certain complex factors that lead to a management solution being adopted that differs from the one normally corresponding to the category to which the waste belongs.

Other criteria, such as stability or the presence of toxic chemicals, must also be borne in mind.

Furthermore, the definition of a management method must also take into account the general principles and guidelines set out in the Environmental Code, particularly the need to reduce the volume and harmfulness of final radioactive waste. Two important points regarding the classification of radioactive waste should therefore be noted:

- there is no single classification criterion that determines the category of a waste item. The radioactivity of the various radionuclides in the waste must be examined to assign it a position in the classification. However, for want of a single criterion, the waste in each category generally falls into a specific radioactivity range, as indicated above;
- waste may fall under a defined category yet, because of other characteristics (such as its chemical composition), may not be accepted in the corresponding disposal solution.

Moreover, waste management options can evolve in the light of advances made in knowledge about waste, when it is recovered or when facilities are dismantled, as a result of progress made in studies on optimisation of treatment and conditioning methods, and design studies for potential or future disposal facilities.

CLASSIFICATION OF RADIOACTIVE WASTE AND ASSOCIATED MANAGEMENT SOLUTIONS

<table>
<tr><th>Category</th><th>Very short-lived waste</th><th>Short-lived waste</th><th>Long-lived waste</th></tr>
<tr><td>Very low-level waste (VLLW)</td><td rowspan="3">VSLW
Management through radioactive decay</td><td colspan="2">VLLW
Surface disposal (Industrial facility for grouping, storage and disposal)</td></tr>
<tr><td>Low-level waste (LLW)</td><td rowspan="2">LILW-SL
Surface disposal
(Aube and Manche disposal facilities)</td><td>LLW-LL
Near-surface disposal under development</td></tr>
<tr><td>Intermediate-level waste (ILW)</td><td rowspan="2">ILW-LL
HLW
Deep geological repository at the project phase</td></tr>
<tr><td>High-level waste (HLW)</td><td>Not applicable</td><td></td></tr>
</table>

SPECIAL CASES

WASTE CONTAINING NATURALLY OCCURRING RADIOACTIVE MATERIAL

Waste containing Naturally Occurring Radioactive Material (NORM) is generated by the use or processing of raw materials that contain naturally occurring radionuclides but are not used for their radioactive properties. In this case it is categorised as low-level or even very low-level long-lived waste.

These radionuclides may be found in materials or waste and require special management.

The naturally occurring radionuclides taken into account for NORM waste are within the uranium-238, thorium-232 and potassium-40 decay chains found in materials used in industrial processes. These processes can concentrate or enhance the radioactivity naturally present in some products used, particularly in the residues they generate.

This waste consists mainly of waste from the chemical or metallurgy industries (phosphate fertilisers, rare earth elements, zircon sand, etc.).

The Circular of 25 July 2006[1] provides for specific management of this category of waste in a conventional waste disposal facility, under strict conditions.

Examples of this might be the disposal of waste from the demolition of old factories, equipment or process residues.

Management regulations for NORM waste will be completely overhauled by French Decree 2018-434 of 4 June 2018[2], which took effect on 1 July 2018. It transposes the provisions EU Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation.

WASTE WITHOUT A SPECIFIC DISPOSAL SOLUTION

It is sometimes impossible to classify certain types of waste in a particular category, either because they cannot be handled using existing management solutions in view of some of their characteristics, and especially their chemical characteristics, or because treatment or conditioning processes are not available or particularly complex to develop, given the sometimes small quantities involved.

Examples include some oils and certain organic liquids that cannot be incinerated, or waste containing mercury.

The development and implementation of treatment processes for this kind of waste is monitored under the National Radioactive Materials and Waste Management Plan (PNGMDR). Most waste without a specific disposal solution is stored on the site where it was produced. It is indexed in the National Inventory.

LEGACY DISPOSAL OF WASTE

In the past, some types of radioactive waste were managed using methods that have since changed.

This waste was disposed of on site or near nuclear facilities, in conventional waste disposal facilities, at former or operational industrial sites or facilities or near these sites, or dumped at sea.

RESIDUES LEFT OVER FROM URANIUM MINES;

Mining waste listed in the National Inventory is usually VLLW or LLW-LL and is disposed of on or near former mining sites (see Chapter 4).

1 Circular of 25 July 2006 on classified facilities - Acceptance of waste containing technologically enhanced or concentrated radioactive material in waste disposal facilities.
2 Decree 2018-434 of 4 June 2018 concerning various nuclear-related measures.

RADIOACTIVE MATERIALS

NATURAL URANIUM FROM MINING ACTIVITIES

In its natural state, uranium is a very dense grey metal. It has three radioactive isotopes: uranium-238 (99.3%), uranium-235 (0.7%, only natural fissile isotope) and uranium-234 (traces). Uranium is extracted from mines. In France, uranium mines were operated until 2001. Today natural uranium is exclusively procured from mining activities outside the country.

It is then processed and formed into a solid uranium concentrate and conditioned. Depending on the processing method used, the concentrates can take the form of uranates, known as *yellowcake*, or uranium oxide (U_3O_3). In the uranium conversion stage, uranium concentrates are converted into uranium tetrafluoride (UF_4) and then into uranium hexafluoride (UF_6), which is gaseous at low temperatures.

Natural uranium is used in this form when it is enriched to manufacture nuclear fuel.

NATURAL ENRICHED URANIUM

Enrichment consists in increasing the levels of uranium-235 (an energy-producing isotope whose content of 0.7% in natural mined uranium is too low) in order to obtain a material that can be used as fuel in pressurised water reactors.
Centrifugation is the enrichment process implemented since 2011 at the Orano Georges Besse II plant on the Tricastin site. The UF_6 gas is introduced into the cylinder rotating at very high speed, under vacuum, in a sealed container. Under the effect of centrifugal force, the heavier molecules move to the walls of the tube while the lighter ones (uranium-235) migrate to the centre. The gas enriched in the light uranium-235 isotope, in the centre of the tube, rises. The gas enriched in heavier uranium-238 descends. The enriched and depleted products are recovered at the two ends of the tube, at the top and bottom. This elementary step of separation of the molecules is repeated in a set of centrifuges placed in series, called cascades.

The enriched uranium used for electricity production contains about 4% uranium-235.
After enrichment, the uranium in gaseous form (UF_6) is converted into uranium dioxide (UO_2) then compacted into pellets used to manufacture fuel.

DEPLETED URANIUM (U_{DEP})

The enrichment process produces both uranium enriched in uranium-235 and depleted uranium. Uranium depleted of uranium-235 (an isotope present at a level of about 0.3%) is transformed into a solid, stable, incombustible, insoluble and non-corrosive substance: uranium oxide (U_3O_8), which takes the form of a black powder.

Depleted uranium has been used regularly for several years as a support matrix for MOX fuel, which is made in France in the Melox plant located in Marcoule. This process produces about a hundred tonnes per year.

REUSE OF DEPLETED URANIUM

France currently has a stock of depleted uranium which, once re-enriched, equates to around 60,000 tonnes of natural uranium (i.e., about eight years of France’s current power plant needs). This uranium can be re-enriched for use as ENU fuel. Depleted uranium, particularly from the second enrichment cycle, could be used to supply the long-term needs of the world’s Generation IV reactors.

Besides its energy-producing potential, depleted uranium has many valuable properties, some of which have been utilised in industries outside the nuclear power sector. An R&D project being conducted by Orano is exploring recycled uranium and the use of these properties.

However, according to the French Nuclear Safety Authority (ASN), there are a number of uncertainties around these recycling opportunities. Andra is carrying out a feasibility study for a depleted uranium disposal concept to manage the depleted uranium stock (or some of it) if it cannot be reused under practical technologically and economically viable conditions.

RECYCLED URANIUM

Uranium extracted from spent fuel (recycled uranium) in reprocessing plants makes up about 95% of the mass of spent fuel and still contains a significant amount of isotope-235. The residual enrichment in uranium-235 is about 0.7% to 0.8% for PWR fuel with burnup levels of 45 to 55 GWd/t. Recycled uranium is stored in the form of U_3O_8.

For reuse in pressurised water reactors such as those currently operated by EDF, further enrichment is necessary.

ENRICHED URANIUM FROM SPENT FUEL REPROCESSING

Uranium from reprocessed spent fuel (recycled uranium) still contains an amount of isotope-235 despite a more complex isotope composition than natural uranium due to the presence of uranium-234 and uranium-236. It can therefore be enriched. Due to the presence of uranium-236, a neutron absorber that acts as a poison at nuclear fission, it needs to be enriched to higher levels than those required for natural uranium in order to compensate for the loss of reactivity. The enriched uranium produced from reprocessed spent fuel can be used to manufacture enriched recycled uranium (ERU) fuel. Just as for natural uranium, centrifugation can be used to enrich uranium from spent fuel reprocessing.

Enriched recycled uranium fuel assemblies for EDF reactors are currently not being produced pending an optimised industrial solution. As a result, there are no stocks of enriched recycled uranium available in France.

THORIUM

Thorium primarily takes the form of thorium hydroxide or thorium nitrate. As part of its rare earth ore processing activities, Solvay generated:

- between 1970 and 1987, a compound stemming from treatment using the monazite chloride method - crude thorium hydroxide (ThH), which could potentially be recovered (see box below);
- up to 1994, thorium nitrate, generated by treatment using the monazite nitrate method.

EXAMPLE OF THE USE OF THORIUM-BEARING MATERIALS BY ORANO MED

Orano Med is the medical subsidiary of Orano. It was created in 2009 and focuses on the development of new targeted therapies for cancer treatment via the use of lead-212.

Lead-212 is a rare isotope produced from the decay chain of thorium-232. This alpha-radiation emitting element is currently the focus of nuclear medicine research projects to develop new cancer treatment.

Orano Med has developed a process for extracting lead-212, which is now used at the Maurice Tubiana laboratory. The therapeutic field in which Orano Med is working is known as alpha therapy or alpha radioimmunotherapy, where lead-212 is combined with the use of an antibody that can recognise and destroy the cancer cells, while limiting the impact on the surrounding healthy cells. Clinical and preclinical trials have been conducted in both the United States and France.

Alpha therapy has been known about for several years, but the development of treatments has been held back by the scarcity of alpha-emitting isotopes and the technical difficulties of producing and purifying these isotopes for medical use. Orano has a thorium nitrate source consisting mainly of thorium-232, and Orano Med is reusing this to produce lead-212 compatible with the requirements of developing new treatments in the long term.

However, the ASN considers that this use of lead-212 does not modify the quantities of thorium-bearing materials held or their radiotoxicity. A feasibility study exploring a disposal concept for the existing stock of thorium-bearing substances is being conducted by Andra.

SUSPENDED PARTICULATE MATTER (SPM)

The suspended particulate matter (SPM) generated from the neutralisation of the chemical effluents produced at the Solvay plant contains an average level of 25% of rare earth element oxides that are recoverable by-products.

RECYCLING SUSPENDED PARTICULATE MATTER AND CRUDE THORIUM HYDROXIDE

The recycling of suspended particulate matter concerns its rare earth element, thorium and uranium content.

Rare earth elements are used in numerous consumer products such as flat screens, certain batteries, optical fibres, lenses, etc. About 10,000 tonnes of rare earth element oxides can be recovered by processing suspended particulate matter (SPM) and crude thorium hydroxide (ThH). The thorium could be reusable in nuclear applications, in a "thorium fuel cycle". Avenues are being explored for the potential reuse of thorium in fields outside the nuclear power sector.

However, these recycling opportunities present uncertainties. In its opinion dated 9 February 2016[1], the ASN therefore considered that securing financing for the long-term management of thorium-bearing substances is crucial.

NUCLEAR FUEL

Several types of nuclear fuel are or have been used in France.

Enriched natural uranium fuel (ENU) is made of fuel rods containing UO_2 pellets grouped into fuel assemblies. This type of fuel is primarily used by EDF.

Enriched recycled uranium fuel (ERU) is made of enriched uranium from reprocessed spent fuel. This fuel is authorised in four nuclear power reactors.

Mixed uranium-plutonium fuel (MOX) is made of depleted uranium and plutonium from reprocessed spent ENU fuel in the form of oxide $(U, Pu)O_2$ powder pellets. MOX fuel is manufactured at the Melox plant at Marcoule and is currently authorised for use in 24 PWR reactors.

Fuel made from mixed uranium and plutonium oxide for the Phénix and Superphénix fast neutron reactors (FNR), which have been permanently shut down and are therefore no longer used.

Civil CEA fuel, which is used in specific reactors for research purposes. This fuel can also be used to produce radioelements for nuclear medicine and the nuclear power industry. There is a greater variety of this fuel in terms of form and physicochemical composition compared with EDF fuel, but there is far less of it; It can come in the form of oxide, metal, hydride and other types of fuel.

Fuel for defence entities in France, used either in reactors designed to make materials for nuclear deterrence weapons, or in the reactors on board submarines and ships, and their prototypes on land.

At any given time, for all these fuel types, there are stocks of fuel before use, fuel in use and spent fuel.

New fuel is transported in special containers via road or rail from the fuel fabrication plant to nuclear production plants. As soon as it arrives on site, it is stored in the fuel building before being inserted into the reactor.

Fuel in use in nuclear power reactors remains in place for three to four years. Then, once its performance drops, it is removed and stored in a cooling pool near the reactor before being sent to the reprocessing plant in La Hague, where natural enriched uranium fuel is reprocessed.

It should be noted that a substance can be classified as a radioactive material as a result of a government decision (as is the case for generic spent fuel) or decision of its owner. In the latter case, the nuclear safety authority can oppose the classification and request classification as radioactive waste.

France's current strategy consists in reprocessing spent ENU fuel.

A fuel assembly is set of rods held in place by support grids. These rods are long zirconium alloy tubes that contain stacked uranium oxide pellets that form the fuel.
A nuclear power reactor contains several fuel assemblies. The walls or cladding of these rods and their end caps contain the radioactive products from the high-pressure and high temperature water.

1 ASN Opinion 2016-AV-0256 of 9 February 2016 on the studies to assess the recoverable nature of radioactive materials, submitted in application of the National Radioactive Materials and Waste Management Plan for 2013-2015, with a view to drawing up the National Radioactive Materials and Waste Management Plan for 2016-2018.

PLUTONIUM OBTAINED FROM SPENT FUEL AFTER REPROCESSING

The plutonium contained in spent ENU fuel assemblies is extracted when they are reprocessed. Light water spent uranium fuel currently contains about 1% plutonium (in weight). This plutonium can be used to produce energy.

After it has been dissolved, extracted and separated from the other materials contained in the spent fuel, the plutonium is purified and conditioned in the stable form of plutonium oxide (PuO_2) powder in units R4 and T4 of the plant at La Hague.

Plutonium is currently used to produce MOX fuel.

The plutonium extracted from spent fuel is owned by Orano customers, i.e. electricity producers in France or in other countries. It is usually shipped to the customers outside France in the form of MOX fuel for use in their reactors.

FUEL SCRAP

Non-irradiated fuel scrap awaiting reprocessing will eventually be reprocessed and recycled in nuclear power reactors.

OTHER MATERIALS

The Superphénix core is the fuel that should eventually have replaced the fuel used when the plant was in operation. Because Superphénix has now been decommissioned, this fuel has never been used and has therefore not been irradiated.

GENERAL PRINCIPLES OF RADIOACTIVE MATERIALS AND WASTE MANAGEMENT

MANAGEMENT POLICY

The principles governing management of radioactive waste are strictly regulated at both national and international levels. Moreover, France has signed the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, drawn up under the aegis of the IAEA[1], which sets out management principles.

AT EUROPEAN LEVEL

On 19 July 2011[2], the European Council adopted a Directive establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, from production to disposal.

This Directive covers all stages of the management of spent fuel and radioactive waste resulting from civilian activities. Each Member State has ultimate responsibility for managing the spent fuel and radioactive waste generated on its territory.

The Directive requires each Member State to establish and maintain a national framework that provides for the following: a national programme for the management of spent fuel and radioactive waste, licensing, the creation of inventories, a control and inspections system, enforcement actions such as the suspension of activities, the allocation of responsibility, public information and participation, and funding schemes for waste management. Furthermore, the Directive stipulates that each Member State shall establish and maintain a competent regulatory authority in the field of spent fuel and radioactive waste management, and lays down certain conditions to ensure the authority's independence.

AT NATIONAL LEVEL

The French government has defined and implemented public policy on radioactive waste. This was defined in a legislative framework in 1991 (in the Act of 30 December 1991[3]) then consolidated in 2006 (with the Act of 28 June 2006). This legislation is set out in the French Environmental Code.

Its policy is managed by the Directorate-General for Energy and Climate (DGEC) within the Ministry for the Ecological and Inclusive Transition, and is based on three main elements:

- a National Radioactive Materials and Waste Management Plan (PNGMDR)[4]. The plan is updated by the government every three years and defines a scheduled programme for research and other activities;
- provisions for independent assessment of research work, public information and dialogue with all stakeholders;
- guaranteed funding: in accordance with Article L. 110-1 of the French Environmental Code, which stipulates that "the costs arising from measures to prevent, reduce or combat pollution must be borne by the polluter", it is for the producer of the waste to finance its management, including in the long-term.

1 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, available at: http://www-ns.iaea.org/conventions/waste-jointconvention.asp.
2 Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.
3 Act 91-1381 of 30 December 1991 on research into radioactive waste management.
4 French National Radioactive Materials and Waste Management Plan (PNGMDR), available at ecologique-solidaire.gouv.fr.

FRENCH LAW

Article L 541-1 of the Environmental Code lays down the following principles: prevention or reduction of waste production, producers' responsibility up to the elimination of their waste, traceability and the need to inform the public.

The Environmental Code stipulates that "the sustainable management of radioactive material and waste of all kinds resulting notably from the operation and dismantling of facilities using radioactive sources or materials, shall be carried out in compliance with the requirements relating to the protection of human health, safety and the environment" (Article L. 542-1).

Numerous provisions are implemented to comply with this legislative framework:

- requirements concerning processing and conditioning, transport and facilities: these are defined by the competent authorities, which subsequently monitor their application;
- procedures to reduce the volume and harmfulness of such waste; for the waste generated, operations involved in sorting, processing, conditioning and characterisation of its radiological content: these are defined and implemented by the producers of the waste. The research and development work that is often required is carried out by various organisations, and especially by the CEA;
- the design and construction of host facilities with the required safety level. These may be storage facilities (temporary solution), which are generally the responsibility of waste producers, or disposal facilities (permanent solution), for which Andra is responsible (see Special Report 1);
- transport, storage and disposal operations, along with traceability and monitoring, including over the long term in the case of disposal facilities;
- provisions relating to public information.

INSPECTION OF NUCLEAR MATERIALS

Due to its nuclear industry and aware of its responsibilities regarding non-proliferation, France has created regulations and set up an organised system to control nuclear materials. These regulations apply to both civil materials and those used for national defence.

At a national level, the protection and control of nuclear materials is subject to specific regulations under the Defence Code and related regulatory measures.

Six nuclear materials are covered by French legislation: plutonium, uranium, thorium, tritium, deuterium and lithium-6 (Article R. 1333-1 of the Defence Code, deuterium and lithium-6 are not radioactive). Their definition is periodically reviewed to reflect changing knowledge and technology. Only plutonium, uranium and thorium are considered in the National Inventory.

The regulations aim to prevent the loss, theft or misuse of nuclear materials and to protect these materials and related facilities or shipments against malicious acts.

In this context, the regulations require operators and industrial facilities holding these materials to comply with a number of provisions that complement each other, such as:

- physical protection measures to protect the materials against malicious acts or sabotage by placing barriers and other devices between publicly accessible areas and the premises holding the materials;
- monitoring of the materials so that their location and use is known at all times;
- accounting measures so that the exact quantity of the materials held is known at all times. Each operator must keep their own nuclear material accounts, which are regularly compared with centralised accounts held by the French Institute for Radiological Protection and Nuclear Safety (IRSN). For instance, for plutonium and uranium these accounts are kept to the nearest gram;
- containment measures to prevent unauthorised movement of materials;
- surveillance measures with the aim of ensuring the integrity of containment and verifying that no materials have been released illegally.

To be in possession of materials, operators require prior authorisation from the competent authority, which in France is the Senior Defence and Security Official of the ministry responsible for energy. This authorisation is issued only after examination of documentation provided by the operator, detailing physical protection, monitoring, accounting, etc. The examination is carried out by IRSN, which is authorised to act on behalf of the ministry.

The granting of authorisation requires the operator to undertake a safety study in order to assess the effectiveness and relevance of the protection against key threats defined by the government. The threats are reviewed periodically by specialised government agencies to reflect the changing national and international situation.

At international level, inspections to ensure compliance with the Non-Proliferation Treaty and the Euratom Treaty are carried out by the IAEA and the European Commission, respectively. These inspections cover both the declaration and monitoring of the movement of nuclear materials (plutonium, uranium and thorium) between countries and declarations concerning flows and stocks of materials held at the national level in the case of nuclear materials that are not used for national defence. These international inspections involve inspections of French facilities by Euratom inspectors and, to a lesser extent, by the IAEA (trilateral agreement between the IAEA, Euratom and France).

THOSE RESPONSIBLE FOR RADIOACTIVE MATERIALS AND WASTE MANAGEMENT

INSTITUTIONAL FRAMEWORK

The National Radioactive Materials and Waste Management Plan (PNGMDR) uses data from the National Inventory as a basis for reviewing existing management strategies, estimating foreseeable needs for storage and disposal facilities and determining the objectives for radioactive waste which does not have a definitive management solution. It also relies on the work of an interdisciplinary working group co-chaired by the ASN and the Directorate-General for Energy and Climate (DGEC), comprising government representatives, representatives of safety authorities, radioactive waste managers, waste producers and environmental protection associations.

The ministry responsible for the environment oversees:

- the Directorate-General for Energy and Climate (DGEC) is responsible for preparing policy and implementing government decisions related to the civilian nuclear sector;
- the Directorate-General for Risk Prevention (DGPR) and in particular the Nuclear Safety and Radiation Protection Mission (MSNR) which prepares, coordinates and implements government projects involving civilian nuclear safety and radiation protection, except for those assigned to the ASN. This mission also works with the ASN to manage issues related to the management of former uranium mines (see Chapter 4) and sites and soils polluted by radioactive substances (see Special Report 4). The DGPR also develops policy on conventional waste management, including NORM waste (see Chapter 4).

French Parliament created its own evaluation body to address scientific matters in general, and specifically those relating to nuclear programmes, called the Parliamentary Office for the Evaluation of Scientific and Technological Choices (OPECST). This body holds hearings with entities responsible for radioactive materials and waste management and publishes evaluation reports and recommendations, which are published on senat.fr/opecst.

The French Parliament relies on the National Assessment Board (CNE), which is tasked with annually evaluating the progress and quality of research on the management of radioactive materials and waste. This Board was set up under the Act of 30 December 1991, and confirmed by Article L.542-3 of the Environmental Code. It publishes an annual report that is submitted to Parliament and made public. It is available at cne2.fr.

The National Committee for the Evaluation of Funding (CNEF) for the costs of dismantling regulated nuclear facilities and managing spent fuel and radioactive waste is a committee created by the Act of 28 June 2006 in order to assess the funding of long-term nuclear costs.

The High Committee for Transparency and Information on Nuclear Safety (HCTISN) is a forum for information, consultation and debate on risks involved in nuclear activities and their impact on human health, the environment and nuclear safety. It was created by the Act of 13 June 2006 on transparency and security in the nuclear field (TSN Act)[1]. Its responsibilities are detailed in Article L. 125-34 of the Environmental Code. The Committee's reports and recommendations can be consulted at hctisn.fr.

The French Nuclear Safety Authority (ASN) is an independent administrative authority created by the Act of 13 June 2006 on transparency and security in the nuclear field (TSN Act). Its responsibilities are set out in Article L. 592-1 of the Environmental Code:

- it is tasked, on behalf of the French government, with regulating nuclear safety and radiation protection. It monitors radioactive waste producers and Andra in their nuclear activities or in activities that require radiation protection measures;
- it also examines the licensing procedures for regulated nuclear facilities (INB);
- it grants individual licences for the possession of certain radioactive sources or equipment using ionising radiation.
- it relies on the expertise of the French Institute for Radiological Protection and Nuclear Safety (IRSN)

The Nuclear Safety Authority for Defence-related facilities and activities (ASND) oversees nuclear safety and radiation protection for defence-related activities and facilities. Like ASN, it relies on the expertise of IRSN.

PRODUCERS OF RADIOACTIVE WASTE

In accordance with Article L. 542-1 of the French Environmental Code, the producers of radioactive waste are responsible for proper management of their waste until it has a final disposal solution. In particular, they are required to sort the waste and define the methods for its treatment and conditioning, depending on the technologies available, with a view to reducing the quantity and harmfulness of radioactive waste.

They condition waste in accordance with the strict quality assurance procedures required by regulations[2]. They must also store waste for which no final disposal solution is currently available.

1 Act 2006-686 of 13 June 2006 on Transparency and Security in the Nuclear Field.
2 Order of 7 February 2012 setting the general rules for regulated nuclear facilities.

In addition, they are responsible for transporting conditioned waste to Andra's disposal facilities.

For some producers that do not have suitable resources, due to the small quantities of radioactive waste they generate, such as non-CEA research laboratories or hospitals, Andra can also perform waste collection, treatment, conditioning and storage.

HOLDERS OF RADIOACTIVE MATERIALS

The following are the main holders of nuclear materials:

- Orano is involved in all aspects of the fuel cycle, except the use of nuclear fuel. The fuel cycle includes the extraction of uranium and its concentration, conversion, enrichment and fabrication into fuel, followed by the reprocessing of spent fuel;
- civil CEA conducts research in the nuclear field. It uses fuel in its reactors for research purposes;
- EDF uses fuel to produce electricity in its electrical power plant reactors;
- Solvay extracts rare earth elements from thorium ore;
- French National Defence activities include nuclear deterrence and the use of fuel for naval propulsion.

THE ROLE OF ANDRA

Andra, the French National Radioactive Waste Management Agency, is responsible for the long-term management of radioactive waste produced in France.

It is an industrial and commercial public undertaking whose role was defined by two successive acts of French legislation:

- Act of 30 December 1991 on research into the management of high-level long-lived radioactive waste. This act created Andra as a public body and entrusted it with the task of conducting research on the deep geological disposal of high- and intermediate-level long-lived radioactive waste.
- The Planning Act of 28 June 2006, codified in the Environmental Code, on the sustainable management of radioactive materials and waste. This act extended and strengthened Andra's role and the scope of its activities.

Placed under the supervision of the French ministries responsible for energy, the environment and research, Andra implements the French government's radioactive waste management policy. It is independent of radioactive waste producers.

The government sets out Andra's objectives in a performance target agreement. The latest version of this agreement covers 2017 to 2021. It is available on Andra's website (andra.fr).

Andra provides the government with its expertise and know-how to design management solutions and operate disposal facilities for all radioactive waste produced in France, ensuring long-term protection for human health and the environment against the impact of this waste.

The French Environmental Code specifies Andra's activities:

- Design, scientific research and technological development activities:
  - design and implement sustainable solutions for the management of high-level waste (HLW), intermediate-level long-lived waste (ILW-LL) and low-level long-lived waste (LLW-LL) that is currently in storage.
- Industrial activities:
  - manage radioactive waste produced by the nuclear power, research, defence and medical sectors, as well as industries outside the nuclear power sector,
  - operate radioactive waste disposal facilities in a way that is safe for human health and the environment.
- Public interest activities:
  - collect radioactive items from private individuals and local authorities,
  - clean up and remediate radioactively contaminated sites, where the owners have disappeared or failed to fulfil their obligations (see Special Report 4),
  - **manage the National Inventory of Radioactive Materials and Waste in France. Radioactive materials and waste stocks are published each year and projected estimates every three years**,
  - provide clear and verifiable information on radioactive waste management,
  - facilitate meetings and encourage dialogue with all stakeholders;
- Activities related to promoting expertise in France and internationally:
  - develop national and international scientific collaboration,
  - promote Andra's entire range of services throughout France and internationally,
  - disseminate scientific and technical culture as widely as possible.


02

STATUS OF STOCKS AT THE END OF 2016

Throughout this chapter, quantities are rounded and differences are calculated using exact figures, then rounded.

This chapter presents the statements of declarations made by the producers or holders of radioactive materials and waste in 2017. In accordance with Decree 2008-875 of 29 August 2008 and the amended Order of 9 October 2008, these declarations concern stocks of radioactive materials and waste on sites on 31 December 2016.

In all, nearly 1,000 geographical sites within the meaning of the National Inventory (see Appendix 1) on which radioactive waste was located at the end of 2016 are listed in the 2018 edition. Details of the sites listed are available at inventaire.andra.fr.

Although most radioactive waste is generated by the nuclear power industry and related research activities, numerous other sectors also generate radioactive waste, such as industries outside the nuclear power sector, defence, research outside the nuclear field, or the medical sector. In spite of their large numbers, these waste producers only account for a small proportion of the volume of radioactive waste present in France.

The first part of this chapter provides a quantitative overview of material and waste stocks at the end of 2016. The second part provides the radioactive materials and waste listed at 31 December 2016 for each economic sector.

THE SCOPE OF THE WASTE TAKEN INTO ACCOUNT IN THE STATEMENTS

The waste taken into account for the statements presented in this chapter does not include waste handled via "specific" management methods (see Chapter 4). This consists of:

- residues from treating uranium ores that are disposed of on certain former mining sites. The National Inventory lists 19 sites where these residues are permanently disposed of;
- "legacy" waste disposed of within or near nuclear facilities, in conventional waste disposal facilities, in legacy repositories, or dumped at sea.

The following are not included in the statements:

- radioactive substances located on polluted sites where activities involving radioactivity handling have been conducted (see Special Report 4);
- very short-lived waste (VSLW) that is managed by decay on site and then disposed of by conventional methods. This waste is not sent to a radioactive waste disposal facility;
- uranium conversion treatment residues from the Orano plant in Malvési are shown separately. In 2014 and 2015, under the National Radioactive Materials and Waste Management Plan (PNGMDR), Orano submitted studies concerning long-term management of this waste, which, for the most part, is stored in settling and evaporation ponds and is not conditioned. Studies are still under way. Pending a decision, this waste is shown separately in the statements setting out figures for the stocks of waste existing at 31 December 2016.

These exclusions concern all the statements included in Chapters 2 and 3. They are not mentioned again below.

BREAKDOWN OF STOCKS BY CATEGORY AT THE END OF 2016

RADIOACTIVE WASTE

Radioactive waste is defined in Article L. 542-1-1 of the French Environmental Code as “radioactive substances for which no subsequent use is planned or intended or which are reclassified as such by the administrative authority in accordance with Article L. 542-13-2. Final radioactive waste is radioactive waste that can no longer be processed by extracting recoverable materials or reducing its polluting or hazardous character under current technical and economic conditions”.

RADIOACTIVE WASTE VOLUMES AT THE END OF 2016

The volume of radioactive waste identified since the beginning of its production up to 31 December 2016 is about 1,540,000 m^3 (conditioned equivalent volume), i.e. about 85,000 m^3 more than at the end of 2013.

VOLUME UNIT

The unit used to prepare the statements is the “conditioned equivalent volume”. It allows the waste to be accounted for using a single, common unit.

The volumes of waste listed correspond to the volumes of conditioned waste, i.e. waste that the producers do not intend to process further before disposal. This conditioned waste constitutes primary packages.

For waste for which the conditioning is not yet known, assumptions are made to assess the conditioned equivalent volume for the planned primary package based on current assumptions.

Further conditioning of the primary package in a disposal package may be necessary for handling or recovery purposes. This volume is not included in the “conditioned equivalent volume”. For example, at this stage of the design studies for the Cigeo project, the volume of the HLW disposal packages could be two to three times greater than the volume of the primary packages, while the volume of the ILW-LL packages could be three to six times greater.

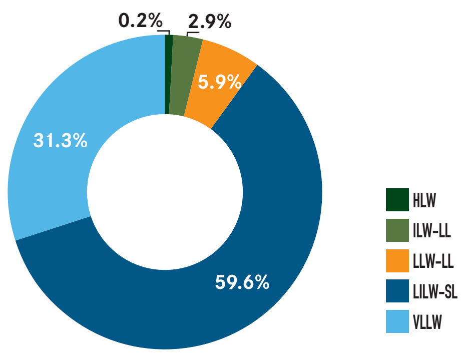
The volumes of radioactive waste in France as at 31 December 2016, including waste from other countries to be returned to those countries (see “Waste from outside France” on page 29), are shown in the table and chart below. In the table, the volumes are compared with those at the end of 2013 (2015 edition of the National Inventory).

BREAKDOWN AND CHANGE IN WASTE VOLUMES BY CATEGORY

Category	Volume at the end of 2016 (m^3)	2016/2013 change (m^3)
HLW	3,650	+ 440
ILW-LL	45,000	+ 1,260
LLW-LL	90,500	- 570
LILW-SL	917,000	+ 39,600
VLLW	482,000	+ 46,200
DSF*	1,800	- 1,970
Total	~ 1,540,000	+ 85,000

** Waste without a specific disposal solution (DSF) accounts for less than 0.1% of the total volume of waste, and is not shown in the chart on the right.*

BREAKDOWN BY VOLUME PER WASTE CATEGORY



MALVÉSI WASTE

The Orano Malvési plant (Narbonne) has been operating the first stage in the nuclear fuel conversion process since 1960. It is France's only entry point for mined natural uranium, which is then purified and converted into uranium tetrafluoride (UF_4). Liquid effluents from the process are neutralised with lime and stored in settling ponds for solid-liquid separation to occur. The settling ponds therefore gradually fill with the solid portion of the effluents (fluorine and metal hydroxide sludge) constituting solid waste from the conversion process. The liquid effluent fraction (nitrated liquids) clarified through settling is pumped into evaporation ponds, where it is concentrated via natural evaporation.

Malvési waste	Volume at the end of 2016 (m^3)[1]
Sludge from settling ponds	70,400
Legacy uranium conversion treatment residues	282,000
Nitrated effluents	374,000
Total	726,000

Waste from the Orano Malvési plant is displayed separately in the statements of waste stocks as at 31 December 2016, and in the forecasts pending a decision on the long-term management of this waste.

Legacy waste from the Orano Malvési plant (legacy uranium conversion treatment residues) is stored on site. Work is under way to find a safe, long-term management solution at the Malvési plant due to the specific nature of the waste it produces (large volumes).

Malvési waste	Volume at the end of 2016 (m^3)	2016/2013 change (m^3)
Total	726,000	+ 33,000

The increase in the volume of waste from the Orano Malvési plant is due to three extra years of production.

For waste produced after 1 January 2019, Orano is currently working on two projects, the first being to reduce solid waste volumes and give priority to existing management solutions, and the second, to use a heat process to treat future process liquid effluents and those currently stored in the evaporation ponds. These future processing changes would result in the production of two different waste streams:

- solid fluorides and gypsum waste, which the plant will produce in the future in the form of densified sludge stored in cells on site;
- solid waste from the heat treatment of nitrated liquid effluents from future conversion plant operations and from the recovery of stocks already being stored in evaporation ponds.

The volumes shown in the table on page 27 are based on a certain number of assumptions, set out in detail in the waste stream data sheets available at (inventaire.andra.fr). The main assumptions are as follows:

- conditioning assumptions for unconditioned waste. In accordance with the amended Order of 9 October 2008, producers must declare "the conditioned equivalent volume of waste, including for unconditioned or preconditioned waste, depending on the associated conditioning assumptions". The assumptions adopted by the producers correspond with their best assessment at the time of the declaration. They may be in the process of being studied or discussed with the French Nuclear Safety Authority or Andra for disposal;
- the waste from dismantling operations is included if the dismantling operation has actually been completed as at 31 December 2016. The graphite LLW-LL still in the GCR reactors (reactor stacks, reflectors in place, support areas) is therefore not included in the stocks at the end of 2016, but is taken into account in the waste volume forecasts, depending on the provisional dismantling date (see Chapter 3);
- when studies concerning the management solutions for a particular waste stream are still under way, the stream is classified in accordance with the assumption made by the producer. Andra checks the proposed classification. The choice of category does not predetermine acceptance of the waste at a disposal facility;
- the waste from outside France referred to in Article L. 542-2-1 of the Environmental Code, which is to be returned to the client in its country of origin, is included in the waste on the site of the Orano plant at La Hague;
- spent sources other than lightning conductors (sealed sources, smoke detectors, source rods, source clusters, etc.) are included in a special stream that is not associated with the waste classification management solutions, except for the legacy packages stored at Cadarache ("core source element" ILW-LL packages). In this edition, no conditioned equivalent volume is allocated to these sources, due to the variability of the possible management and conditioning assumptions at this stage. Lightning conductors are assigned to two waste streams of LLW-LL.

1 Quantities are expressed in gross volume.

MATERIALS AND WASTE FROM OUTSIDE FRANCE

France has adopted the principle of banning the disposal of radioactive waste from other countries in France. This was introduced into French law in 1991, taking into account the industrial activities involved in treating spent nuclear fuel or radioactive waste, and it was reaffirmed and set out in greater detail in the Act of 28 June 2006, codified in the Environmental Code.

The French nuclear industry has developed technology for reprocessing spent fuel in order to remove the materials that can be recovered (uranium and plutonium) for other nuclear power uses and separate out the final waste for disposal.

This technology, applied to the French nuclear cycle, was opened up by the CEA in the 1970s (under contract) to electricity companies in other countries. Since 1977, the CEA, then COGEMA (which became Areva and is now Orano), have included a clause in all their contracts enabling the final waste from processing their fuel to be returned to these foreign customers.

To verify compliance with these measures, in accordance with Article L. 542-1-1 of the Environmental Code, the operators concerned are required to prepare a report on the stocks and movements of radioactive substances to and from other countries. This report must include a prospective section.

These reports are publicly available:
- CEA Report – *Informations relatives aux opérations portant sur des combustibles usés ou des déchets radioactifs en provenance de l'étranger* – 2017 Report, June 2017, available on the CEA website: cea.fr ;
- Areva Report – *Traitement des combustibles usés provenant de l'étranger dans les installations d'Areva NC La Hague* – 2016 Report, June 2017, available on Orano's website: orano.group.

CHANGES SINCE THE 2015 EDITION

The differences noted between the volumes of waste in existence at the end of 2013 and those at the end of 2016 are due to the current production of waste, but also to other changes, as detailed below:

HLW HIGH-LEVEL WASTE

The changes in HLW stocks at the end of 2016 correspond mainly to the current production of waste generated by the vitrification of solutions from fission products generated by spent fuel processing at the Orano plant at La Hague.

ILW-LL INTERMEDIATE-LEVEL LONG-LIVED WASTE

The volume in stock at the end of 2016 was about 1,260 m^3 greater than the stocks at the end of 2013, as reported in the 2015 edition.

In addition to the current production of ILW-LL, minor changes can be identified:
- the change in the conditioning assumption for alpha-emitting contaminated waste from the Orano plant at La Hague. Orano is currently exploring an incineration/melting/vitrification process. Although this type of waste is still being produced, the change in conditioning assumptions decreases the total volume for this waste stream without decreasing the quantity of radioactive waste;
- the reclassification of several CEA ILW-LL bituminised waste packages as LILW-SL due to their radioactive contents.

LLW-LL LOW-LEVEL LONG-LIVED WASTE

The volume of LLW-LL has decreased by about 570 m^3 since the previous edition of the National Inventory.

With current annual production of waste in this category at around 700 m^3, the decrease is mainly due to following:
- the fact that a new conditioning scenario was taken into account for GCR fuel structural waste at La Hague, in line with the waste studies submitted to the ASN, resulting in a total decrease in volume for this stream (approx. - 4,000 m^3). However, this change does not correspond to a decrease in the quantity of radioactive waste;
- certain ion exchange resins from Orano La Hague, previously declared in the LILW-SL were reclassified as LLW-LL (approx. +1,200 m^3);
- the inclusion of waste from defence activities (approx. +1,300 m^3);
- the change in conditioning assumptions for graphite sleeves stored on the EDF Saint-Laurent-des-Eaux site (approx. +300 m^3).

LILW-SL LOW- AND INTERMEDIATE-LEVEL SHORT-LIVED WASTE

The increase in the volume of LILW-SL at the end of 2016 is mainly due to the three extra years of operation of the nuclear power reactor units and to the dismantling operations carried out during this period.

Changes observed in the conditioning assumptions made by waste producers have led to changes in the conditioned equivalent volume. For example, the assumptions concerning the incorporation rate of CEA fuel magnesium structural waste were reassessed, resulting in an increase in the total volume for the stream.

VLLW VERY LOW-LEVEL WASTE

By comparison with the figures as at the end of 2013, an increase of about 46,200 m^3 in the volume of VLLW can be reported for the end of 2016, mainly due to dismantling operations.

FOR WASTE WITHOUT A SPECIFIC DISPOSAL SOLUTION

The decrease in volume of waste without a specific disposal solution is due to the identification of a waste management solution for some of this waste, such as asbestos waste, classified as VLLW or LILW-SL.

RADIOLOGICAL CONTENT OF RADIOACTIVE WASTE AT THE END OF 2016

Radiological activities as at 31 December 2016 have been declared by waste holders.

For VLLW and LILW-SL, the producers declare the radioactivity levels of waste present on their sites. Andra declares the radioactivity of waste located in its disposal facilities.

The radioactivity levels are estimated using a method based on measurements or evaluations using calculations.

In the case of HLW, ILW-LL and LLW-LL, radioactivity is measured during production of the waste packages. The radioactivity of waste awaiting conditioning is estimated using calculations or based on sample analysis. They will be checked in greater detail when the waste is conditioned.

The total radioactivity declared by producers is around 205,000,000 TBq.

The table and chart summarise the total declared radioactivity.

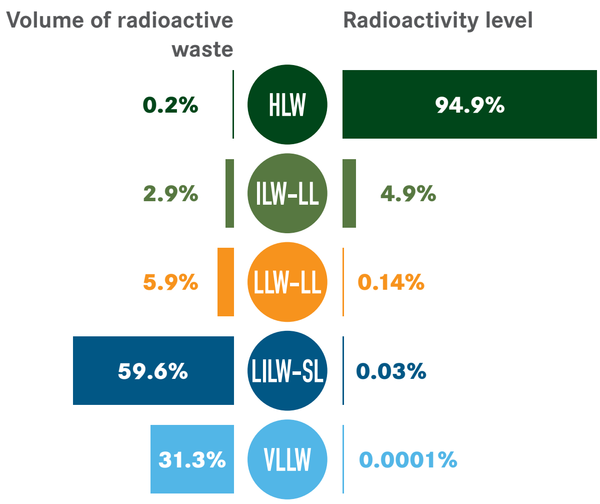
DECLARED RADIOACTIVITY AS AT 31 DECEMBER 2016

Category	Radiological activity as at the end of 2016 (TBq, i.e. 10^{12} Bq)
HLW	194,000 000
ILW-LL	10,100 000
LLW-LL	280,000
LILW-SL	52,000
VLLW	300
Total	~ 205,000,000

The radioactivity levels declared as at 31 December 2016 show that:

- **HLW accounts for 94.9% of total radioactivity** of the radioactive waste present at 31 December 2016. This is waste extracted from spent fuel (fission products and minor actinides generated in reactors). The main radionuclides that contribute to this radioactivity are caesium-134, caesium-137 and its metastable daughter, barium-137, strontium-90 and its daughter, yttrium-90;
- **ILW-LL accounts for 4.9%** of total radioactivity. The activated waste from reactors and the structural waste from nuclear fuel (CSD-C packages containing compacted hulls and end caps) account for around 75% of the total radioactivity of ILW-LL. The main radionuclides contained in the activated waste are iron-55, cobalt-60, cadmium-109, tritium for short-lived emitters, nickel-63 and metastable silver-108 for long-lived emitters. In the case of structural waste from fuel, the radionuclides that account for most of the radioactivity are iron-55, strontium-90 and its daughter, yttrium-90, caesium-137 and its metastable daughter, barium-137, tritium and cobalt-60 for short-lived emitters, and nickel-63 for long-lived emitters;
- **LLW-LL accounts for 0.14%** of total radioactivity. Graphite waste contains mainly tritium and cobalt-60 for short-lived emitters, carbon-14, nickel-63 and small quantities of chlorine-36 for long-lived emitters. Radium-bearing waste contains mainly alpha-emitting radionuclides of natural origin (radium, uranium, thorium, etc.);
- **LILW-SL accounts for 0.03%** of total radioactivity. Solid waste packages produced by CEA and Orano La Hague, as well as EDF packages containing ion exchange resins are mostly from waste streams that contribute the most to the radioactivity of the LILW-SL inventory;
- **VLLW accounts for 0.0001%** of total radioactivity.

BREAKDOWN BY VOLUME AND RADIOACTIVITY LEVEL OF RADIOACTIVE WASTE, END OF 2016



STORAGE OF RADIOACTIVE WASTE

Storage of radioactive materials or waste is defined in Article L. 542-1-1 of the French Environmental Code as "the operation consisting in placing the substances on a temporary basis in a surface or near-surface facility specially developed for the purpose, until such time as they are to be recovered".

Waste is stored on sites in dedicated facilities. This consists of:

- for waste to be taken to existing disposal facilities:
  - buffer storage of conditioned waste in the form of packages, of a logistical nature, for management of the flows to Andra facilities,
  - storage of waste, especially legacy waste, awaiting treatment, conditioning and subsequent removal;
- for waste to be taken to disposal facilities under development:
  - storage of waste, especially legacy waste, awaiting recovery and removal to other storage facilities or Andra facilities under development,
  - storage until such time as disposal solutions are made available,
  - storage of high-level waste, which has to be stored for several decades to decay, before it can be placed in deep disposal facilities.

WASTE ON PRODUCER/HOLDER SITES

Category	Volume (m^3) on producer/holder sites at end of 2016
HLW	3,650
ILW-LL	45,000
LLW-LL	90,500
LILW-SL	74,100
VLLW	154,000
DSF	1,800

Article 3 of the amended Order of 9 October 2008 requires producers to declare to Andra information concerning storage facilities designed for radioactive waste packages, for which definitive management solutions do not exist or are at the planning stage.

In addition, the PNGMDR provides forecasts of storage facility needs and identifies the capacities and storage durations required for these facilities, in order to ensure that they are suitable pending the opening of HLW, ILW-LL and LLW-LL disposal facilities. The operators usually assign a planned service life of about fifty years to the existing storage sites.

Furthermore, extensions to storage sites or new facilities are planned to meet the assessed needs of producers. The table on page 32 lists the storage sites licensed as at the end of 2016 used to store radioactive waste packages without a definitive management solution or with a solution still in the planning stage, with the level of use for the facilities in use. The table on page 33 shows the planned extensions for some of these storage sites.

The types of waste, the quantities stored and the storage locations are detailed in the *Inventaire géographique* [Geographical Inventory].

LICENSED STORAGE FACILITIES AT THE END OF 2016 USED TO STORE RADIOACTIVE WASTE PACKAGES WITHOUT A DEFINITIVE MANAGEMENT SOLUTION OR WITH A SOLUTION STILL IN THE PLANNING PHASE

Declaring entity	Site	Waste packages for which the storage facility is designed	Date of commissioning	Total storage capacity (number of packages)	Used capacity in number of packages at end of 2016	Level of use at end of 2016
Framatome	CEZUS (Jarrie)	Radium-bearing waste	2005	5,980[1]	3,800[1]	64%
Orano	Building S (La Hague)	Bituminised sludge packages	1987	20,000	11,798	59%
Orano	Building ES (La Hague)	Bituminised sludge packages[2]	1995	30,404	12,123	40%
Orano	Building R7 (La Hague)	CSD-V and CSD-B packages	1989	4,500	4,136	92%
Orano	Building T7 (La Hague)	CSD-V packages	1992	3,600	3,387	94%
Orano	Building EEV/SE (La Hague)	CSD-V and CSD-B packages	1996	4,428	4,406	100%
Orano	Building EEV/LH Ditch 30 (La Hague)	CSD-V and CSD-B packages	2013	4,212	3,872	92%
Orano	Building EEV/LH Ditch 40 (La Hague)	CSD-V and CSD-B packages	2017	4,212	0	0%
Orano	Building ECC (La Hague)	CSD-C packages	2002	20,800	14,981	72%
Orano	Building EDS/EDT (La Hague)	CBF-C'2 and CAC packages	1990	6,512	5,581	86%
Orano	Building EDS/ADT1 (La Hague)	CBF-C'2 packages	2006	660	0	0%
Orano	Building EDS/ADT2 (La Hague)	CBF-C'2 packages	2008	2,759	992	36%
Orano	Building EDS/EDC-A (La Hague)	Packages of cemented hulls and end caps	2009	1,125	1,125	100%
Orano	Building EDS/EDC-B and C (La Hague)	Packages of cemented hulls and end caps	1990	1,656	1,518	92%
CEA/DAM	Storage of tritiated waste (Valduc)	Tritiated waste	1995	5,000	3,733	75%
			2012	16,620	11,455	69%
Civilian CEA	Storage of bituminised waste packages (new generation) (Marcoule)	Bituminised sludge packages	2000	4,235[1]	3,957[1]	93%
Civilian CEA	Storage of vitrified waste packages (production) (Marcoule)	Vitrified waste packages and production shop operating waste packages	1978	3,800	3,470	91%
Civilian CEA	DIADEM	Dismantling irradiating and alpha-emitting waste packages	2021-2022	2,004	0	0%
Civilian CEA	INB 56 (Cadarache)	Miscellaneous waste packages	1968	7,500[1]	6,150[1]	82%
Civilian CEA	INB 164 (Cadarache)	500 L and 870 L packages, 500 L concrete packages for filtration sludge	2006	9,000	3,288	37%
Civilian CEA	ICPE 420 and 465 (Cadarache)	Radium-bearing waste	1992	26,800	25,315	94%
Civilian CEA	Storage of vitrified waste packages (pilot phase) (Marcoule)	Pilot phase glass packages	1976	46[1]	13[1]	28%
Civilian CEA	Storage of bituminised waste packages (previous generation) (Marcoule)	Bituminised sludge packages	1966	60,000	52,911	88%
EDF	Iceda (Bugey)	Cemented packages	2019[3]	2,186	0	0%
Solvay	Chef-de-Baie plant (La Rochelle)	Radium-bearing waste	1988	56,980[1]	7,593[1]	13%

1 Capacity shown in m^3.
2 The ES Building at La Hague is now used to store alpha drums (Pivic).
3 Iceda has existed administratively (INB 173) since the construction licence granted by the Decree of 23 April 2010.

PLANNED EXTENSIONS FOR STORAGE SITES

Declaring entity	Site	Waste packages to be stored	Provisional commissioning date[2]	Total storage capacity *(number of packages)*
Orano	Building ECC (La Hague)	CSD-C packages	2023	6,000
Orano	Building EEV/LH Ditches 50 and 60 (La Hague)	CSD-V and CSD-B packages	2022	8,424
Civilian CEA	Storage of bituminised waste packages (new generation) (Marcoule)	Bituminised sludge packages	~ 2020	4,235[1]
Civilian CEA	INB 164-CEDRA (Cadarache)	500 L and 870 L packages, 500 L concrete packages for filtration sludge	~ 2028	9,000
CEA/DAM	Storage of tritiated waste (Valduc)	Tritiated waste	2025	7,200
			2022	2,400

DISPOSAL OF RADIOACTIVE WASTE

Andra operates three disposal facilities (see Special Report 1). The Manche disposal facility (CSM) is in the closure phase. The industrial facility for grouping, storage and disposal (Cires) for VLLW and the Aube disposal facility (CSA) for LILW-SL are currently in operation.

The disposal of radioactive waste is defined in Article L. 542-1-1 of the Environmental Code as "the operation consisting in placing substances in a facility specially designed for their potentially final disposal in compliance with the principles stated in Article L. 542-1, with no intention of retrieving them at a later date".

FILL FACTORS OF ANDRA'S VARIOUS DISPOSAL FACILITIES

Site		Category	Total storage capacity	Used capacity at end of 2016	Fill factor at end of 2016
Cires	Morvilliers	VLLW	650,000 m^3	330,000 m^3	51%
CSA	Soulaines-Dhuys	LILW-SL	1,000,000 m^3	320,000 m^3	32%
CSM	Digulleville	LILW-SL	530,000 m^3	530,000 m^3	100%

76% of radioactive waste already generated is definitively disposed of at Andra facilities: VLLW at Cires (Industrial facility for grouping, storage and disposal) and LILW-SL at CSM (Manche disposal facility) and CSA (Aube disposal facility).

1 Capacity shown in m^3.
2 Extensions or new storage facilities are gradually put into service as needed.

RADIOACTIVE MATERIALS

A radioactive material is defined in Article L. 542-1-1 of the Environmental Code as “a radioactive substance for which a subsequent use is planned or envisaged, where applicable after processing” (see Chapter 1).

The following radioactive materials are presented in this chapter:

- **fuel before use** (ENU, ERU, mixed uranium-plutonium fuel or research reactor fuel);
- **fuel in use** in nuclear power plants (ENU, ERU or mixed uranium-plutonium fuel) and research reactors;
- **spent fuel** (ENU, ERU, mixed uranium-plutonium fuel, FNR fuel or research reactor or national defence fuel) awaiting reprocessing;
- **non-irradiated fuel scrap** (uranium or mixed uranium-plutonium);
- **non-irradiated separated plutonium**;
- **mined natural uranium**;
- **enriched natural uranium**;
- **uranium from spent fuel reprocessing**;
- **enriched uranium from spent fuel reprocessing**;
- **depleted uranium**;
- **thorium**;
- **suspended particulate matter** (by-product of the treatment of rare earth elements);
- **other materials**.

QUANTITIES OF RADIOACTIVE MATERIALS

The quantities of radioactive materials present in French territory as at 31 December 2016, including materials from other countries covered by Article L. 542-2-1 of the French Environmental Code are presented in the table below.

The unit used to present the quantities of radioactive materials is the tonne of heavy metal (tHM), which represents the quantity of uranium, plutonium or thorium contained in the materials, except in the case of fuel for defence purposes, which is expressed in tonnes of assemblies (t).

BREAKDOWN OF AND CHANGES TO RADIOACTIVE MATERIAL QUANTITIES

Radioactive materials	Mass at end of 2016 (tHM except defence-related spent fuel - in tonnes)	2016/2013 change (tHM except defence-related spent fuel - in tonnes)
ENU fuel before use	448	+ 3
ENU fuel in use in nuclear power plants	4,450	+ 95
Spent ENU fuel, awaiting reprocessing	11,400	- 548
ERU fuel before use	-	-
ERU fuel in use in nuclear power plants	53	- 150
Spent ERU fuel, awaiting reprocessing	578	+ 156
Mixed uranium-plutonium fuel before use or in production	38	0
Mixed uranium-plutonium fuel in use in nuclear power plants	430	+ 16
Spent mixed uranium-plutonium fuel, awaiting reprocessing	1,840	+ 325
Non-irradiated mixed uranium-plutonium fuel scrap, awaiting reprocessing	267	+ 33
Non-irradiated uranium fuel scrap awaiting reprocessing	-	-
FNR spent fuel, awaiting reprocessing	120	- 28
Research reactor fuel before use	-	- 0.2
Fuel in use in research reactors	0.8	+ 0.6
Other civil spent fuel	59	- 16
Non-irradiated separated plutonium, in all its physicochemical forms	54	+ 2
Mined natural uranium, in all its physicochemical forms	29,900	+ 3,810
Enriched natural uranium, in all its physicochemical forms	3,860	+ 1,090
Enriched uranium from spent fuel reprocessing, in all its physicochemical forms	-	-
Uranium from spent fuel reprocessing, in all its physicochemical forms	29,600	+ 2,690
Depleted uranium, in all its physicochemical forms	310,000	+ 23,500
Thorium, in nitrate and hydroxide form	8,570	+ 45
Suspended particulate matter (by-products of rare earth ore processing)	5	0
Other materials	70	- 2
Spent fuel for defence purposes	177	+ 21

CHANGES SINCE THE 2015 EDITION

The material category "Other civil spent fuel" was created by the Order of 16 March 2017 amending the Order of 9 October 2008. It corresponds to a merger of the categories "Other civil spent oxide fuel" and "Other civil spent metal fuel" in the 2015 edition of the National Inventory.

The differences noted between the quantities of radioactive materials in existence at the end of 2013 and those at the end of 2016 are due not only to nuclear production of waste, but also to:

- the reprocessing of spent ENU fuel to extract the plutonium and uranium they contain, resulting in a decrease of the stock of spent ENU fuel in 2016 and an increase in the stock of uranium from spent fuel reprocessing;
- the interruption in the supply of ERU fuel for EDF reactors pending an optimised industrial solution;
- the change in scope taken into account for fuel declarations for research reactors, including a portion of FNR spent fuel and other civil spent fuel;
- the creation of a strategic stock of enriched natural uranium;
- the storage of spent MOX fuel, ERU, scrap fuel, depleted uranium and recycled uranium awaiting reuse;
- the comparison of National Inventory declarations and national nuclear materials numbers for Superphénix FNR assemblies stored in the Creys-Malville fuel storage facility (APEC). The declaration for the end of 2016 includes a slightly different breakdown of the quantities of materials in new and spent fuel assemblies between the "FNR spent fuel awaiting reprocessing" and "Other materials", and takes into account the radioactive decay of plutonium in new fissile and spent fuel assemblies. The total quantity of Superphénix FNR fuel is 176 tHM.

STORAGE OF RADIOACTIVE MATERIALS

SPENT FUEL

The first step of spent fuel management begins with a period of storage in a pool. The role of the water is to protect operators from radiation and cool the fuel.

Fuel assemblies are unloaded from the power plant's reactor core underwater so that they are not in the open air at any time. They are stored in a pool located in the immediate vicinity of the reactor (the pool is also used for loading operations).

In France, fuel is stored in pools located in the immediate vicinity of the reactor for 13 to 40 months, until radioactivity decays sufficiently and the fuel cools enough for transport to the La Hague plant.

Assemblies to be reprocessed are transported to the La Hague plant, where they are stored in pools. The fuel is cooled in these pools for at least three years before being reprocessed. After spending, on average, a total of eight years in pools, ENU fuel is reprocessed to recover the uranium and plutonium it contains. The fission products and minor actinide residual waste are conditioned as vitrified waste and the hulls and end caps are compacted.

Spent ERU and MOX fuel is also stored in these pools until it is recycled at a later date, as EDF's intention is to eventually reprocess this fuel so its materials can be reused.

DEPLETED URANIUM

Depleted uranium can come in two forms, which are stored under conditions suited to their characteristics:

- UF_6 is generally stored as a solid, in cylindrical containers that meet very strict international regulations. This is because it is highly toxic when it comes into contact with water vapour in the air. The containers are designed to be stored in the open air;
- U_3O8 (which is very stable, like natural uranium) is conditioned in sealed metal containers known as "green cubes", with an average capacity of about 7 tonnes of uranium. These containers are stored in buildings.

In France, in order to reduce storage-related risks "at source", depleted uranium to be stored for a long period of time is stored as U_3O_8.

RECYCLED URANIUM

Recycled uranium is generally conditioned in containers as U_3O_8. These containers are stored in special buildings on the Orano Tricastin plant.

Some countries have made the decision not to reprocess their spent fuel. In the United States, fuel is stored in pools at the reactor facilities where it was used. Once the fuel has cooled enough, the assemblies are removed from the pools to be stored dry with ventilation, inside thick-walled casks that protect against radiation. In Sweden, spent fuel is grouped and stored in water in a subsurface facility (25 metres below ground) pending the creation of a geological disposal facility.

LOCATION OF RADIOACTIVE MATERIALS

At 31 December 2016 radioactive materials were located as detailed below.

Mined natural uranium is mainly stored at the Malvési and Pierrelatte Orano plants.

Enriched natural uranium is stored at the Orano Pierrelatte, Romans and Marcoule plants, and at CEA Cadarache.

A little over 173,000 tHM of depleted uranium is stored at the Orano Tricastin plant, around 136,000 tHM is stored at the Orano Bessines-sur-Gartempe plant, 500 tHM at the Orano Malvési plant, 200 tHM at the Orano Marcoule plant and 110 tHM at various CEA facilities.

Of the 29,600 tHM of recycled uranium stored at the Tricastin and La Hague plants, 2,700 tHM belong to foreign clients.

Around 6,300 tHM of thorium is stored in nitrate and hydroxide form at the plant in La Rochelle. There were also just under 2,300 (tHM) of thorium stored at CEA Cadarache. Lastly, a few tonnes of heavy metal of thorium owned by Orano are stored at the Bessines and Tricastin plants.

Suspended particulate matter (SPM), by-products of rare earth element processing, is stored at the plant in La Rochelle.

ENU fuel before use and in use is located at the 19 different PWR nuclear power plants currently in operation. MOX fuel before use and in use is located at the Blayais, Chinon, Dampierre, Gravelines, Saint-Laurent-des-Eaux and Tricastin nuclear power plants.

ERU fuel is currently used in the reactors at the Cruas nuclear power plant.

3,400 tHM of spent ENU fuel is stored at the 19 nuclear power plants and around 8,000 tHM at the La Hague plant. 30 tHM of fuel from outside France is also stored at the La Hague plant.

140 tHM of spent ERU fuel is stored at the Cruas nuclear power plant and around 440 tHM at the La Hague plant.

Around 500 tHM of spent MOX fuel is stored at the Blayais, Chinon, Dampierre, Gravelines, Saint-Laurent-des-Eaux and Tricastin nuclear power plants and around 1,300 tHM is stored at the La Hague plant.

106 tHM of FNR spent fuel from the Superphénix reactor is stored at Creys-Malville, 14 tHM of FNR spent fuel from the Phénix reactor is stored at the La Hague plant.

55 tHM of other civil spent fuel from research reactors is stored at the CEA facility and 4 tHM is stored at the La Hague plant.

Approximately 41 tonnes of plutonium is stored at the Orano La Hague plant, including 15 tonnes belonging to customers outside France. 10 tonnes of plutonium are in use in the process to manufacture MOX fuel (in the form of PuO_2, mixed oxide (U, PU)O_2 or in finished MOX assemblies), including one tonne belonging to customers outside France. Finally, 2 tonnes of plutonium are stored in various CEA facilities.

Non-irradiated mixed uranium-plutonium fuel scrap awaiting reprocessing is stored at the La Hague plant.

The Superphénix core is currently stored in the Creys-Malville plant.

CASCAD: SPENT FUEL DRY STORAGE BUNKER AT CADARACHE

France also has dry storage facilities for storing spent fuel until another management solution is decided on. The Cascad facility at Cadarache is operated by the CEA and has been in operation since 1990. It was designed to store irradiated nuclear fuel in steel containers for at least 50 years. At present, for the civil-related portion, it primarily holds the irradiated fuel from first-generation reactors (EL2-EL3, the Brennilis power plant), and spent fuel from the Phénix reactor. Besides its technical facilities for receiving, checking and conditioning, part of the facility has a storage unit with 319 shafts. These are cooled by ventilation through natural convection.

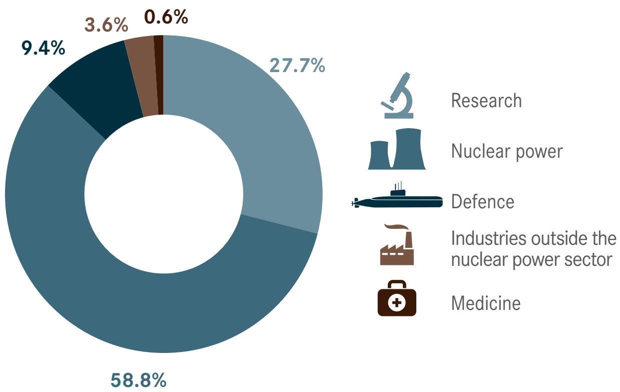
BREAKDOWN OF STOCKS BY ECONOMIC SECTOR

This section presents the inventory of radioactive waste and radioactive materials at 31 December 2016 broken down by economic sector.

The five economic sectors are defined as follows:

- **the nuclear power sector,** which mainly includes nuclear power plants for electricity production, as well as facilities used for nuclear fuel production (uranium ore extraction and processing, chemical conversion and enrichment of uranium concentrates), and reprocessing spent fuel;
- **the research sector,** which includes research in the civil nuclear field, and the fields of medicine, nuclear and particle physics, agronomy, chemistry and biology, among others.
- **the defence sector,** which mainly involves deterrence, including nuclear propulsion for certain ships and submarines, as well as associated research and the activities of the armed forces;
- **industries outside the nuclear power sector,** which includes rare earth mining, the manufacture of sealed sources, and various other applications such as weld inspection, medical equipment sterilisation, food sterilisation and preservation, etc.;
- **the medical sector**, which includes diagnostic and therapeutic activities (scintigraphy, radiotherapy, etc).

BREAKDOWN OF RADIOACTIVE WASTE BY ECONOMIC SECTOR AT THE END OF 2016



BREAKDOWN OF THE TOTAL VOLUME OF WASTE BY ECONOMIC SECTOR AND BY CATEGORY

Volume at the end of 2016 (m^3)	Nuclear power	Research	Defence	Industries outside the nuclear power sector	Medicine
HLW	3,250	161	232	-	-
ILW-LL	27,900	10,700	6,300	161	2
LLW-LL	38,300	13,900	18,000	20,300	-
LILW-SL	592,000	232,000	63,100	22,200	8,410
VLLW	243,000	170,000	56,500	12,100	88
Total	~ 905,000	~ 427,000	~ 144,000	~ 54,700	~ 8,500

BREAKDOWN OF THE TOTAL MASS OF RADIOACTIVE MATERIALS BY ECONOMIC SECTOR

Economic sector	Quantity at end of 2016 (in tHM)
Nuclear power	395,000
Research	210
Defence	177 tonnes
Industries outside the nuclear power sector	6,400
Medical	-

NUCLEAR POWER SECTOR

This sector includes nuclear power plants, fuel cycle facilities, waste treatment facilities and the sector's facility maintenance centres.

Most of the waste in the HLW, ILW-LL and LILW-SL categories is produced by this economic sector.

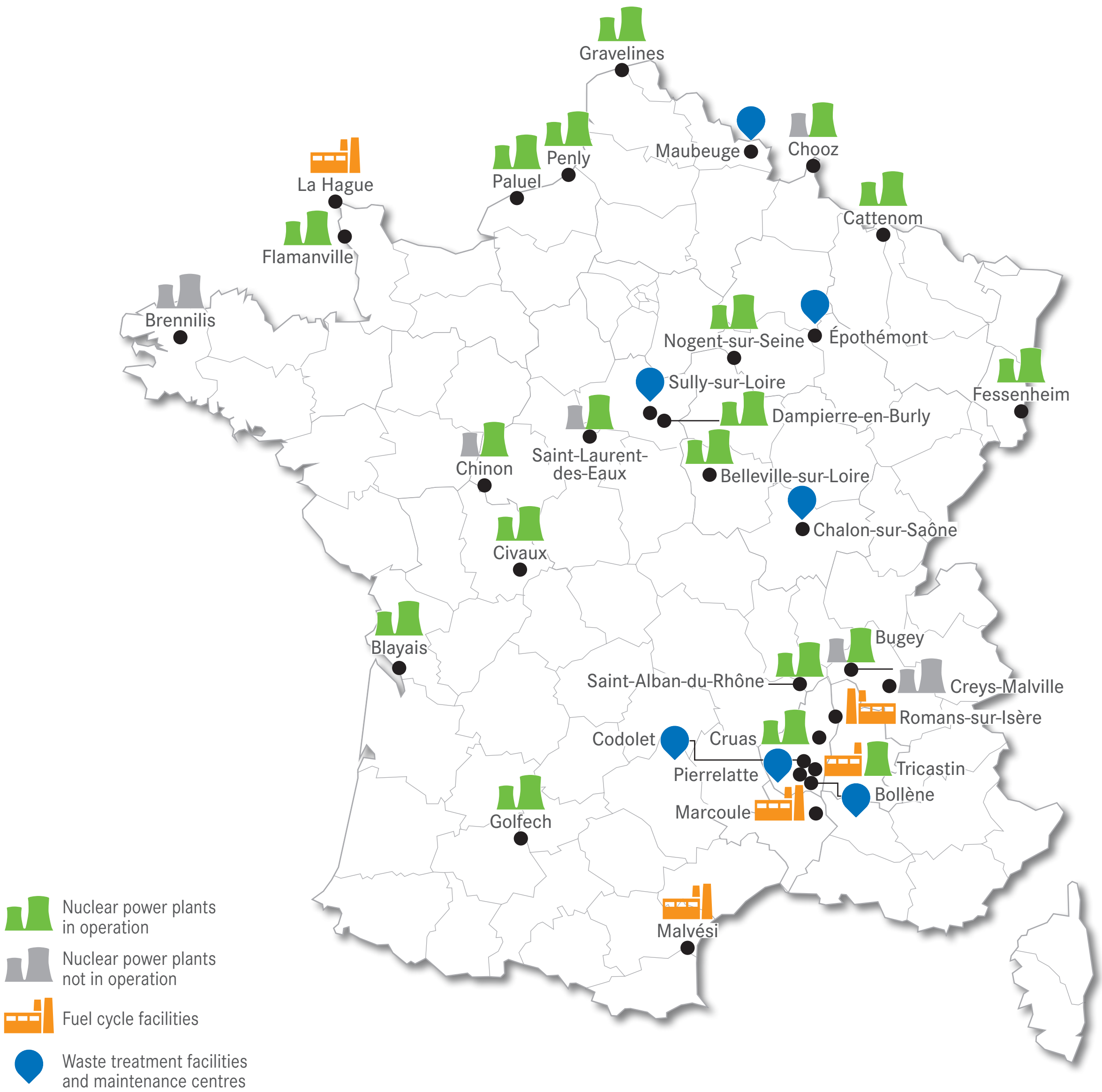
This sector includes all the radioactive materials related to ENU, MOX and ERU fuel, as well as plutonium, thorium and uranium in all its physicochemical forms. New and irradiated fuel from Superphénix is included in this sector.

NUCLEAR POWER PLANTS

REACTORS IN OPERATION

France's nuclear power industry currently comprises 58 working nuclear reactors, located on 19 sites.

In France, the operating nuclear power plant fleet consists entirely of light water units, with 58 pressurised water reactors (PWRs) using enriched uranium commissioned between 1977 and 1999.



Another pressurised water reactor, the EPR (Flamanville) is currently under construction and will join the reactor fleet in operation when it is commissioned.

The operation of EDF's nuclear power plants and related maintenance activities mainly generate VLLW and LILW-SL, and to a lesser extent, ILW-LL.

Besides HLW and ILW-LL from the reprocessing of irradiated fuel from nuclear power plants, the reprocessing plant also produces ILW-LL, LILW-SL and VLLW.

ILW-LL from nuclear operation, mainly involves burnable poison rod assemblies (absorber rod assemblies whose role is to reduce core reactivity during the first operating cycle) and control rods (absorber rod assemblies in which the absorber rods slide inside the fuel assemblies to control reactor power).

The conditioning assumption adopted by EDF is cementation of this metal waste at a centralised facility on the Bugey site (Iceda), responsible for cutting, conditioning in concrete containers and intermediate storage of the packages.

LILW-SL and VLLW consists of equipment, filtration/purification residue (resins, filters, sludge, etc.), consumables (vinyl or cotton suits, etc.), as well as scrap parts (valves, tubes, etc.).

This waste has been contaminated by contact with fluids (reactor coolant, ventilation air, etc.) that carry fission products or corrosion products activated when they pass through the core.

LILW-SL produced by EDF is conditioned on site at the nuclear power plants in concrete waste packages or in metal drums or containers, with the exception of incinerable waste and scrap iron that can be melted down, which is sent to the Cyclife Centraco plants.

Spent fuel reprocessing: one reactor produces between 2 and 3 m^3 of HLW and 4 to 5 m^3 of ILW-LL per year. Dismantling: deconstruction of a PWR is expected to produce on average 18,000 m^3 of radioactive waste. This amount of waste, which is primarily LILW-SL and VLLW, varies according to the power of the reactor.

The VLLW produced by EDF varies in nature. It comes from "potential nuclear waste production zones" in the nuclear power plants with a very low level of radioactivity, in some cases, so low that it is difficult to measure. Part of this waste is generated by the dismantling of the oldest reactors and by the operation of nuclear power plants.

Major maintenance operations in nuclear power plants, in particular the replacement of steam generators and reactor vessel heads, produce voluminous waste. EDF considers that a portion of steam generators can be recycled.

Nuclear power plant fuel

PWR fuel assemblies remain in nuclear power reactor cores for a few years. Once they are removed, they are stored in a cooling pool near the reactor and then sent to the La Hague reprocessing plant. A 900 megawatt reactor constantly draws on 157 fuel assemblies, each of which contains around 500 kg of uranium. Radioactive materials in nuclear power reactors are primarily uranium oxide-based ENU fuel and to a lesser extent, uranium and plutonium MOX fuel authorised in 24 reactors. Enriched reprocessed uranium (ERU) fuel is currently not being supplied. Four reactors are authorised to use ERU fuel manufactured using enriched reprocessed uranium.

REACTORS IN SERVICE

Sites and dates of connection to the grid (first reactor – last reactor)	Number of reactors in operation - PWR series	Net capacity per reactor in MWe*	Number of reactors licensed to load MOX fuel
Fessenheim (04/1977 – 10/1977)	2	880	-
Bugey (05/1978 – 07/1979)	4	910/880	-
Gravelines (03/1980 – 08/1985)	6	910	6
Dampierre (03/1980 – 08/1981)	4	890	4
Tricastin (05/1980 – 06/1981)	4	915	4
Saint-Laurent-des-Eaux B (01/1981 – 06/1981)	2	915	2
Blayais (06/1981 – 05/1983)	4	910	4
Chinon B (11/1982 – 11/1987)	4	905	4
Cruas (04/1983 – 10/1984)	4	915	-
Paluel (06/1984 – 04/1986)	4	1,330	-
Saint-Alban - (08/1985 – 07/1986)	2	1,335	-
Flamanville (12/1985 – 07/1986)	2	1,330	-
Cattenom (11/1986 – 05/1991)	4	1,300	-
Belleville (10/1987 – 07/1988)	2	1,310	-
Nogent-sur-Seine (10/1987 – 12/1988)	2	1,310	-
Penly (05/1990 – 02/1992)	2	1,330	-
Golfech (06/1990 – 06/1993)	2	1,310	-
Chooz B (08/1996 – 04/1997)	2	1,455	-
Civaux (12/1997 – 12/1999)	2	1,450	-
19 sites	**58 reactors**	**63.1 GWe**	**24 reactors**

** MWe: megawatt electrical*

The Flamanville EPR is expected to have a rated capacity of 1,650 MWe.

REACTORS IN THE DISMANTLING PHASE

EDF operated six previous generation gas-cooled graphite-moderated reactors (GCRs) developed by the CEA and located on three different sites: the three Chinon A reactors, the two Saint-Laurent-des-Eaux A reactors and the Bugey 1 reactor. The dismantling of these reactors is under way and the resulting waste is included in this economic sector.

Dismantling operations on the first GCR reactor tank of EDF's lead GCR unit is scheduled to begin some time around 2035. The first graphite LLW-LL packages should start being produced in 2030 with the reconditioning of waste (sleeves) stored in the Saint-Laurent A silos. EDF graphite LLW-LL is to be removed around 2070. Graphite sleeves stored in silos at the Saint-Laurent-des-Eaux plant and the Marcoule and La Hague plants are counted as waste already generated.

In addition, three reactors of three different types are also being dismantled. These are the first Chooz PWR, the Brennilis EL4 heavy water reactor, and the fast neutron reactor at Creys-Malville.

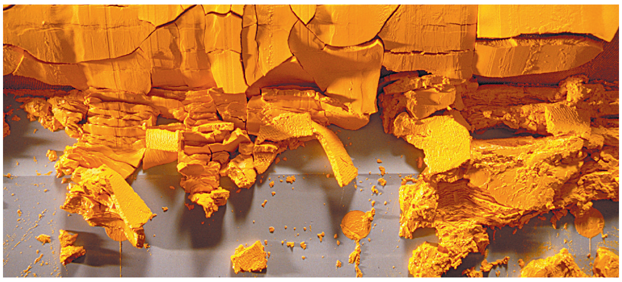
Irradiated FNR fuel and the core of the Superphénix reactor are currently being stored at Creys-Malville.

REACTORS IN THE DISMANTLING PHASE

Site	Type	Number of reactors
Chooz	PWR: pressurised water reactor	1
Brennilis	HWR: heavy water reactor	1
Saint-Laurent-des-Eaux	GCR: Graphite-moderated gas-cooled reactor	2
Chinon	GCR: Graphite-moderated gas-cooled reactor	3
Bugey	GCR: Graphite-moderated gas-cooled reactor	1
Creys-Malville	FNR: Fast neutron reactor (fast breeder reactor)	1

FUEL CYCLE FACILITIES

Uranium ore extracted from mines is crushed, ground and then impregnated with an oxidising acid solution to dissolve the uranium and selectively extract the solution. This is followed by several purification steps before obtaining a uranium mining concentrate called yellowcake. It is in this form that the ore arrives at the conversion plant in France.



Yellowcake

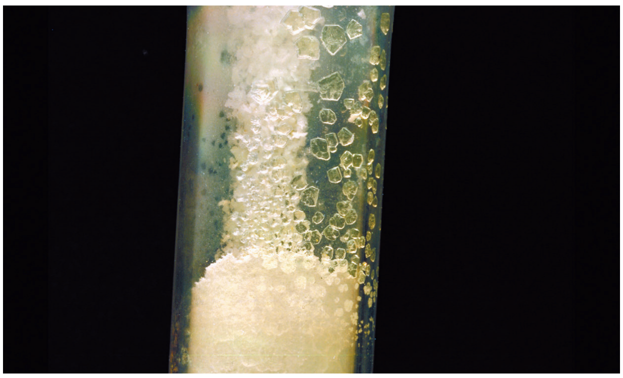
Open-cast uranium mine

WASTE FROM THE EXTRACTION OF URANIUM ORE

Uranium mining in France ended in 2001. The residues from the treatment of ore and some of the waste produced are permanently disposed of on former mining sites (see Chapter 4).

CONVERSION

After purification of the uranium contained in the ore concentrates, it is transformed into uranium hexafluoride (UF_6), in which form it is in a gaseous state at a temperature of 60°C. This is the conversion step. This gaseous state is essential to the process used in enrichment plants.



Uranium hexafluoride crystals

The transformation takes place in two steps:

- in the Orano plant at Malvési where the yellowcake is converted into uranium tetrafluoride (UF_4);
- then in the Orano plant at Tricastin, where a fluorination process changes the uranium tetrafluoride into uranium hexafluoride.

The chemical process used at the Orano Malvési plant generates solid residue and liquid effluents.

The radioactive material used in the conversion step is mined natural uranium in various physicochemical forms.

ENRICHMENT

Natural uranium consists mainly of two isotopes: uranium-238 and uranium-235. The fissile uranium-235 is much less abundant in the natural state than uranium-238. It only accounts for 0.7% of natural uranium.

Enrichment involves increasing the proportion of uranium-235.

Today, most reactors use uranium enriched to about 4% in uranium-235 as fuel.

Centrifugation is the enrichment process implemented since 2011 at the Orano Georges Besse II plant on the Tricastin site.

The UF_6 gas is introduced into a cylinder rotating at very high speed under vacuum, in a sealed container.

Under the effect of centrifugal force, the heavier molecules move to the walls of the tube while the lighter ones (uranium-235) migrate to the centre.

Furthermore, the gas is placed in axial circulation using physical mechanisms. The gas containing the lightest molecules, located at the centre, rises, whereas the gas containing the heaviest molecules descends.

The enriched and depleted products are recovered at the two ends of the tube, at the top and bottom.

This elementary step to separate the molecules is repeated in a set of centrifuges placed in series, called cascades.

The fuel conversion and enrichment facilities produce low-level or very low-level uranium-contaminated radioactive operating waste, which is disposed of at CSA and Cires. It is usually conditioned in drums or cement containers.

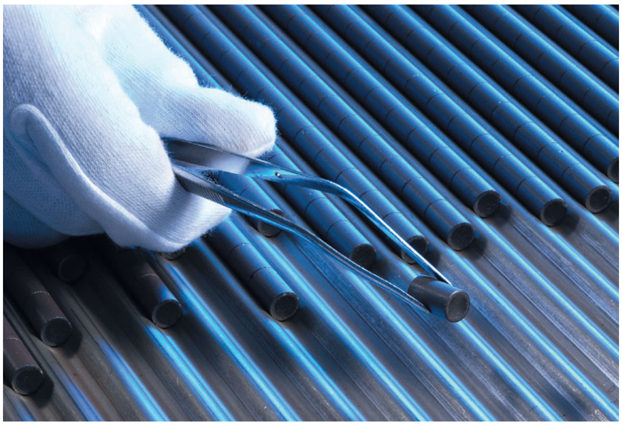
The radioactive materials obtained after the enrichment process are enriched natural uranium, and depleted natural uranium.

FUEL MANUFACTURING

There are basically two types of fuel manufactured to produce electricity: ENU (enriched natural uranium oxide) and MOX (mixed uranium and plutonium oxide).

Enriched natural uranium oxide fuel (ENU fuel)

Enriched uranium hexafluoride (UF_6) is converted into uranium oxide powder then compacted into pellets to manufacture ENU fuel. The pellets are inserted into metal cladding to hold them in place, thus forming fuel assemblies.



Fuel pellets

The Romans Framatome plant performs both these operations. Waste produced by the plant is primarily VLLW from the operation and maintenance of the facilities;

Uranium and plutonium mixed oxide fuel (MOX fuel).

The Orano Melox plant located on the Marcoule site has been manufacturing MOX fuel since 1995 using a process similar to that for ENU fuel, but using a blend of uranium oxide and plutonium oxide powders.

The plutonium used comes from spent fuel reprocessing at the Orano La Hague plant. Depleted natural uranium from the uranium enrichment process is also used.

The waste produced by Melox is technological LILW-SL and ILW-LL, part of which is non-irradiating yet contaminated by alpha-emitting radionuclides.

Melox also produces non-irradiated mixed uranium and plutonium fuel scrap (pellets, powder, etc.) considered as radioactive materials that cannot be directly recycled in the production cycle. Scrap is sent to La Hague for storage pending use at a future date.

The Cadarache fabrication complex (CFCa) located at the Cadarache CEA centre also produced MOX fuel until July 2003.

MOX fuel is no longer produced at Cadarache. Dismantling operations began in 2007. The Melox plant started industrial production in 1995. Its production licence is for 195 tHM (tonne of heavy metal) of MOX fuel per year, intended for use in light water reactors in France and other countries.

FUEL REPROCESSING

When removed from the reactor, spent ENU fuel contains around 95% uranium, 1% plutonium and 4% final waste.

Spent fuel reprocessing consists in recovering reusable materials, namely uranium and plutonium, and conditioning the final waste.

The operations performed in the reprocessing plants can be broken down into three steps:

- spent fuel assemblies are received and stored in pools to cool down (for several years) prior to processing;
- the spent fuel assemblies are reprocessed by:
  - mechanically shearing the assemblies into approximately 35 mm sections,
  - chemically dissolving the spent fuel contained in these sections using nitric acid,
  - separating the dissolved uranium and plutonium by chemical extraction and purification. The recycled uranium recovered from the spent fuel reprocessing is transferred to the Tricastin shop to be transformed into U_3O_8. The separated plutonium is sent to the MOX fuel manufacturing plant (Melox);
- treatment and conditioning of final waste in stable forms, adapted to the radioactivity and radioactive half-life of the elements they contain:

- the fission products and minor actinides are incorporated into a glass matrix, poured into a stainless steel container (CSD-V). This waste makes up the majority of HLW,
- the metal components of PWR fuel assemblies, (cladding tubes, spacer grids, end caps) are now decontaminated, compacted and conditioned in standard compacted waste containers (CSD-C). Previously, this structural waste was mixed into a cement matrix. Compacting enables the waste disposal volume to be optimised. These two waste streams make up the majority of ILW-LL,
- structural waste from GCR fuel assemblies is currently stored in silos at La Hague, Marcoule or at Saint-Laurent-des-Eaux. The conditioning process is currently being studied.

Fuel reprocessing also generates waste from maintenance and operations, which is conditioned in different types of containers according to type, level of radioactivity and its management solution. In general, solid ILW-LL (tools, gloves, filters, etc.) is compacted and put into drums. The methods for conditioning the sludge from liquid waste treatment have changed over time. Initially, a bituminisation process, which involved embedding sludge in bitumen was used. Optimisation of the conditioning processes and changes to safety-related constraints led to the use of other processes, such as vitrification and cementation. LILW-SL is disposed of at the CSA facility. It may first be treated at the Cyclife Centraco plant via incineration or melting down, depending on its physicochemical nature.

VLLW is conditioned in big bags or metal containers to be transferred and disposed of at the Cires facility.

OPERATIONS CONDUCTED AT REPROCESSING PLANTS

Spent fuel reprocessing operations at the first reprocessing plant (at Marcoule) ceased in late 1997 and were quickly followed by the dismantling project, the largest decommissioning site in France.

These decommissioning operations (now under the responsibility of the CEA), not including the support installations, will produce several thousand tonnes of waste, most of which will be suitable for transfer to a surface disposal facility.

In 1966 a second spent fuel reprocessing plant was commissioned on the La Hague site, UP2-400. It was operated by the CEA until 1976, then by Cogema (which became Areva and is now Orano), and has now been shut down. With a capacity of 400 tonnes of fuel per year, the UP2-400 plant started by reprocessing spent fuel assemblies from the GCR series. It was then adapted to reprocess PWR fuel assemblies.

Between 1976 and 1987, the UP2-400 plant alternated between reprocessing spent fuel assemblies from the GCR and PWR series.

From 1987, UP2-400 was assigned specifically to the PWR series, while the Marcoule plant reprocessed fuel from the other series.

In the early 1980s, Orano began building two new plants, each of the same capacity (around 800 tonnes/year), which now reprocess spent fuel to cater to French and foreign demand:

- UP3 (started up in 1990) was initially dedicated to spent fuel supplied by foreign customers;
- UP2-800 was commissioned in August 1994 and took over from the UP2-400 plant (shut down on 1 January 2004).

WASTE TREATMENT FACILITIES AND MAINTENANCE CENTRES

Running the various facilities that handle radioactivity entails ancillary but required industrial support operations: treating the waste generated by facility operation and maintenance centres. The operator usually carries out this treatment and manages any waste produced.

In some cases, the operator may call upon dedicated off-site facilities to carry out these operations.

WASTE TREATMENT CENTRES

The Cyclife Centraco facility at Codolet operates two processes:

- metal waste is melted;
- certain types of waste are incinerated.

It treats low-level incinerable solid waste and liquid waste produced by nuclear facilities, research laboratories and hospitals. The resulting ash and clinker is rendered inert and conditioned in packages sent to Andra's waste disposal facilities in the Aube. The ingots produced by melting metal waste is either recycled for radiological protection incorporated in the waste packages, or sent to Andra's waste disposal facilities in the Aube.

STMI and Socatri in Bollène specialise in decontaminating radioactive materials via conversion, conditioning and disposal operations. They thus produce radioactive waste.

Daher in Épothémont specialises in sorting and conditioning VLLW according to Andra or Cyclife Centraco specifications. The Onet Technologies Sogeval facility at Pierrelatte offers radioactive waste treatment and storage services.

MAINTENANCE CENTRES

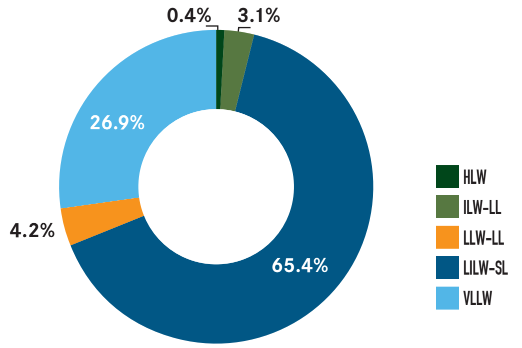
Specialised companies provide maintenance for major facilities or the decontamination of certain equipment.

These maintenance centres generally hold more limited quantities of waste than the waste treatment centres, mostly intended for the CSA.

Somanu (*Société de Maintenance Nucléaire*), in Maubeuge, specialises in repairing, servicing and assessing equipment, primarily from reactor coolant and auxiliary systems.

The tooling maintenance centre (Cemo) in Chalon-sur-Saône and the Sully-sur-Loire tooling maintenance and decontamination centre perform maintenance of tooling used during operations on nuclear sites.

RADIOACTIVE WASTE FROM THE NUCLEAR POWER SECTOR



Category	Volume at the end of 2016 (m^3)
HLW	3,250
ILW-LL	27,900
LLW-LL	38,300
LILW-SL	592,000
VLLW	243,000
Total	~ 905,000

VOLUME OF WASTE FROM THE ORANO MALVÉSI PLANT

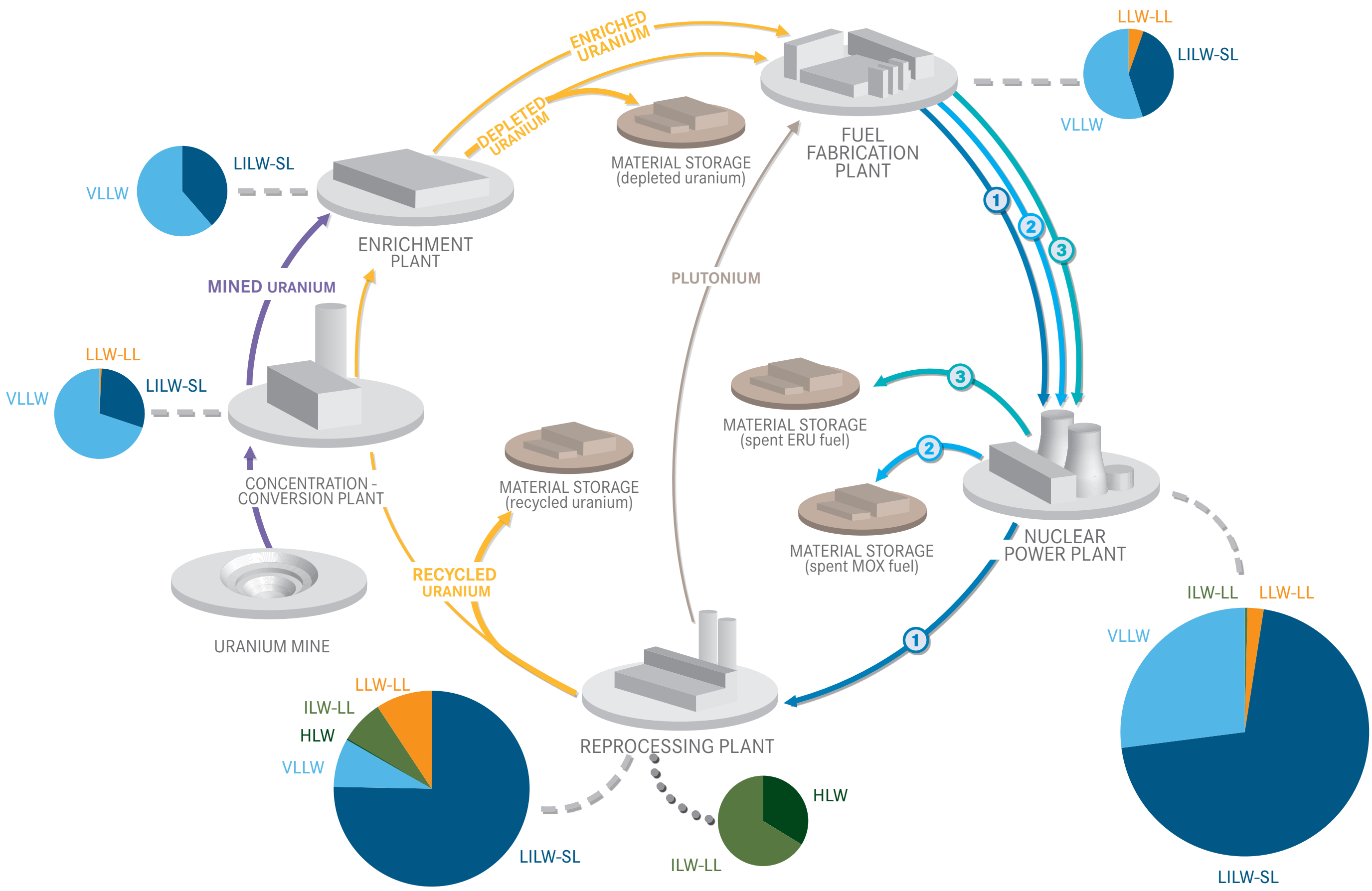
Malvési waste	Volume at the end of 2016 (m^3)[1]
Sludge from settling ponds	70,400
Legacy uranium conversion treatment residues	282,000
Nitrated effluents	374,000

RADIOACTIVE MATERIALS FROM THE NUCLEAR POWER SECTOR

Category	Mass at end of 2016 (tHM)
ENU fuel before use	448
ENU fuel in use in nuclear power plants	4,450
Spent ENU fuel, awaiting reprocessing	11,400
ERU fuel before use	-
ERU fuel in use in nuclear power plants	53
Spent ERU fuel, awaiting reprocessing	578
Mixed uranium-plutonium fuel before use or in production	38
Mixed uranium-plutonium fuel in use in nuclear power plants	430
Spent mixed uranium-plutonium fuel, awaiting reprocessing	1,840
Non-irradiated mixed uranium-plutonium fuel scrap, awaiting reprocessing	267
Non-irradiated uranium fuel scrap awaiting reprocessing	-
FNR spent fuel, awaiting reprocessing	106
Non-irradiated separated plutonium, in all its physicochemical forms	52
Mined natural uranium, in all its physicochemical forms	29,800
Enriched natural uranium, in all its physicochemical forms	3,850
Enriched uranium from spent fuel reprocessing, in all its physicochemical forms	-
Uranium from spent fuel reprocessing, in all its physicochemical forms	29,600
Depleted uranium, in all its physicochemical forms	310,000
Thorium, in nitrate and hydroxide form	2,270
Other materials (Superphénix core)	70

1 Quantities are expressed in gross volume.

FOCUS ON THE PRODUCTION OF RADIOACTIVE MATERIALS AND WASTE BY THE FRENCH NUCLEAR POWER SECTOR



1	Enriched natural uranium oxide fuel (ENU)
2	Uranium and plutonium mixed oxide fuel (MOX)
3	Enriched recycled uranium oxide fuel (ERU)
	Operation and dismantling waste - Inventory at the end of 2016
	Residual waste after spent fuel reprocessing - Inventory at the end of 2016

RESEARCH SECTOR

The research sector covers all research activities, excluding those carried out for the defence sector, which are included in that sector. Research activities for the nuclear power industry and the medical sector are therefore included.

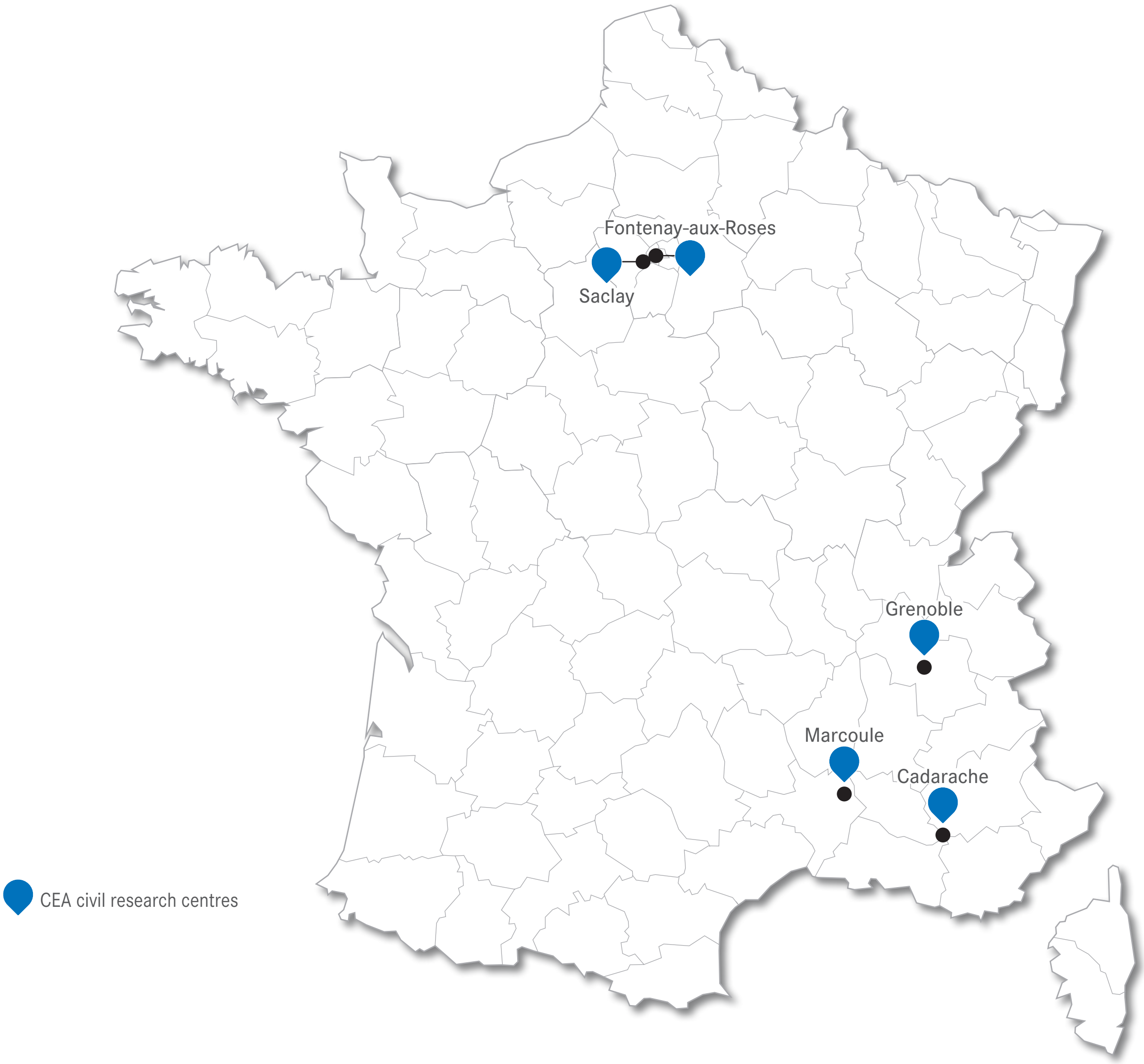
This sector includes:

- the installations and facilities of the French Alternative Energies and Atomic Energy Commission's (CEA) four civil research centres: Cadarache, Marcoule, Paris-Saclay, Grenoble ;
- all public or private research facilities, for example the European Organization for Nuclear Research at Prévessin (CERN), the Institut Laue-Langevin (ILL) in Grenoble and the large-scale heavy ion accelerator (GANIL) in Caen, or the Institute of Nuclear Physics of Orsay (IPNO). Most of these facilities use radioactivity as a characterisation tool.

The radium-bearing waste generated during the work to remediate the former uranium ore treatment plant at Le Bouchet, operated by the CEA between 1946 and 1970, is allocated to this economic sector.

The radioactive materials from the research sector correspond to research reactor fuel before use, in use, or spent fuel. This sector also includes some plutonium and uranium in all physicochemical forms. The Phénix fuel awaiting reprocessing is also included in this economic sector.

CEA CIVILIAN RESEARCH CENTRES



Due to the number and diversity of the CEA's civil nuclear activities, a large array of waste is produced and requires management. Most of this waste is generated from nuclear power activities within the Nuclear Energy Division.

The Nuclear Energy Division provides public and industrial authorities with expertise and innovation on current and future nuclear energy production systems with a focus on three major areas:

- future nuclear systems, referred to as fourth-generation systems, with associated reactors and fuel cycles (including the Astrid project);
- optimisation of the current industrial nuclear sector in support of industry;
- development and operation of major experimental and simulation tools essential for research.

As a civil nuclear operator, the CEA Nuclear Energy Division manages and updates its nuclear research facilities (research reactors or critical assemblies, hot laboratories used for studies on irradiated objects, experimental platforms) and support facilities (workshop, analysis and characterisation laboratory, waste treatment and storage facilities, etc.). It conducts construction and renovation projects on its facilities, as well as cleanup and dismantling projects on facilities at the end of their service life, and manages the waste it produces. In some cases, it develops specific methods and tools for these operations.

The Nuclear Energy Division carries out most of its activities at three centres:

MARCOULE (GARD)

Nuclear activities at the Marcoule centre primarily focus on nuclear fuel cycle research and major cleanup and dismantling, and waste recovery and conditioning projects for facilities no longer in operation (reprocessing pilot project shop and plant, GCR and Phénix reactors, etc.).

The facilities operated at the Marcoule centre (e.g. Atalante) are dedicated to research and development of uranium preparation techniques, spent nuclear fuel reprocessing, dismantling techniques for nuclear facilities at the end of their life and management of the most radioactive waste.

The Phénix reactor (shut down since late 2009) was built and operated by the CEA and EDF and was a research tool especially for plutonium consumption and actinide incineration projects.

CADARACHE (BOUCHES-DU-RHÔNE)

Nuclear activities at the Cadarache centre primarily focus on research to optimise nuclear reactors and studies on the behaviour of uranium and plutonium-based fuel in different configurations, and on fourth-generation reactors.

The site has R&D facilities for nuclear fuel (Rapsodie experimental FNR reactor now shut down, and PWR series Scarabée and Cabri reactors) and irradiated materials, waste treatment facilities and waste and materials storage facilities. The Jules-Horowitz reactor (JHR) currently being built will be used to develop and qualify nuclear materials and fuel and for nuclear medicine.

PARIS-SACLAY

The multidisciplinary Paris-Saclay centre (which has grouped the Saclay and Fontenay-aux-Roses facilities since 2017) is used for activities in all of the civil CEA's fields, such as nuclear power, life sciences, physical sciences and matter, climate and the environment, technological research and education.

Fontenay-aux-Roses Facility (Hauts-de-Seine)

The Fontenay-aux-Roses facility is undergoing major changes and switching its focus to medical applications (radiobiology, emerging infectious diseases, innovative and gene therapies, etc.). Its nuclear research facilities, which have been shut down, are undergoing cleanup and dismantling. Most of the waste produced is contaminated by alpha emitters and fission products.

Nuclear research fields at this site included chemical engineering, fuel assembly reprocessing and the chemistry of transuranian elements.

Saclay Facility (Essonne)

The main activities at the Saclay facility focus on energies, global warming, medicine (cancer, Alzheimer's, prions, etc.), nanoscience, robotics, fundamental research, etc. It also plays a major role in the design and construction of very large-scale research infrastructures.

The nuclear activities focus particularly on upstream research, simulation, materials and chemistry, as well as cleanup and dismantling and waste recovery and conditioning.
The Saclay centre is equipped with major nuclear facilities (research laboratories, Orphée and Osiris reactors, which have been shut down since 2015) for fundamental research, applied research in nuclear power production, the production of medical radioisotopes, research for medical applications.

Part of the waste produced is treated and conditioned at the Centre's support facilities: INB 72 for solids and INB 35 for liquid waste. Other waste is sent to Marcoule or Cadarache for treatment and possible storage, in preparation for disposal at an existing or future Andra site.

Grenoble centre (Isère)

The denuclearisation programme of the CEA centre in Grenoble focuses on six nuclear facilities, the oldest dating back to 1958, including three research reactors (Mélusine, Siloette, Siloé), the Active Materials Analysis Laboratory (LAMA) and two effluent and nuclear waste treatment facilities (STED). The project consisted in dismantling and remediating up these six facilities. The three reactors were decommissioned and demolished. The LAMA was decommissioned in 2017 and cleanup operations are being completed on the STED so that it can be decommissioned The Grenoble centre now focuses most of its research on the development of new technologies in energy, healthcare, information and communication.

RESEARCH FACILITIES (EXCLUDING CEA CENTRES)

This sector covers all public and private research centres, together with the units of all the major institutions or industrial groups that are primarily or exclusively involved in research.

WASTE TO BE PRODUCED BY THE ITER FACILITY

ITER is an international civil nuclear fusion research facility being built at Cadarache. It is based on a magnetic confinement concept that uses magnetic fields to contain a plasma in a ring-shaped vacuum vessel called a "tokamak". The first plasma experiments are scheduled to begin in late 2025 and the first waste will be produced after 2030.

The waste generated by ITER will consist of technological waste such as the elements from replacing some components of the machine during its operation or dismantling waste. This waste will be characterised by the presence of tritium, which is used as fuel, and radionuclides generated by the activation of the vacuum vessel walls by high-energy neutrons.

The amount of radioactive waste generated during its operation is estimated at approximately 5,200 m^3. Waste generated from dismantling the facility at the end of its use is estimated at approximately 30,000 m^3. Over 90% will be VLLW or LILW-SL managed through existing disposal solutions.

ILW-LL will be treated, conditioned and disposed of through solutions that will be implemented for this type of waste in accordance with regulations. ITER will not produce any high-level waste.

Research is currently planned for defining materials with low activation under irradiation (such as Eurofer), in order to significantly reduce the amount of waste produced. This is the objective of the IFMIF programme (International Fusion Materials Irradiation Facility). It is a research and development project using a materials irradiation facility to be built in Japan.

Many public and private facilities use radionuclides. Altogether, Andra has listed 500 producers in the research sector (excluding the CEA) at the end of 2016.

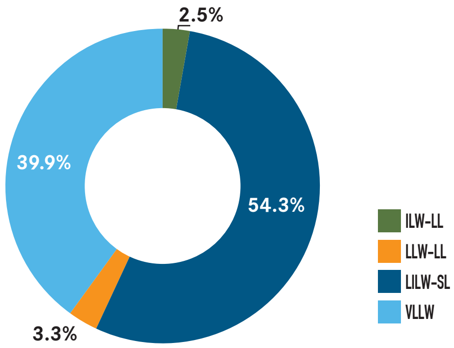
These include:

- medical research or Inserm laboratories, attached to medical or pharmacological faculties, and located in hospitals or university teaching hospitals;
- CNRS laboratories or mixed research units associated with the CNRS, usually located within faculties, institutes or *Grandes Ecoles*;
- units of the French National Institute of Nuclear and Particle Physics (IN2P3), including the particle accelerators at Orsay and Caen (Ganil);
- the reactor at the Laue Langevin Institute (ILL) in Grenoble and the European Organization for Nuclear Research (CERN), on the border between France and Switzerland;
- private sector firms such as Sanofi and L'Oréal;
- various reactors and facilities no longer in operation.

In cellular and molecular biology, very short-lived radionuclides are used to mark molecules into which they are incorporated. For short-lived radionuclides, tritium is often used. For long-lived radionuclides, carbon-14 is frequently used as a marker. These radionuclides are often used in the form of unsealed sources (i.e. small liquid samples). After use, they become liquid waste, which is generally collected by Andra to be sent to Cyclife Centraco for treatment.

Waste with a half-life of less than 100 days is left in situ to allow it to decay.

RADIOACTIVE WASTE FROM RESEARCH



Category	Volume at the end of 2016 (m^3)
HLW	161
ILW-LL	10,700
LLW-LL	13,900
LILW-SL	232,000
VLLW	170,000
Total	~ 427,000

At the end of 2016, CEA centres had produced around 94% of the waste from the research sector.

RADIOACTIVE MATERIALS FROM RESEARCH

Radioactive materials	Mass at end of 2016 (tHM)
Fuel in use in research reactors	0.8
Other civil spent fuel	59
FNR spent fuel, awaiting reprocessing	14
Non-irradiated separated plutonium, in all its physicochemical forms	2
Mined natural uranium, in all its physicochemical forms	17
Enriched natural uranium, in all its physicochemical forms	7
Depleted uranium, in all its physicochemical forms	110

DEFENCE SECTOR

This economic sector comprises the activities of the research, production and experimentation centres working for nuclear deterrence and the various armed forces (navy, air force, army, etc.), the Defence Medical Services (SSA), General Directorate for Armament (DGA) and Gendarmerie.

HLW and ILW-LL in this sector is generated solely by nuclear deterrence activities.

RESEARCH, PRODUCTION AND EXPERIMENTATION CENTRES WORKING IN NUCLEAR DETERRENCE

This relates to all the activities of the nuclear deterrence centres of the Military Applications Division (DAM) of the CEA and the DAM nuclear propulsion installations at Cadarache.

The DAM is in charge of the design and development of nuclear steam supply systems for the French navy's fleet and manufacturing reactor cores for on-board steam supply systems.

CEA/DAM FACILITIES

The CEA Military Applications Division (DAM) designs, manufactures and services France's Defence System nuclear warheads. It also dismantles nuclear weapons withdrawn from service.

The sites involved in weapons and steam supply system activities are classified as regulated nuclear defence facilities (INBS):

▪ **Bruyères-le-Châtel centre**
Since it was created, the Bruyères-le-Châtel site has manufactured nuclear devices that were tested in the Sahara and then in the Pacific between 1960 and 1996, and has followed up testing and research on constituent materials. The installations of this centre are being dismantled and mainly produce VLLW and LILW-SL.

Some limited specific activities relating to physics and analyses are continuing on the site.

▪ **Valduc centre**
The Valduc centre produces certain nuclear weapons components. It processes the radioactive materials (plutonium, uranium) for them and also carries out research on materials.

Its activities produce waste that is contaminated with alpha emitters and tritium. Valduc ILW-LL comprises various technological waste conditioned in metal drums and sent to Cadarache for storage.

Most of the sludge and concentrate packages locked in metal drums, previously produced by the centre's effluent treatment station, have been transferred for storage at Cadarache.

LILW-SL consists of various metal and technological waste conditioned in 200-litre drums or in 5 m^3 metal containers, and liquid waste from the facility.

The VLLW produced is mainly operating waste.

The Valduc centre also produces tritiated waste. The waste that with the highest radioactivity and gas release rates is conditioned in 200-litre drums and stored at the Valduc site.

The centre has begun cleanup operations for some of its facilities.

▪ **Other centres**
Explosive tests were carried out at Moronvilliers up to the end of 2013. They used depleted uranium with a lower content of isotope 235. The centre is now in a cleanup phase.

Similarly, explosive tests have been carried out in the past at the Cesta centre, some of which also used depleted uranium with a lower content of isotope 235. For several years, the main role of Cesta has been to develop the industrial architecture of nuclear deterrence weapons.

These sites mainly contain uranium-contaminated VLLW (metal waste, various technological waste and waste from dismantling or cleanup).

The Gramat centre is a centre of defence expertise on vulnerability and weapons efficiency in the face of conventional and nuclear weapons attacks. This test centre also used depleted uranium. The waste present on this site is VLLW waste - slightly contaminated metal waste (steel) and operating waste. The centre is now in a cleanup phase.

Finally, the DAM nuclear propulsion facilities at Cadarache, including land reactors, are used to develop, qualify and service certain systems and equipment for nuclear steam supply systems on the French navy's nuclear-powered fleet.

▸ FACILITIES NO LONGER IN OPERATION

Some facilities operated by Orano for the DAM have been shut down since 2009. Part of the waste from the cleanup/ dismantling of these facilities is tritiated waste classified as LILW-SL.

The waste from fuel reprocessing operations for nuclear deterrence is included in the statements shown in this section.

Since the production of fissile materials for defence purposes has ceased, resulting in the closure of enrichment and recycling plants, the CEA/DAM has acted as project owner for dismantling these plants at Pierrelatte.

Moreover, the CEA/DAM acts as project owner for dismantling the land-based prototype reactors (PAT) and new generation reactor (RNG) at Cadarache.

▸ THE PACIFIC TEST CENTRE

Waste from nuclear experiments carried out in the past is disposed of on the sites at Mururoa, Fangataufa and Hao in French Polynesia.

i

At the end of 2016, the volume of tritiated waste in France was around 5,600 m^3, the majority of which was generated by nuclear deterrence activities. In accordance with the guidelines for the disposal of tritiated waste drawn up by the CEA under the PNGMDR 2007-2009, the CEA/DAM built an initial storage facility at Valduc to increase the capacity for holding tritiated waste from facilities involved in nuclear deterrence activities. This first building was commissioned in 2012.

DEFENCE FACILITIES

This activity sector covers professional activities relating to French defence (excluding research, production and test centres involved in the nuclear deterrence activities covered above) holding radioactive waste, whether working directly under the Ministry of Defence or working on their own behalf, such as the French Air Force, Army, Navy, General Directorate for Armament (DGA), Defence Medical Services (SSA) and the Gendarmerie.

It should be noted that since 1 January 2009, the Gendarmerie is no longer under the Ministry of Defence but the Ministry of the Interior. However, their waste typologies are the same as those of other branches of the armed forces. In the remainder of this chapter, the Gendarmerie is therefore attached to French defence facilities.

▸ ARMED FORCES EQUIPMENT TAKEN OUT OF SERVICE

All the armed forces have equipment that draws on the properties of radioactivity, especially for night vision.

When this equipment is worn out or becomes obsolete, it constitutes waste and is listed in the inventory of each defence facility (around one hundred sites listed).

Some aircraft engine parts taken out of service and containing thorium are also listed (magnesium/thorium alloy housing, for example).

Several facilities have grouped this waste by category to centralise and streamline the way it is managed. This is the case, for example, for the Air Force's Châteaudun facility.

Eventually, the plan is to have a single joint forces collection centre for radioactive waste: the Châteaudun site.

▸ FRENCH DEFENCE HARBOURS

The military harbours of Brest/Île Longue, Cherbourg and Toulon produce mostly VLLW waste, from construction activities, operation, maintenance and dismantling of nuclear submarine and aircraft carrier steam supply systems.

The reactor units of submarines being dismantled are stored at Cherbourg.

▸ DGA FACILITIES

The DGA Bourges site holds radioactive waste from experiments and tests carried out on weapons containing depleted uranium with a lower content of isotope 235.

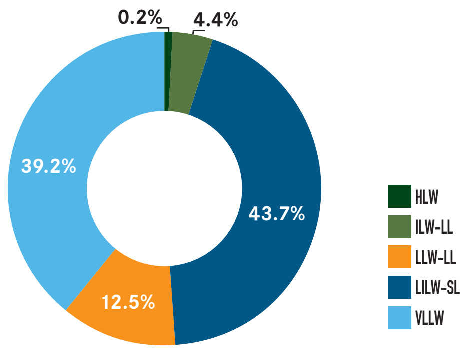
▸ WASTE PRODUCED BY FRENCH DEFENCE FACILITIES

Just over fifty sites producing and/or holding radioactive waste have been listed.

This mainly consists of small items of equipment taken out of service, containing luminescent paint containing radium or tritium (compasses, plates, sights, dials, etc.).

Most of these objects are considered as radioluminescent objects.

▸ RADIOACTIVE MATERIALS FROM DEFENCE



Category	Volume at the end of 2016 (m^3)
HLW	232
ILW-LL	6,300
LLW-LL	18,000
LILW-SL	63,100
VLLW	56,500
Total	~ 144,000

Currently, almost all tritiated waste is produced by the defence sector.

▸ RADIOACTIVE MATERIALS FROM DEFENCE

Radioactive materials	Mass at end of 2016 (t)
Spent fuel from the French defence industry	177

INDUSTRIES OUTSIDE THE NUCLEAR POWER SECTOR

INDUSTRY USING NATURALLY RADIOACTIVE MATERIALS FOR THEIR RADIOACTIVITY

This activity encompasses the manufacture and use of radioactive sources (sealed and unsealed) outside the medical field.

It also includes the manufacture and use of miscellaneous devices that use radioactive products (radioactive lightning rods manufactured between 1932 and 1986 progressively removed and collected by Andra, smoke detectors, etc.) or the properties of radioactivity (monitoring sources for compliance, maintenance, etc.).

The life of a sealed source is limited and makes it unusable after a few months or years, depending on the half-life of the radionuclide in question. The sources are not automatically considered as final waste (see Special Report 6).

Furthermore, Article R. 4452-12 of the French Labour Code requires that sealed sources used be subject to regular technical radiation protection inspections. Many sealed sources are returned to their suppliers abroad.

It should be noted that ILW-LL allocated to industries outside the nuclear power sector corresponds to the “core source elements” containing spent sealed sources.

Pursuant to Article R. 1333-161 of the Code of Public Health, “a sealed radioactive source is considered to have expired ten years at the latest after the date of first registration marked on the supply form or, if none, after the date of its initial market introduction, unless an extension is granted by the competent authority. If a decision is not issued by the Nuclear Safety Authority within six months of the request, the extension shall be considered rejected”.

Sources are stored in suitable premises. Some could be disposed of at the CSA provided they are compatible with the facility’s safety requirements.

INDUSTRY USING NATURALLY RADIOACTIVE MATERIALS FOR PROPERTIES OTHER THAN THEIR RADIOACTIVITY

This sector also covers residues from the treatment of ores and by-products containing a significant amount of thorium and uranium. The suspended particulate matter in its present state still contains radioactive materials.

The radionuclides contained in some natural mineral raw materials are handled in activities related to the chemical, metallurgy and electricity production industries.

These activities may therefore produce radioactive waste, which is mainly low- or very low-level waste.

Some industries only work with naturally occurring radioactivity. Sometimes the nature of the materials used or the process employed tends to concentrate the radioactivity. For instance, this is the case of Solvay in the rare earth mining field.

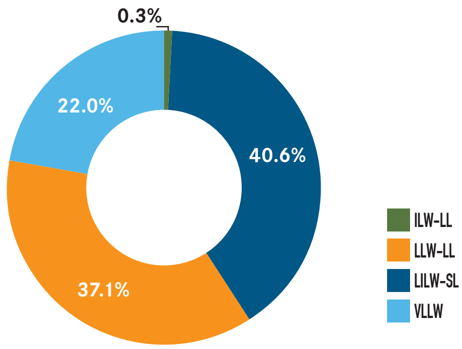
Therefore, the radioactivity levels of the waste produced may be sufficiently high to warrant special management. The regulations provide for a potential impact study to be carried out in such cases, to define the appropriate conventional or specific management solution.

It is hard to identify all the industries likely to produce this type of naturally occurring radioactive waste.

The currently listed management solutions for this type of waste are Cires, the future LLW-LL disposal centre, the conventional disposal centres when the impact study has shown that there is no effect on human beings or the environment.

In the past, some waste was disposed of close to the facilities.

RADIOACTIVE WASTE FROM INDUSTRIES OUTSIDE THE NUCLEAR POWER SECTOR



Category	Volume at the end of 2016 (m^3)
HLW	-
ILW-LL	161
LLW-LL	20,300
LILW-SL	22,200
VLLW	12,100
Total	~ 54,700

RADIOACTIVE MATERIALS FROM INDUSTRIES OUTSIDE THE NUCLEAR POWER SECTOR

Radioactive materials	Mass at end of 2016 (tHM)
Mined natural uranium, in all its physicochemical forms	98
Thorium, in nitrate and hydroxide form	6,290
Suspended particulate matter (by-products of rare earth ore processing)	5

MEDICAL SECTOR

Use of radioactive products in a pharmaceutical laboratory

This sector includes all public and private facilities that use radionuclides for medical analysis or treatment.

Medical research centres are not included as they form part of the research economic sector.

This sector primarily covers three major areas:
- *in vitro* biological analyses carried out on biological samples for making diagnoses;
- medical imaging techniques, used in diagnosis;
- therapeutic applications, carried out *in vitro* or *in vivo*.

The facilities in this sector mainly use unsealed sources, i.e. radionuclides in liquid solutions.

The main users of these radionuclides are nuclear medicine departments and their associated laboratories.

The same facilities also use sealed sources for radiotherapy, brachytherapy and calibration of instruments used to measure the radioactivity of the products injected into patients (see Special Report 6).

Liquid waste products are managed in two different ways depending on the half-life of the radionuclides they contain (see Special Report 5):
- decay on site for those with very short half-lives;
- treatment at Cyclife Centraco and then disposal in Andra centres for other waste.

Apart from these sources, solid waste is also managed either by decay on site then stored in conventional facilities, or directly at an Andra centre after treatment and conditioning.

RADIOACTIVE WASTE FROM THE MEDICAL SECTOR AT THE END OF 2016

At the end of 2016, the volume of waste produced by these medical activities, excluding spent sealed sources, is approximately 8,500 m^3. Almost all this waste is in the LILW-SL category and is disposed of at the Andra CSM.

Category	Volume at the end of 2016 (m^3)
HLW	-
ILW-LL	2
LLW-LL	-
LILW-SL	8,410
VLLW	88
Total	~ 8,500

No radioactive materials were declared for the medical sector at the end of 2016.


03

FORECAST INVENTORIES

The purpose of forecast inventories is to estimate the quantities of radioactive materials and waste at different time scales based on several scenarios. They aim to present the impacts of different strategies or potential changes in French energy policy over the long term on the quantities of radioactive materials and waste, without anticipating the industrial decisions that may be made.

Pursuant to Decree no. 2008-875 of 29 August 2008 and the Order of 9 October 2008, as amended, the forecast inventories of radioactive waste and materials are declared by the producers or holders of radioactive waste and materials. Furthermore, in contrast to the inventories that have to be declared by all producers or holders of waste or materials each year, forecasts are only required every three years for operators of regulated nuclear facilities, defence-related facilities (regulated nuclear defence facilities, defence-related nuclear experimental facilities and sites), or "nuclear" environmentally regulated facilities (terms in the nomenclature for radioactive substances).

Only the quantities of waste and materials from facilities (due to their operation and dismantling) with a construction licence dated on or before 31 December 2016 will be taken into account. The radioactive materials and waste generated by the operation of new reactors replacing the reactors in the current nuclear power plant fleet are not included[1].

Assumptions need to be made and scenarios defined in order to estimate projected quantities of waste and materials.

The scenarios meet the requirements of the French National Radioactive Materials and Waste Management Plan (PNGMDR) for 2016-2018. In accordance with the Act on Energy Transition for Green Growth, the scenarios consider that the nuclear generating capacity is limited to 63.2 GW with an associated net average electricity production of 420 TWh/year (except for the SR2 scenario which was defined before the energy transition act).

The forecast inventories were drawn up on the basis of four different scenarios for the development of current energy policy. There are three scenarios in which the French nuclear power plant fleet is renewed, and one scenario in which it is not. The purpose of these scenarios is to provide a framework and illustrate potential developments in energy policy, taking into account uncertainties without necessarily seeking to produce a representative prediction. They therefore illustrate both a continuation of current trends and the consequences of a more breakaway decision. The renewal scenarios assume the deployment of new reactors to replace reactors in the current nuclear power plant fleet, with different assumptions of the type of reactor deployed. The fleet renewal scenarios assume the existence of reactors capable of using recycled plutonium, which is not used by the current fleet, when the fleet is due for renewal. They do not take into account the quantities of radioactive waste and materials produced by these new reactors, because they were not licensed at the end of 2016. The renewal scenarios assume different operating periods for current nuclear power reactors. These assumptions reflect the strategies of EDF with regard to extending the operating period beyond 40 years.

The non-renewal scenario corresponds to the shutdown of nuclear power production after 40 years of operation (60 years for EPR). No reactor will be deployed to replace current nuclear power reactors.

REPROCESSING OF SPENT FUEL

French energy policy makes provision for fuel to be reprocessed after use. The reprocessing operations that currently take place at the Orano plant in La Hague make it possible to extract around 96% of reusable materials (plutonium and uranium), and around 4% radioactive waste from spent fuel.

The plutonium extracted is used to manufacture MOX fuel (uranium and plutonium mixed oxide fuel). Mono-recycling involves recycling plutonium once in MOX fuel, which is then stored after use pending reuse at a later date. Irradiated MOX fuel unloaded from the PWRs still contains a significant quantity of plutonium. Multi-recycling involves reprocessing irradiated fuel to extract the reusable materials, and then manufacturing new fuel several times over. Multi-recycling generates radioactive waste that will require disposal.

Multi-recycling of plutonium would only be possible with the deployment of a Generation IV fleet.

Orano La Hague site

1 The estimated quantities of materials and waste that would be produced by a new nuclear power plant fleet are currently being studied by the CEA for the 2016-2018 French National Radioactive Materials and Waste Management Plan (PNGMDR).

For these four scenarios, the waste producers and holders gave a rough estimate of the quantities of waste and materials generated by all nuclear facilities (licensed at the end of 2016) until the end of their life cycle, i.e. end of dismantling.

The scenarios adopted are based on the following shared assumptions:

- there are 59 nuclear power reactors in the current fleet: with 58 PWR-type reactors in operation and the EPR reactor under construction on the Flamanville site, which is scheduled to be commissioned in 2019;
- the scenarios have different assumptions concerning the operating periods of current nuclear power reactors. These assumptions do not anticipate any decisions to be taken by the French Nuclear Safety Authority (ASN) following the safety reviews for each of these reactors, performed every 10 years;

"At term" means after the dismantling of the nuclear facilities licensed at the end of 2016 for this edition.

- the plutonium extracted during spent fuel reprocessing is recycled in MOX assemblies distributed across the twenty-four 900 MW reactors currently licensed for this type of fuel, and later, in EPRs (for scenarios with fleet renewal);
- for waste from uranium conversion at the Orano Malvési plant, low-level long-lived uranium conversion treatment residues, which will be produced from 2019, will not be taken into account in forecast inventories as the conditioning of this waste has not yet been defined. However, VLLW produced from 2020 at the Orano Malvési plant is taken into account in prospective inventories for VLLW.

As for existing waste inventories, the unit adopted for the forecast waste inventories is the "conditioned equivalent volume".

PRESENTATION OF SCENARIOS TO DETERMINE FORECAST INVENTORIES

SR1: RENEWAL OF THE NUCLEAR POWER PLANT FLEET WITH EPR THEN FNR REACTORS

Scenario SR1 assumes that nuclear power generation is ongoing and that spent fuel continues to be reprocessed (the current strategy is maintained). The assumption is also made that all fuel used by current nuclear power reactors is reprocessed to separate the materials (uranium, plutonium) from the final waste. Therefore, no spent fuel is directly disposed of and all the plutonium extracted from spent fuel is recycled in current or future reactors.

The key assumptions made for this scenario are:

- continuation of nuclear power production;
- an operating period of 50 to 60 years for current nuclear power reactors;
- gradual replacement of current nuclear power reactors with EPR reactors and then FNR reactors, which could eventually comprise the entire future fleet;
- reprocessing of all spent fuel, which is the current management policy, including spent fuel from the Phénix and Superphénix FNRs, EDF EL4 fuel and spent fuel from research and defence activities. By convention, this assumes that:
  - there are fuel reprocessing plants available to perform these operations;
  - the materials will be separated gradually (as is currently the case) to meet the actual fuel requirements of new reactors, which depends directly on their rate of deployment and MOX integration;
  - the materials from ENU, uranium and plutonium spent fuel reprocessing will be reused in reactors in the current fleet (PWR reactors and EPR reactor at Flamanville) or in EPR reactors in future fleets. Separated plutonium from spent fuel reprocessing is recycled into MOX fuel, and reprocessed uranium into ERU fuel;
  - materials from MOX and spent ERU fuel reprocessing will be reused in a fast neutron reactor (FNR) fleet, allowing for multi-recycling.
- annual spent fuel reprocessing flows correspond to the needs of plutonium to be recycled, which is determined by the number of MOX reactors;
- the recycling of recycled uranium gradually begins again;
- depleted uranium is recycled into MOX fuel;
- dismantling of the first EDF GCR reactor tank will begin by 2035.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE AT TERM FOR SCENARIO SR1

Radioactive waste at term, in m^3	
HLW	12,000
ILW-LL	72,000
LLW-LL	190,000
LILW-SL	2,000,000
VLLW	2,300,000
Total	**4,500,000**

The assumptions regarding the reprocessing of all spent fuel and the deployment of EPR then FNR reactors presume that all materials are reused. No materials are therefore reclassified as waste at term.

The materials from reprocessing part of the spent fuel produced by the current nuclear power plant fleet will be reused in a future fleet of EPR then FNR reactors. The quantities of spent fuel produced by the current fleet, whose material will be reused in a future fleet after reprocessing, are 20,000 tHM for ENU fuel, 3,700 tHM for ERU fuel and 5,200 tHM for MOX fuel.

SR2: RENEWAL OF THE NUCLEAR POWER PLANT FLEET WITH EPR AND FNR REACTORS, VERSION B

Scenario SR2 uses the assumptions and data from the scenario in the 2015 edition of the National Inventory. Like scenario SR1, it assumes that nuclear power generation continues and that the current strategy for spent fuel reprocessing and recycling is maintained. The assumption is also made that all fuel used by current nuclear power reactors is reprocessed to separate the materials (uranium, plutonium) from the final waste. Therefore, no spent fuel is directly disposed of and all plutonium extracted from spent fuel is recycled in the current or future fleet.

The key assumptions made for this scenario are:

- continuation of nuclear power production;
- unlike scenario SR1, there is a uniform 50-year operating period for all reactors;
- gradual replacement of current nuclear power reactors with EPR reactors and then FNR reactors, which could eventually comprise the entire future fleet;
- reprocessing of all spent fuel, which is the current management policy, including spent fuel from the Phénix and Superphénix FNR, EDF EL4 fuel and spent fuel from research and defence activities. By convention, this assumes that:

   - there are fuel reprocessing plants available to perform these operations,
   - the materials will be separated gradually (as is currently the case) to meet the actual fuel requirements of new reactors, which depends directly on their rate of deployment and MOX integration,
   - the materials from ENU, uranium and plutonium fuel reprocessing will be reused in reactors in the current fleet (PWR reactors and EPR reactor at Flamanville) or in EPR reactors in future fleets. Separated plutonium from spent fuel reprocessing is recycled into MOX fuel, and reprocessed uranium into ERU fuel.
   - materials from MOX and spent ERU fuel reprocessing will be reused in a fast neutron reactor (FNR) fleet, allowing for multi-recycling.
- annual spent fuel reprocessing flows correspond to the needs of plutonium to be recycled, which is determined by the number of MOX reactors;
- recycling of recycled uranium;
- depleted uranium is recycled into MOX fuel;
- dismantling of GCR reactor tanks will begin by 2025[1].

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE AT TERM FOR SCENARIO SR2

Radioactive waste at term, in m³	
HLW	10,000
ILW-LL	72,000
LLW-LL[2]	190,000
LILW-SL	1,900,000
VLLW	2,200,000
Total	**4,400,000**

The assumptions regarding the reprocessing of all spent fuel and the deployment of EPR then FNR reactors presume that all materials are reused. No materials are therefore reclassified as waste at term.

The materials from reprocessing part of the spent fuel produced by the current nuclear power plant fleet will be reused in a future fleet of EPR then FNR reactors.

SR3: RENEWAL OF THE NUCLEAR POWER PLANT FLEET WITH EPR REACTORS ONLY

The SR3 scenario assumes that nuclear power generation continues. The assumption is also made that all ENU fuel used in current nuclear power reactors is reprocessed to separate the materials (uranium, plutonium) from the final waste. All the plutonium extracted from spent ENU fuel is recycled in the current or future fleet, in the form of mixed uranium and plutonium oxide fuel. However, spent MOX and ERU fuel is not reprocessed as a result of non-deployment of a FNR fleet.

The key assumptions made for this scenario are:
- continuation of nuclear power production;
- an operating life of 50 to 60 years for current nuclear power reactors;
- gradual replacement of current nuclear power reactors with EPR reactors only, which would eventually comprise the entire future fleet;
- reprocessing of spent ENU fuel only. By convention, this assumes that:
   - there are fuel reprocessing plants available to perform these operations;
   - the materials from ENU, uranium and plutonium fuel reprocessing will be reused in reactors in the current fleet (PWR reactors and EPR reactor at Flamanville) or in reactors in the future fleet (EPR). Separated plutonium from spent fuel reprocessing is recycled into MOX fuel and reprocessed uranium into ERU fuel;
   - spent MOX and ERU fuel is not reprocessed (mono-recycling). Superphénix and Phénix FNR fuel is also not reprocessed.
- annual spent fuel reprocessing flows correspond to the needs of plutonium to be recycled;
- the recycling of recycled uranium gradually begins again;
- dismantling of the first EDF GCR reactor tank will begin by 2035.

1 Since the 2015 edition of the National Inventory, the new dismantling strategy for EDF's "GCR"-type reactors, considered in scenarios SR1, SR3 and SNR, has pushed back the dismantling of certain reactor tanks by several decades, which explains the ten-year difference observed for the SR2 scenario.

2 The quantity of LLW-LL has been recalculated since the 2015 edition.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE AND MATERIALS THAT MAY BE RECLASSIFIED AS WASTE AT TERM FOR THE SR3 SCENARIO

Radioactive waste at term, in m³	
HLW	9,400
ILW-LL	70,000
LLW-LL	190,000
LILW-SL	2,000,000
VLLW	2,300,000
Total	**4,500,000**
Radioactive materials that may be reclassified as waste at term, in tHM	
Spent ENU fuel	-
Spent ERU fuel	3,700
Spent mixed uranium-plutonium fuel	5,200
Non-irradiated mixed uranium-plutonium fuel scrap	290
Non-irradiated uranium fuel scrap	-
FNR spent fuel	160
Other civil spent fuel	5
Non-irradiated separated plutonium, in all its physicochemical forms	-
Mined natural uranium, in all its physicochemical forms[1]	-
Enriched natural uranium, in all its physicochemical forms	-
Enriched uranium from spent fuel reprocessing, in all its physicochemical forms	-
Uranium from spent fuel reprocessing, in all its physicochemical forms	-
Depleted uranium, in all its physicochemical forms	470,000
Thorium, in nitrate and hydroxide form[2]	4
Other materials	70
Total	**480,000**

In this scenario (fleet renewal limited to mono-recycling), the following materials that may be reclassified as waste will require disposal:

- approximately 3,700 tHM of spent ERU fuel, 5,200 tHM of spent MOX fuel and 290 tHM of MOX scrap;
- depleted uranium from the enrichment of mined uranium could be considered waste at term. However, all (approximately 470,000 tHM) or part of the depleted uranium could be reused in France or overseas;
- around 100 tHM of FNR spent fuel from Superphénix and 60 tHM of FNR spent fuel from Phénix;
- 70 tHM of the Superphénix core ("other materials" category);
- a small proportion of thorium cannot be reused. The remainder (and majority) of thorium belonging to Orano is considered to be fully reusable.

The materials reclassified as waste will need to be incorporated into dedicated management solutions until disposal.

1 Does not take into account mined natural uranium for industries outside the nuclear power sector.
2 Does not take into account thorium for industries outside the nuclear power sector.

RECLASSIFICATION OF MATERIALS AS RADIOACTIVE WASTE

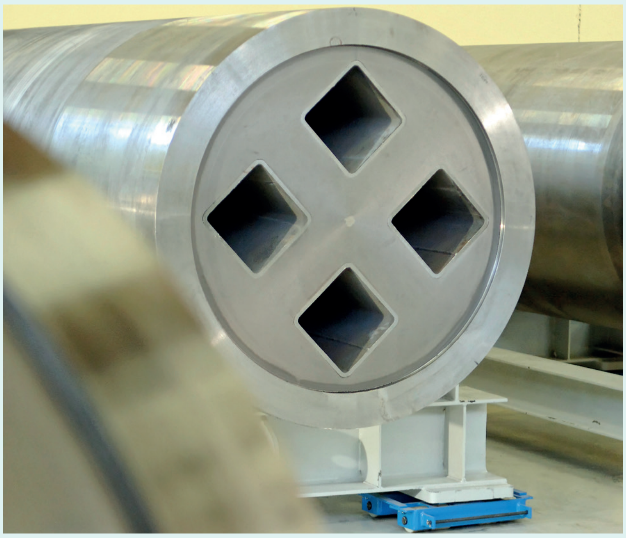
The future of radioactive substances considered radioactive materials by their owners must be periodically reviewed.

Assuming that the possibilities for reuse of a radioactive substance are compromised, the necessary guarantees, in particular financial guarantees, need to be provided for the inclusion of these substances in dedicated management solutions up to disposal.

The legislative framework allows the French government to reclassify radioactive materials as radioactive waste after an ASN opinion. Studies are also periodically requested to provide a conservative assessment of the potential management solutions should the materials be reclassified as waste in the future, primarily in the event that nuclear power programmes are discontinued in France or overseas.

A review of whether radioactive materials could actually be recovered and reused was requested under the PNGMDR 2013-2015 and Decree no. 2013-1304 of 27 December 2013, which laid out requirements. The owners of radioactive materials, Orano, the CEA, EDF and Solvay, submitted their updated projected reuse processes, with analysis of whether the potential reuse options correspond to the quantities held now and in the future. The ASN and ASND issued an opinion on this subject[1].

For the PNGMDR 2016-2018, Andra has to produce more detailed studies on the disposal of spent fuel, depleted uranium, recycled uranium and thorium if they were classified as waste in the future, working alongside the owners of these materials.



Demonstrators of spent fuel containers exhibited at Marcoule CEA

SNR: NUCLEAR POWER PLANT FLEET IS NOT RENEWED

This scenario assumes that the existing fleet is not renewed after 40 years of operation (60 for EPR). Its main objective is to prevent plutonium production through fuel reprocessing in the nuclear power industry, if it could not be recycled in the current fleet. This restriction would lead to the early shutdown of spent fuel reprocessing activities to avoid holding separated plutonium.

Plutonium recycling is limited to MOX fuel manufacture for the operation of the reactors currently licensed to use this type of fuel.

The key assumptions made for this scenario are:
- shutdown of nuclear power production;
- an operating period of 40 years for the 58 PWR reactors and 60 years for the Flamanville EPR;
- reactors in the current nuclear power fleet are not renewed;
- early shutdown of the reprocessing of spent ENU fuel to avoid holding separated plutonium, leading to the shutdown of all fuel reprocessing operations at the Orano La Hague plant at the earliest possible date. Residual ENU fuel that has not been reprocessed at the end of the reactor operating period, as well as ERU and MOX fuel that has not been reprocessed, would be recategorised as waste and assumed to be disposed of as is;
- no further recycling of recycled uranium;
- dismantling of the first EDF GCR reactor tank will begin by 2035.

1 ASN Opinion no. 2016-AV-0256 of 9 February 2016 on the evaluation of the reusable nature of radioactive materials is available online at asn.fr The ASND issued its opinion on 29 April 2016.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE AND MATERIALS THAT MAY BE RECLASSIFIED AS WASTE AT TERM FOR THE SNR SCENARIO

Radioactive waste at term, in m³	
HLW	4,200
ILW-LL	61,000
LLW-LL	190,000
LILW-SL	1,800,000
VLLW	2,100,000
Total	**4,200,000**
Radioactive materials that may be reclassified as waste at term, in tHM	
Spent ENU fuel	24,000
Spent ERU fuel	630
Spent mixed uranium-plutonium fuel	3,100
Non-irradiated mixed uranium-plutonium fuel scrap	290
Non-irradiated uranium fuel scrap	-
Spent FNR fuel	160
Other civil spent fuel	54
Non-irradiated separated plutonium, in all its physicochemical forms[1]	2
Mined natural uranium, in all its physicochemical forms[2]	17
Enriched natural uranium, in all its physicochemical forms	7
Enriched uranium from spent fuel reprocessing, in all its physicochemical forms	-
Uranium from spent fuel reprocessing, in all its physicochemical forms	34,000
Depleted uranium, in all its physicochemical forms	400,000
Thorium, in nitrate and hydroxide form[3]	4
Other materials	70
Total	**460,000**

In this scenario (non-renewal of the fleet), materials reclassified as waste would require disposal.

All plutonium recovered during ENU fuel reprocessing operations is recycled in the form of MOX fuel.

Around 100 tHM of FNR spent fuel from Superphénix and 60 tHM of FNR spent fuel from Phénix would not be reprocessed. Approximately 50 tHM of EL4 fuel from Brennilis ("other civil spent fuel" category) would not be reprocessed and would be reclassified as waste.

Depleted uranium, natural uranium, plutonium and recycled uranium could be considered as waste at term. However, natural uranium and plutonium could be reused in the current fleet, prior to reactor shutdown. Depleted uranium and recycled uranium could potentially be reused in France or overseas.

A small proportion of thorium cannot be reused. The remainder (and majority) of thorium belonging to Orano is considered to be fully reusable.

1 From the research sector.
2 Does not take into account mined natural uranium for industries outside the nuclear power sector.
3 Does not take into account thorium for industries outside the nuclear power sector.

SUMMARY OF SCENARIOS

Materials are placed in the waste category with which they share comparable typologies and physicochemical characteristics. Particularly in the case of uranium, this does not determine the management solution that will be selected. As part of the 2016-2018 PNGMDR, studies are underway regarding management options in the event that depleted uranium and recycled uranium are reclassified as waste in the future.

		SR1	SR2[1]	SR3	SNR
Continuation or shutdown of nuclear power production		Continuation (total operating period of 50 to 60 years)	Continuation (total operating period of 50 years)	Continuation (total operating period of 50 to 60 years)	Shutdown after 40 years (except EPR after 60 years)
Type of reactor deployed in future fleet		EPR then FNR	EPR then FNR	EPR	/
Reprocessing of spent fuel		All: ENU, ERU, MOX and FNR	All: ENU, ERU, MOX and FNR	ENU only	Early shutdown of ENU reprocessing
Reclassification of spent fuel and uranium as waste		None	None	ERU, MOX, FNR and depleted uranium	All spent fuel, depleted uranium and recycled uranium
HLW	Spent uranium oxide fuel from nuclear power reactors (ENU, ERU)	-	-	3,700 tHM	25,000 tHM
	Spent uranium and plutonium mixed oxide fuel from nuclear power reactors (MOX, FNR)	-	-	5,400 tHM	3,300 tHM
	Vitrified waste	12,000 m^3	10,000 m^3	9,400 m^3	4,200 m^3
ILW-LL	Waste	72,000 m^3	72,000 m^3	70,000 m^3	61,000 m^3
LLW-LL	Waste[2,3]	190,000 m^3	190,000 m^3	190,000 m^3	190,000 m^3
	Depleted uranium, in all its physicochemical forms	-	-	470,000 tHM	400,000 tHM
	Uranium from spent fuel reprocessing, in all its physicochemical forms	-	-	-	34,000 tHM
LILW-SL	Waste	2,000,000 m^3	1,900,000 m^3	2,000,000 m^3	1,800,000 m^3
VLLW[4]	Waste	2,300,000 m^3	2,200,000 m^3	2,300,000 m^3	2,100,000 m^3

Waste quantities are expressed in "conditioned equivalent volume". Material quantities are expressed in "tonnes of heavy metal". Fuel quantities can also be expressed in "number of assemblies" and would represent around 20,000 assemblies at term in scenario SR3 or 57,000 assemblies at term in scenario SNR.

1 The data for SR2 was reported at the end of 2013.
2 Does not take into account the low-level long-lived uranium conversion treatment residues that will be produced from 2019.
3 Value recalculated since the 2015 edition of the National Inventory.
4 Takes into account VLLW waste from the thermal treatment of nitrated effluents at Malvési.

The lessons learned from comparing the various scenarios for each category are explained below. By definition, these lessons are directly linked to the scenarios' key assumptions, particularly the fact that quantities of waste produced by potential future fleets covered in scenarios SR1, SR2 and SR3 are not taken into account.

Certain assumptions made in scenario SR2 (drawn up in late 2013) have since changed, which may make it difficult to compare scenarios SR1, SR3 and SNR to scenario SR2.

HLW HIGH-LEVEL WASTE

The operating period of current nuclear power reactors and continuation of spent fuel reprocessing has a direct impact on the quantity of vitrified waste. Logically, the longer the fleet operating period, the more fuel to reprocess and the higher volume of vitrified waste at term.

Due to its characteristics, the fleet's spent fuel could be considered high-level waste if not reprocessed.

The type and quantity of waste at term for the current fleet can be impacted by:

- whether or not the existing fleet is renewed;
- the type of reactors deployed to replace current reactors for the renewal scenarios.

Consequently:

- for renewal of the fleet by EPR and then FNR (SR1 and SR2 scenarios), only vitrified waste from spent fuel reprocessing is present at term;
- for renewal of the fleet with EPR only (scenario SR3), the reprocessing of ENU fuel produces vitrified waste. ERU and MOX fuel is not reprocessed, and therefore no vitrified waste is produced from reprocessing. The volume of vitrified waste at term is therefore lower than the volume of vitrified waste in scenarios SR1 and SR2, but spent ERU and MOX fuel would be reclassified as waste under scenario SR3;
- when the nuclear power plant fleet is not renewed (scenario SNR), early shutdown of spent ENU fuel reprocessing would lead to early shutdown of the production of vitrified waste and therefore a lower quantity of vitrified waste. On the other hand, ENU, ERU and MOX spent fuel would need to be disposed of as they would be reclassified as waste.

ILW-LL INTERMEDIATE-LEVEL LONG-LIVED WASTE

The operating period of current nuclear power reactors and continuation of spent fuel reprocessing has a direct impact on the quantity of ILW-LL. Extension of the operating period will increase the quantity of ILW-LL generated.

Since the 2015 edition, feedback from the production of compacted waste packages (CSD-C) at Orano La Hague under scenarios SR1, SR3 and SNR has resulted in a lower volume of ILW-LL[1]. Furthermore, forecasts for the production of cemented solid operating waste packages, which have been produced since 1994 (CBF-C'2) at the Orano La Hague plant, have been revised down for scenarios SR1, SR3 and SNR[2].

The type and quantity of waste at term for the current fleet can be impacted by:

- whether or not the existing fleet is renewed;
- the type of reactors deployed to replace current reactors for the renewal scenarios.

LLW-LL LOW-LEVEL LONG-LIVED WASTE

The production of LLW-LL depends on the dismantling of existing facilities. The volume of waste at term is therefore independent of scenarios associated with forecast inventories.

Due to the typology of depleted uranium, it could be categorised with LLW-LL if reclassified as waste. Scenarios SR1 and SR2 assume that all depleted uranium is reusable. In scenarios SR3 and SNR, all or part of the depleted uranium could be reclassified as waste at term. Natural uranium enrichment operations are continued in scenario SR3, leading to an increased quantity of depleted uranium. After re-enrichment, this stock could provide France with a potential source of ENU to supply reactors, depending on the economic conditions. The shutdown of nuclear power production, assumed in scenario SNR, leads to the shutdown of fuel manufacture operations, so the depleted uranium is not reused. This stock could potentially be reused outside of France.

Due to the typology of uranium from spent fuel reprocessing, it could be categorised with LLW-LL, should it be reclassified as waste. In scenarios SR1, SR2 and SR3, uranium from spent fuel reprocessing is assumed to be reusable in ERU fuel. Cancellation of the nuclear programme results in the definitive shutdown of recycled uranium recycling, so recycled uranium is not reused. However, this stock could potentially be reused outside of France.

1 Projected production of compacted waste packages is estimated using a production ratio (number of CSD-C per tonne of reprocessed heavy metal). In scenarios SR1, SR3 and SNR, this ratio was recalculated and takes into account feedback from Orano on the production of CSD-C packages.

2 This corresponds to Orano's industrial target.

LILW-SL VLLW LOW- AND INTERMEDIATE-LEVEL SHORT-LIVED WASTE AND VERY-LOW-LEVEL WASTE

The volume of LILW-SL and VLLW produced is directly linked to the operating period of the reactors in the current nuclear power plant fleet. Extension of the operating period increases the volume of waste produced.

MALVÉSI WASTE

Waste from the Orano Malvési plant is shown separately in the projected figures until a decision is made concerning the long-term management of this waste.

CURRENT AND PROJECTED VOLUMES OF WASTE STORED AT THE MALVÉSI SITE (m^3)[1]

	End of 2016	End of 2030	End of 2040
Sludge in the settling ponds	70,400	0	0
Legacy uranium conversion treatment residues	282,000	310,000	310,000
Low-level long-lived uranium conversion treatment residues	0	24,000	40,000
Nitrated effluents	374,000	200,000	110,000

The changes in volumes can be explained by:

- drainage of the sludge in the settling ponds for the 2017 - 2030 period. After treatment, dehydrated sludge will be recategorised as low-level long-lived uranium conversion treatment residues and stored at the Malvési site until a management solution becomes available;
- shutdown of legacy uranium conversion treatment residue production from 2019. A long-term management solution at the Malvési site for this waste is currently being studied;
- production of uranium conversion treatment residues from 2019, which will come under the LLW-LL management solution after treatment and conditioning;
- thermal treatment of future liquid process effluents and those already stored in the settling ponds (nitrated effluents) from 2020, leading to reduced volume and the production of VLLW (not considered here but considered in VLLW forecasts).

Entrance to the Orano Malvési plant

1 Quantities are expressed in gross volume and not in conditioned equivalent volume.

ESTIMATED QUANTITIES OF MATERIALS AND WASTE AT INTERMEDIATE DATES

The regulations require holders to estimate the quantities of radioactive materials and waste at specific dates. For both scenarios with renewal of the nuclear power plant fleet and deployment of EPR then FNR reactors, quantities of waste and materials are also estimated for intermediate dates: end of 2030 and end of 2040 for scenario SR1; end of 2020 and end of 2030 for scenario SR2.

These estimates are based on the declarations of producers and holders of radioactive materials and waste. They do not include:
- the waste that would be produced by a new nuclear power plant fleet;
- reuse of radioactive materials from the current fleet in a future fleet;
- the radioactive materials that would be generated by a future fleet.

Continuing nuclear power production leads to an increased volume of radioactive waste. This increase is tempered by:
- a decrease in annual production of HLW and ILW-LL, due to the gradual shutdown of nuclear power reactors in the current fleet, leading to reduced quantities of ENU used in current reactors and therefore a reduced quantity of ENU fuel reprocessed in the current fleet;
- an increase in the volume of LLW-LL due to the dismantling of GCR reactor tanks, which will begin in 2035 and continue beyond 2040;
- an increase in LILW-SL and VLLW production due to the dismantling of current nuclear power reactors, support plants and facilities.

FOR SCENARIO SR1

ESTIMATED VOLUMES OF WASTE AT INTERMEDIATE DATES FOR SCENARIO SR1 (m^3)

Category	Inventories at the end of 2016	Forecasts at end of 2030	Forecasts at end of 2040	Forecasts at term for the current fleet
HLW	3,650	5,700	6,900	12,000
ILW-LL	45,000	51,000	58,000	72,000
LLW-LL	90,500	110,000	120,000	190,000
LILW-SL	917,000	1,200,000	1,500,000	2,000,000
VLLW	482,000	970,000	1,600,000	2,300,000
Total	1,540,000	2,300,000	3,300,000	4,500,000

ESTIMATED QUANTITIES OF MATERIALS AT INTERMEDIATE DATES FOR SCENARIO SR1 (IN tHM, EXCEPT FOR SPENT FUEL PRODUCED BY DEFENCE-RELATED ACTIVITIES, WHICH IS SHOWN IN TONNES OF ASSEMBLIES)

Radioactive materials	Inventories at end of 2016	Forecasts at end of 2030	Forecasts at end of 2040
ERU fuel before use	448	370	270
ENU fuel in use in nuclear power plants	4,450	3,700	2,700
Spent ENU fuel, awaiting reprocessing	11,400	11,000	10,000
ERU fuel before use	-	60	60
ERU fuel in use in nuclear power plants	53	620	620
Spent ERU fuel, awaiting reprocessing	578	800	2,200
Mixed uranium-plutonium fuel before use or in production	38	50	30
Mixed uranium-plutonium fuel in use in nuclear power plants	430	520	300
Spent mixed uranium-plutonium fuel, awaiting reprocessing	1,840	3,600	4,700
Non-irradiated mixed uranium-plutonium fuel scrap, awaiting reprocessing	267	310	290
Non-irradiated uranium fuel scrap awaiting reprocessing	-	-	-
FNR spent fuel, awaiting reprocessing	120	120	110
Research reactor fuel before use	-	0.1	0.1
Fuel in use in research reactors	0.8	0.1	0.1
Other civil spent fuel	59	57	56
Non-irradiated separated plutonium, in all its physicochemical forms	54	28	38
Mined natural uranium, in all its physicochemical forms	29,900	22,000	22,000
Enriched natural uranium, in all its physicochemical forms	3,860	1,300	1,300
Enriched uranium from spent fuel reprocessing, in all its physicochemical forms	-	-	-
Uranium from spent fuel reprocessing, in all its physicochemical forms	29,600	38,000	33,000
Depleted uranium, in all its physicochemical forms	310 00	400,000	470,000
Thorium, in nitrate and hydroxide form	8,570	8,600	8,600
Suspended particulate matter (by-products of rare earth ore processing)	5	5	-
Other materials	70	70	70
Spent fuel for defence purposes	177	260	340

Changes to the quantities of ENU and mixed uranium-plutonium fuel before use and during use in the current fleet between 2016 and 2040 can be explained by the gradual shutdown of nuclear power reactors and the resulting decrease in the number of ENU and mixed uranium-plutonium fuel used in these reactors.

Continuing spent fuel reprocessing (maintaining the current strategy) stabilises the quantity of spent ENU fuel awaiting processing for the 2016-2040 period. Spent mixed uranium and plutonium fuel will be stored for reuse in a future FNR fleet, resulting in an increased quantity between 2016 and 2040.

An increased quantity of ERU fuel before use and during use in nuclear power reactors between 2016 and 2040 is due to the gradual return to using ERU fuel in EDF reactors. This has a direct impact on the quantity of uranium produced through spent fuel reprocessing, which is used to make ERU fuel once enriched. The increase in the stock of uranium from spent fuel reprocessing therefore slows before the stock declines. The gradual return to using ERU fuel in EDF reactors also represents an increased quantity of spent ERU fuel, which could be reused in a future FNR fleet after reprocessing.

Non-irradiated mixed uranium-plutonium fuel scrap awaiting reprocessing will be processed then recycled in the current or future fleet, which explains the variations observed.

In particular, continued nuclear production results in continued uranium enrichment. The quantity of depleted uranium stored continues to increase between 2016 and 2040. Depleted uranium could be reused in fourth-generation fast neutron reactors.

The quantities of enriched natural uranium and mined natural uranium, in all its physicochemical forms, level out during the 2016 - 2030 period and are then maintained in balance.

The drop in plutonium quantity between 2017 and 2030 is due to the manufacture and shipment of MOX fuel overseas. The recycling of plutonium in future reactors was not yet authorised in late 2016, so has not been taken into account, resulting in an increased quantity of plutonium between 2030 and 2040.

The change in stock of “other civil spent fuel” between the end of 2016 and 2030 is due to reprocessing of the final Osiris, Isis and Orphée research reactor cores.

The suspended particulate matter (containing rare earth oxides and traces of thorium and uranium) are reused in the 2030-2040 period.

FOR SCENARIO SR2

The following is a reminder of data from the scenario in the 2015 edition of the National Inventory (scenario SR2 in this inventory), which assumes the continuation of nuclear power production with a uniform 50-year operating period for all reactors.

ESTIMATED VOLUMES OF WASTE AT INTERMEDIATE DATES FOR SCENARIO SR2 (m^3)

Category	Forecasts at end of 2020	Forecasts at end of 2030	Forecasts at term
HLW	4,100	5,500	10,000
ILW-LL	48,000	53,000	72,000
LLW-LL	92,000	120,000	190,000
LILW-SL	1,000,000	1,200,000	1,900,000
VLLW	650,000	1,100,000	2,200,000
Total	**1,800,000**	**2,500,000**	**4,400,000**

ESTIMATED QUANTITIES OF MATERIALS AT INTERMEDIATE DATES FOR SCENARIO SR2 (IN tHM, EXCEPT FOR SPENT FUEL PRODUCED BY DEFENCE-RELATED ACTIVITIES, WHICH IS SHOWN IN TONNES OF ASSEMBLIES)

Radioactive materials	Forecasts at end of 2020	Forecasts at end of 2030
ERU fuel before use	440	420
ENU fuel in use in nuclear power plants	4,600	3,700
Spent ENU fuel, awaiting reprocessing	11,000	11,000
ERU fuel before use	-	20
ERU fuel in use in nuclear power plants	-	290
Spent ERU fuel, awaiting reprocessing	530	1,200
Mixed uranium-plutonium fuel before use or in production	45	45
Mixed uranium-plutonium fuel in use in nuclear power plants	490	390
Spent mixed uranium-plutonium fuel, awaiting reprocessing	2,500	3,900
Non-irradiated mixed uranium-plutonium fuel scrap, awaiting reprocessing	240	200
Non-irradiated uranium fuel scrap awaiting reprocessing	-	-
FNR spent fuel, awaiting reprocessing	150	100
Research reactor fuel before use	0.2	0.3
Fuel in use in research reactors	0.1	0.1
Other civil spent fuel	75	77
Non-irradiated separated plutonium, in all its physicochemical forms	33	39
Mined natural uranium, in all its physicochemical forms	25,000	25,000
Enriched natural uranium, in all its physicochemical forms	960	960
Enriched uranium from spent fuel reprocessing, in all its physicochemical forms	-	-
Uranium from spent fuel reprocessing, in all its physicochemical forms	34,000	44,000
Depleted uranium, in all its physicochemical forms	330,000	410,000
Thorium, in nitrate and hydroxide form	8,500	8,400
Suspended particulate matter (by-products of rare earth ore processing)	3	-
Other materials	72	72
Spent fuel for defence purposes [1]	200	260

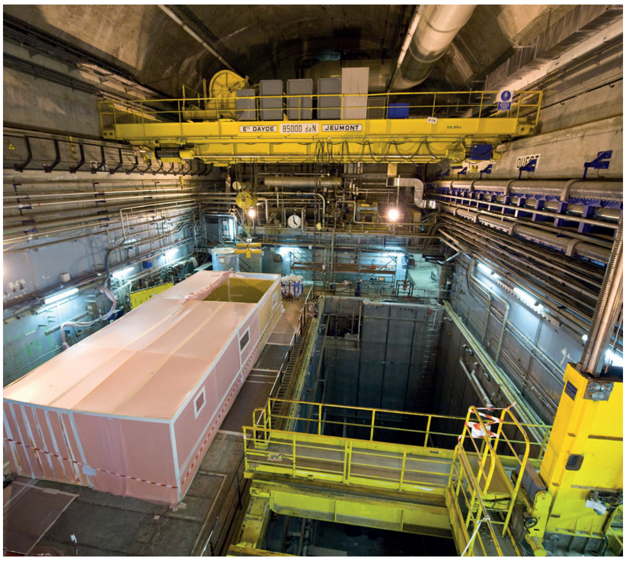
1 Quantities of spent fuel produced by the national defence sector were updated at the end of 2016.

VOLUMES OF DISMANTLING WASTE

As nuclear power is a relatively recent industry (dating back to the early 1960s), the main dismantling work on nuclear fuel cycle facilities and nuclear power plants is yet to come. The dismantling of a nuclear facility constitutes a significant source of radioactive waste. Optimising management and, above all, reducing the volume of waste produced represents a major challenge for the years to come. Waste from dismantling operations can either be conventional or radioactive. To identify which of these two categories the waste falls into, facilities are divided into zones based on the history of the facility and the operations conducted there:

- waste from conventional waste zones is not radioactive and is therefore inspected and then eliminated through approved conventional waste solutions;
- waste from potential nuclear waste production zones is all managed as if it were radioactive, even if no radioactivity is detected. This waste is conditioned and characterised for treatment by Andra with a view to long-term management.

Waste zoning can be revised between facility operation and dismantling, to take into account the specific characteristics of various operating phases and thereby optimise waste management.



Dismantling of the Chooz A plant

PRINCIPLES FOR THE MANAGEMENT OF WASTE FROM DISMANTLING OPERATIONS

The policy for the management of radioactive waste from dismantling operations is, like that of other waste, based on:

- ensuring traceability of waste from nuclear facilities (waste zoning, characterisation, inspections);
- minimising the volume of waste produced;
- optimising categorisation;
- sending waste to existing waste disposal facilities immediately after production. If waste has no available disposal solution, it is stored in dedicated facilities.

NATURE OF WASTE FROM DISMANTLING OPERATIONS

Most waste from dismantling is conventional waste, especially rubble and metal. For example, during dismantling of the Chooz A nuclear power plant, 80% of the 40,000 tonnes of waste produced was conventional and only 20% radioactive.

The radioactive waste from dismantling was mostly (> 99%) very low-level waste (VLLW) and low- and intermediate-level short-lived waste (LILW-SL). This included:

- materials from facility demolition work (concrete, rubble, scrap metal, glove box walls, piping, etc.);
- process equipment (e.g. metal parts);
- tools and protective clothing (gloves, vinyl overalls, etc.);
- effluents used for rinsing equipment.

There is also low-level long-lived waste (LLW-LL), particularly graphite waste from the first-generation French reactor system known as “graphite-moderated gas-cooled reactors” (GCR) and small quantities of intermediate-level long-lived waste (ILW-LL) (primarily activated waste, including metal parts from reactor cores).

Radioactive dismantling waste is managed in the same way as operating waste. It is sorted and may require treatment before conditioning (See Special Report 2). It is then transported to existing waste disposal facilities adapted to its level of radioactivity (Cires for VLLW and CSA for LILW-SL) or stored until adequate disposal solutions become available.

ESTIMATED QUANTITIES OF DISMANTLING WASTE

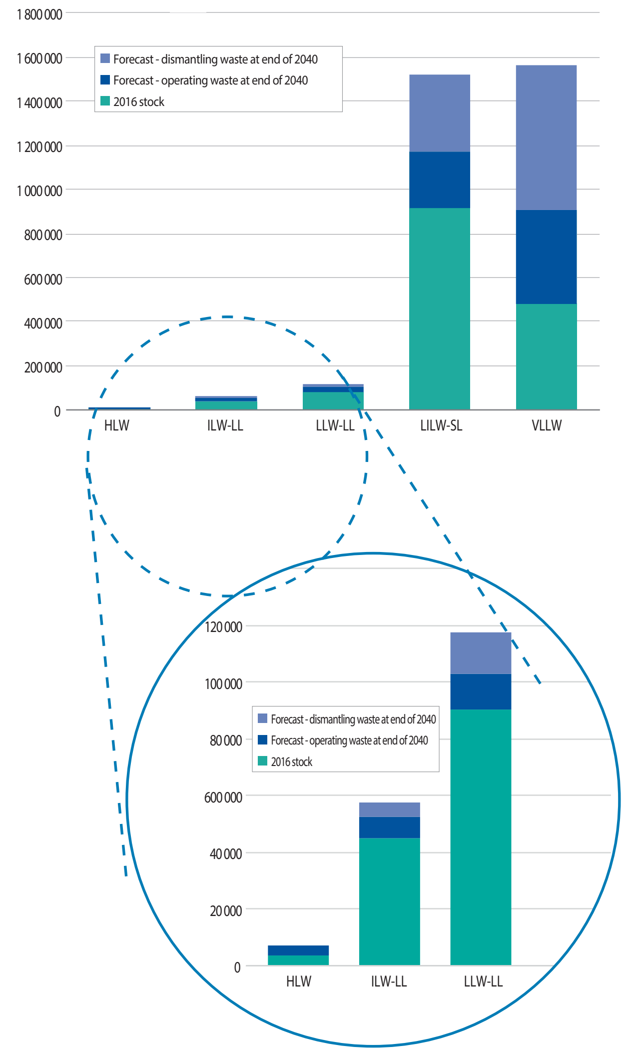
During the preparation of dismantling operations, the quantity and type of waste to be produced are estimated as accurately as possible and the treatment and conditioning methods are defined. The estimates take into account all the waste resulting from the operation, including secondary waste, such as the volumes of effluents generated by decontamination.

This starts with drawing up an exact inventory of the facilities to be remediated, including the equipment they contain and their residual contamination level, which requires good knowledge of the history of facility operation.

The quantities of waste produced will be estimated using “technical ratios”, which are created and regularly updated on the basis of feedback from previous dismantling operations. The ratios are used to calculate the quantity of waste resulting from the dismantling of each part of a facility, depending on its type, technical characteristics and the radiological contamination measurements taken there (see Special Report 3).

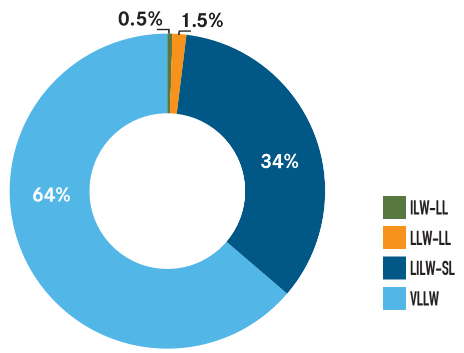
The diagrams below show the projected quantities of waste at the end of 2040 for scenario SR1, broken down by category, differentiating between inventories of waste produced at the end of 2016, dismantling waste forecasts and operating waste forecasts.

PROJECTED QUANTITIES OF WASTE AT THE END OF 2040 FOR SCENARIO SR1



The following diagram shows the category distribution of dismantling waste produced between 2017 and 2040. Most radioactive waste generated by dismantling operations is VLLW, and to a lesser extent, LILW-SL. In some special cases and depending on the type of facility, dismantling waste may also be ILW-LL. The dismantling of GCR reactors will produce LLW-LL.

PRODUCTION OF DISMANTLING WASTE FROM 2017 TO END OF 2040



04

SPECIFIC MANAGEMENT METHODS

Some radioactive waste is processed using specific management methods.

This includes:
- radioactive waste for which management choices were made at the time of production, and which have since changed. These are legacy situations, with waste disposed of in or near nuclear facilities, in conventional waste disposal facilities, in or close to former or operational industrial sites, or at sea;
- uranium mine processing residues, which are managed in situ due to their large volume;
- waste containing naturally occurring radioactive material (NORM), which, depending on its radiological characteristics, may be disposed of in situ, be recovered for reuse, or sent to conventional waste disposal facilities or Andra disposal facilities.

All sites used for radioactive waste disposal (except those related to disposal in international seas) are subject to suitable environmental monitoring, which checks that the impact of this waste is negligible, or if not, that suitable measures are taken to protect the environment and populations.

The sites mentioned here are listed in the *Geographical Inventory*. The quantities of waste set out in this chapter are not included in the statements set out in Chapters 2 and 3, since the corresponding waste will not be dealt with in Andra's operational or planned disposal facilities due to their legacy status and the fact that they are already managed.

MANAGING LEGACY SITUATIONS

In the past, some types of radioactive waste were managed using methods that have since changed.

Radioactive waste was disposed of by producers or holders on sites known as "legacy disposal facilities", which do not fall under Andra's responsibility.

These include:
- conventional waste disposal facilities that received VLLW from the conventional or nuclear industry;
- waste disposed of in or near nuclear facilities;
- deposits of NORM waste on or close to former or operational industrial sites;
- defence disposal sites in French Polynesia;
- areas for disposal at sea.

LEGACY DISPOSAL OF RADIOACTIVE WASTE IN CONVENTIONAL WASTE DISPOSAL FACILITIES

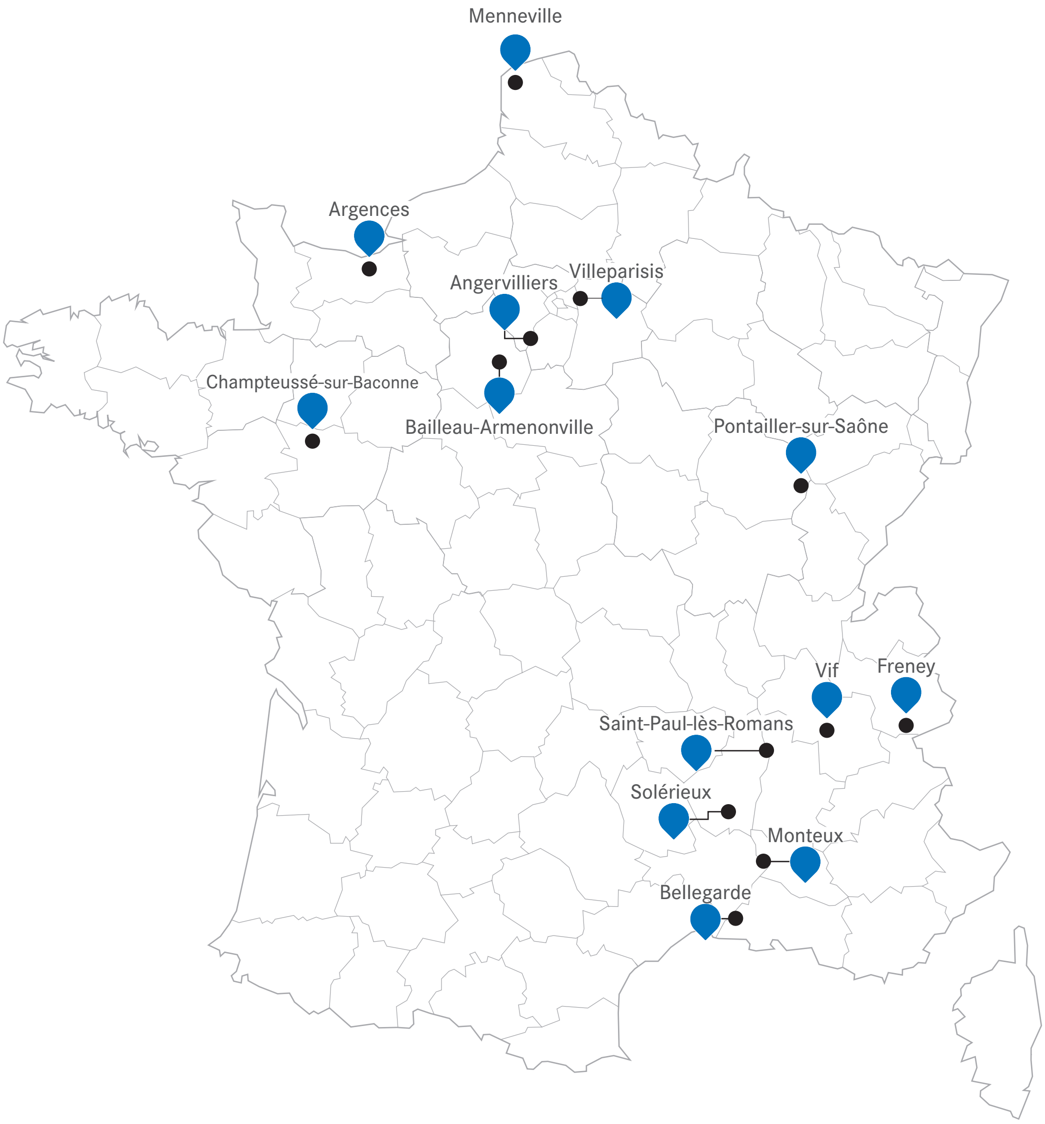
Conventional waste disposal facilities regularly or occasionally received waste containing very small quantities of radioactivity at levels of a few becquerels per gram. This mainly consisted of sludge, earth, industrial residues, rubble and scrap metal from the conventional industry or the civil or military nuclear industry.

The disposal of radioactive waste in conventional waste disposal facilities has been prohibited since 1997 for non-hazardous waste disposal facilities, 1992 for hazardous waste disposal facilities, and 2004 for inert waste disposal facilities.

The thirteen conventional waste disposal facilities that received radioactive waste regularly or occasionally are listed in the *Geographical Inventory*.

They are located in the following municipalities:
- **Angervilliers** in the Essonne *département*;
- **Argences** in the Calvados *département*;
- **Bailleau-Armenonville** in the Eure-et-Loir *département*;
- **Bellegarde** in the Gard *département*;
- **Champteussé-sur-Baconne** in the Maine-et-Loire *département*;
- **Freney** in the Savoie *département*;
- **Menneville** in the Pas-de-Calais *département*;
- **Monteux** in the Vaucluse *département*;
- **Pontailler-sur-Saône** in the Côte-d'Or *département*;
- **Saint-Paul-lès-Romans** in the Drôme *département*;
- **Solérieux** in the Drôme *département*;
- **Vif** in the Isère *département*;
- **Villeparisis** in the Seine-et-Marne *département*.

CONVENTIONAL WASTE DISPOSAL FACILITIES THAT HAVE RECEIVED RADIOACTIVE WASTE



LEGACY DISPOSAL OF WASTE IN OR NEAR NUCLEAR FACILITIES INCLUDING THOSE FOR DEFENCE-RELATED ACTIVITIES

Waste facilities within or close to nuclear facilities regularly or occasionally received waste that generally contained added radioactivity at levels of a few becquerels per gram. In total, a dozen legacy disposals have been registered to date.

THE A126 MOTORWAY IN CHILLY-MAZARIN

Very-low level radioactive waste (2,200 m^3) and earth (1,700 m^3) were used for the construction of this motorway in the 1970s. The earth came from the cleanup of the former *Société Nouvelle du Radium* (SNR) plant in Gif-sur-Yvette, and the very low-level radioactive materials from cleanup operations for the former plant in Le Bouchet. The average radium and uranium content of this earth is comparable to that found in nature (up to 3 becquerels per gram).

MONTBOUCHER MOUND

This mound mainly contains waste that would be categorised today as VLLW (24,600 m^3) produced during the cleanup of the former Le Bouchet plant between May 1975 and March 1977.

BUILDING 133 AT THE CEA SACLAY FACILITY

Waste backfill that would today be categorised as VLLW (17 m^3 of sandstone debris from old conduits and 57 m^3 of rubble and earth) was placed in the north and south foundations of Building 133 at the Saclay facility.

THE CONCRETE BASIN OF THE FORMER PILOT DECLADDING PLANT AT THE CEA MARCOULE FACILITY

This is an old basin that was equipped for underwater fuel decladding for a few months before a dedicated facility was commissioned in 1959. This partially underground basin, containing some machinery and equipment, was then filled with concrete. The basin has a total volume of 1,116 m^3 and is completely isolated from the process, with all piping removed. It has been sealed at the top. A quarterly inspection of surface contamination is carried out by the radiation protection department as part of periodic inspections.

INTERNAL DISPOSAL AT MARCOULE

The current volume is estimated at approximately 126,000 m^3 of waste consisting mainly of earth mixed with rubble. In order to characterise this volume, 32 uniformly distributed boreholes were drilled into the disposal down to the natural ground between 5 and 12 metres in depth;

It is important to note that the investigations carried out have not indicated any radiological marking, however, consistency in management practices implemented has led to the precaution of declaring this disposal to be similar to those at Cadarache (inert waste storage zone, ZEDI) and Valduc.

TRENCHES AT MARCOULE

Four trenches were operated one after the other from 1963 to 1993 to receive very low-level and low-level nuclear waste. This waste consists mainly of rubble, scrap metal, concrete, ash, sludge and earth from site excavations, for which conditioning in drums was not justified at the time and disposal in landfills was not acceptable. At the end of each trench's operation, backfill was placed to a depth of 1 m to 1.5 m over the waste. The four trenches contain approximately 50,000 m^3 of waste.

INERT WASTE STORAGE ZONE (ZEDI) AT THE CEA CADARACHE FACILITY

This waste disposal zone was created when the facility opened. 192,000 m^3 of inert waste was disposed of here between 1961 and 2007, including 1,650 m^3 of contaminated waste (4,600 MBq) disposed of between 1963 and 1991. The zone's chemical and radiological monitoring plan includes groundwater monitoring using piezometers and samples every 6 months or one year, depending on the parameters measured.

EXPERIMENTAL WELLS AT THE PEM EXPERIMENT CENTRE AT MORONVILLIERS

There are around one hundred wells containing residues from experiments conducted at the PEM experiment centre at Moronvilliers. These wells have been filled in and sealed. As part of the survey of polluted sites and soils, the CEA declared the PEM site in the Basol database in May 1997. The entire site, including the one hundred wells, is subject to enhanced environmental monitoring and the results are regularly sent to the Prefect by the representative in charge of nuclear safety and radiation protection for defence-related activities and facilities (DSND). Finally, radiometric mapping of the site by helicopter confirmed control of the site's radiological reference framework.

THE FIRST SIX CONVENTIONAL WASTE FACILITIES AT THE CEA VALDUC FACILITY

Due to the facility's geographic isolation, until the early 1990s, ordinary household and industrial waste and rubble were dumped in six locations at the facility, in accordance with the standards of the time and the practices of all municipalities in France. These disposal sites mainly contained ordinary, non-hazardous materials, deposited in hollows, such as valley heads. Waste and rubble were used to smooth out these areas. Radiological marking cannot be totally excluded due to former decontamination practices. The volumes in question are estimated at 100,000 m^3 to 150,000 m^3, and the level of radioactive contamination is estimated at zero or very low by the CEA. These disposal zones are monitored using piezometers downstream of the zones.

AREA 045 DISPOSAL SITES AT THE CEA VALDUC FACILITY

This area mainly received contaminated earth from the remediation operation in the "au tilleul" valley in 1995. It consists of a silo, whose bottom and walls are lined with a membrane consisting of welded HDPE, sandwiched between two layers of geotextile fabric, which is then all covered with sand, thereby ensuring confinement. This earth has low-level activity (an average of 1 Bq/g and a maximum of below 10 Bq/g). The volume is 8,990 m^3. This disposal area is monitored, particularly using piezometers located downstream.

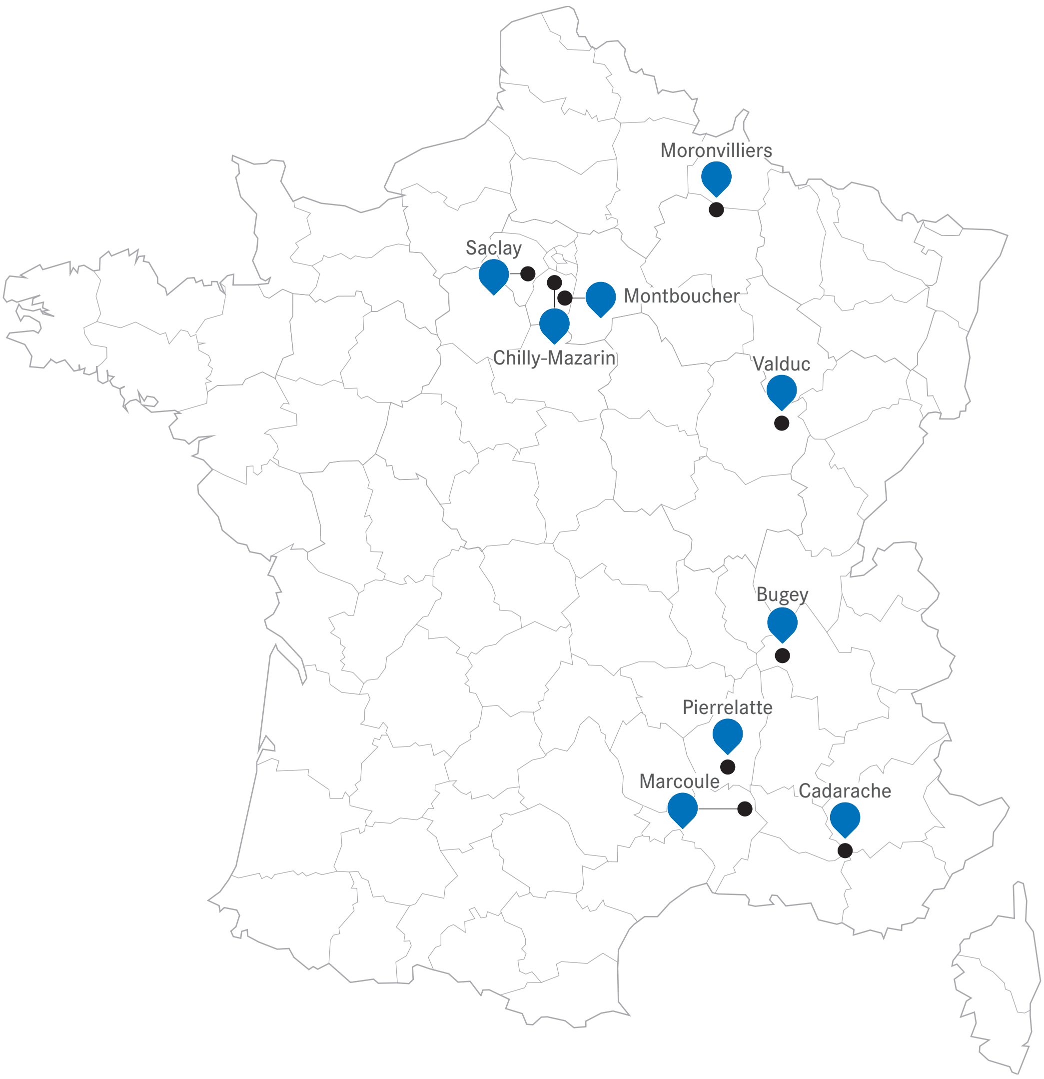
MOUND AT THE PIERRELATTE FACILITY

This mound has an area of approximately 37,000 m^2 and was formed in the early 1960s. Between 1964 and 1977, trenches were made to dispose of around 14,000 m^3 of waste, including fluorites from the treatment of uranium and chromate sludge. A groundwater quality monitoring plan has been in place since 1998 and the integrity of the structure is monitored.

BUGEY MOUND

The presence of approximately 130 m^3 of ion-exchange resins (non-radioactive according to the criteria of the time), buried between 1979 and 1984 in an artificial mound of around one million m^3 of landfill was revealed in 2005 during the initial siting studies for the Iceda facility south of the Bugey site. This mound consists of miscellaneous natural excavation materials and non-radioactive waste from construction of the various production units. The quality of the groundwater in this area is monitored by eleven piezometers distributed around the mound.

LEGACY DISPOSAL OF WASTE IN OR NEAR NUCLEAR FACILITIES INCLUDING THOSE FOR DEFENCE-RELATED ACTIVITIES



LEGACY DEPOSITS OF WASTE CONTAINING NATURALLY OCCURRING RADIOACTIVE MATERIAL

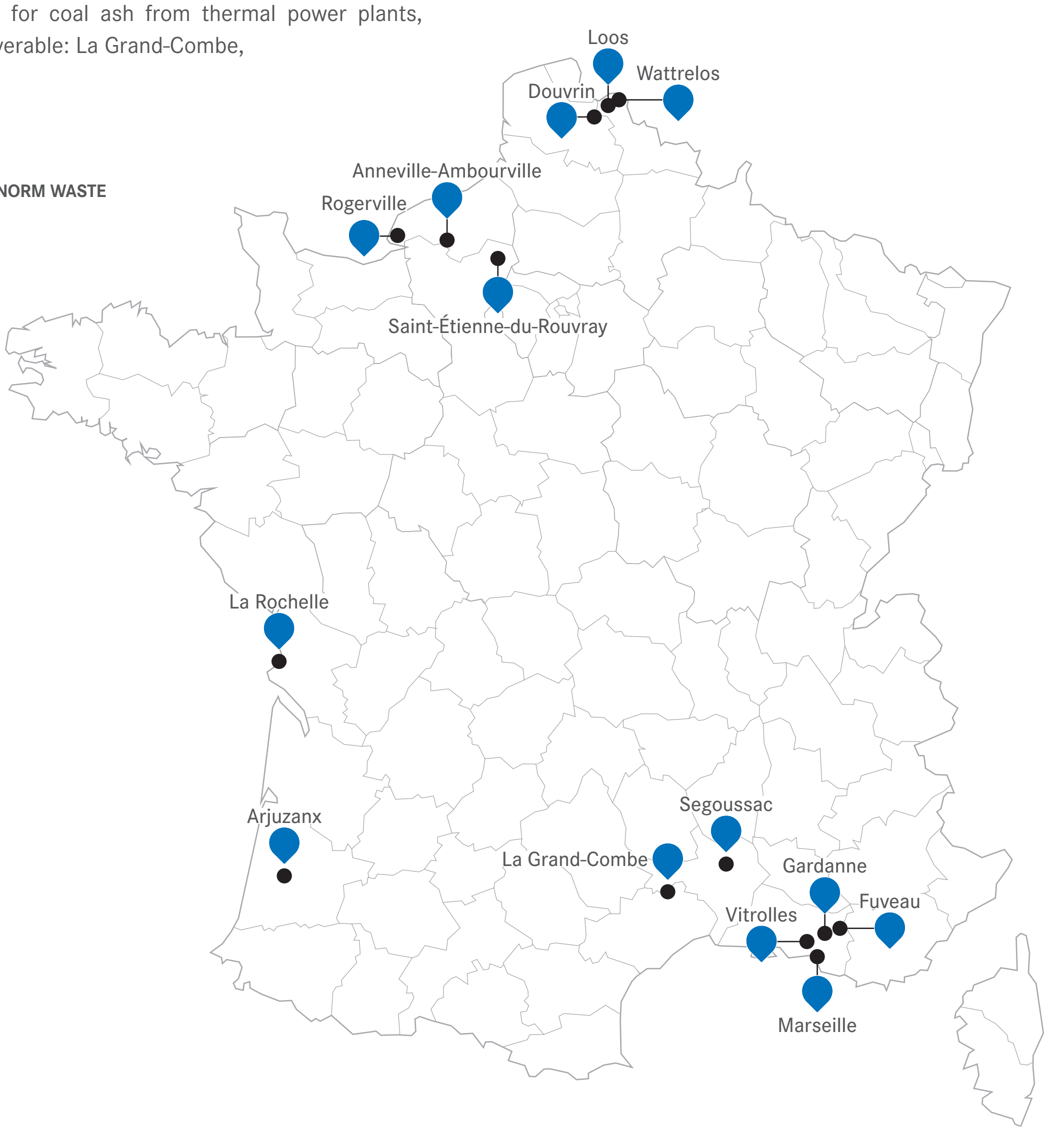
There are several dozen disposal facilities containing NORM waste registered in the *Geographical Inventory.* This especially includes phosphogypsum waste deposits from the production of fertilisers, residues from the production of alumina and coal ash from thermal power plants, some of which is still recoverable. The French Environmental Code applies to these deposits, particularly for the implementation of monitoring to check that there is no significant environmental pollution. Most of these legacy deposits of NORM waste can be compared to very low-level waste (VLLW) with an extremely low or non-existent level of radioactivity.

The main disposal sites for NORM waste are:

- disposal facilities for residues from alumina production: Gardanne, Vitrolles, Marseille (Aygalades, La Barasse-Saint-Cyr, La Barasse-Montgrand), Segoussac;
- disposal facilities for coal ash from thermal power plants, which is not recoverable: La Grand-Combe, Fuveau, Arjuzanx;
- disposal facilities for phosphogypsum from the production of phosphoric acid used in the manufacture of fertiliser. These sites are no longer in use and are monitored: Anneville-Ambourville, Douvrin, Rogerville, Saint-Étienne-du-Rouvray, Wattrelos;
- Vernay lagoon in Loos. This ore treatment site generated filtration sludge that was disposed of on the site (3,600 m^3);
- the port areas in La Rochelle, whose facilities were backfilled with residues from historic rare earth production activities using monazite ore: the site of the Chef-de-Baie plant in La Rochelle where 35,000 m^3 of solid residues from monazite treatment were used as backfill, La Pallice port in La Rochelle: the Solvay plant produced residues resulting from the treatment of natural materials that were very slightly radioactive. 50,000 m^3 of these residues were used as backfill in the port.

It should be noted that some coal ash slag heaps are recovered for use in building materials (concrete).

LEGACY DEPOSITS OF NORM WASTE



DEFENCE DISPOSAL SITES IN FRENCH POLYNESIA

Between 1966 and 1996, France carried out nuclear experiments at the Pacific Test Centre (CEP), located on the Mururoa and Fangataufa atolls in the South Pacific, in French Polynesia.

These nuclear tests were initially carried out in the atmosphere (1966-1974), and then underground in vertical shafts sunk into the rocks of the coral reefs (1975-1987) or under the lagoons (1981-1996).

The waste produced by these experiments and the dismantling of the associated facilities was disposed of in situ in wells or dumped in French territorial waters (see section on Disposal at Sea).

The waste disposed of in situ as part of these operations is set out in the *Geographical Inventory* (Overseas).

When French nuclear testing in the Pacific finally ceased in 1996, France asked the IAEA to conduct a radiological assessment of the experimental sites of Mururoa and Fangataufa and the nearby areas. This assessment constitutes the baseline for activity levels in the environment of these two atolls.

Although the IAEA's experts had concluded that it was not necessary to continue radiological monitoring of the atolls of Mururoa and Hao, the decision was made to maintain a monitoring programme, particularly in order to detect any release of radionuclides from cavities and lagoon sediments.

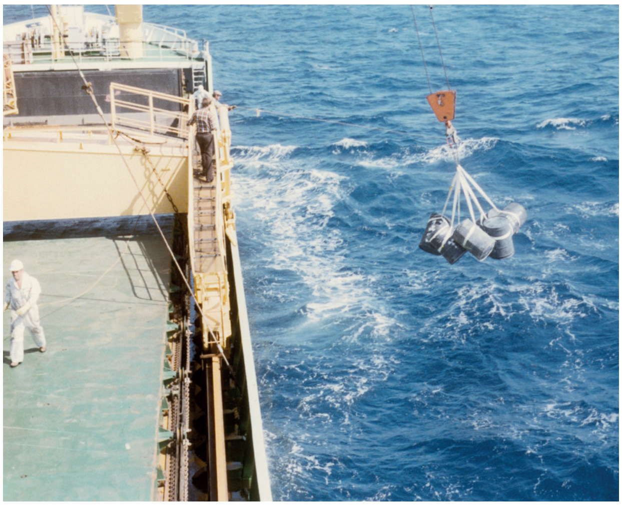
This monitoring focuses on the environment of the two atolls and has two components:

- continuous monitoring of atmospheric aerosols and the integrated dose;
- an annual sampling campaign. No release has been detected to date.

Mururoa Atoll

DISPOSAL AT SEA

Disposal at sea has always been a means of managing all types of waste. Radioactive waste has been no exception. The solution of simply dumping this waste at sea was in fact considered safe by the scientific community, since the dilution and assumed duration of isolation provided by the marine environment were deemed sufficient. This practice was therefore implemented by many countries for more than four decades, starting in 1946.



Radioactive waste being dumped in the sea in the 1960s

Disposal at sea was first organised by the waste producing countries themselves, before being coordinated by international bodies from the 1960s. It is within this framework that France disposed of radioactive waste in the Atlantic, taking part in campaigns organised by the NEA in 1967 and 1969. During these two operations, France disposed of 14,200 tonnes of conditioned radioactive waste at sea, with a total activity of about 350 TBq, all from the Marcoule site.

When the Manche disposal facility was commissioned in 1969, France stopped using sea disposal for the management of most radioactive waste.

However, this management method was still used by France until 1982 for waste generated by activities related to nuclear testing in French Polynesia, representing 3,200 tonnes of radioactive waste, with a total activity of less than 0.1 TBq, disposed of in French territorial waters in Polynesia.

It should be noted that France did not dispose of radioactive waste in the English Channel: only the United Kingdom and Belgium used the Casquets trench to the north-west of Cap de La Hague.

URANIUM MINE PROCESSING RESIDUES

Uranium mining in France between 1948 and 2001 (in open-cast or underground mines) led to the production of 76,000 tonnes of natural uranium. Exploration, extraction and processing activities involved approximately 250 sites of varying sizes (from straightforward exploratory work to large-scale operating sites) spread over 27 *départements* in France. Ore processing was mainly carried out in eight plants. All these sites are described in the national inventory of uranium mining sites, *Mimausa* (memory and impact of uranium mines: summary and archives), drawn up by IRSN.

There are two categories of products from uranium mining:

- mine waste which means products consisting of soil and rocks excavated to access the deposits of interest. The volume of mine waste extracted can be estimated at around 170 million tonnes. Most mine waste remained where it was produced. It was used for filling open-cast mines or underground mining structures such as shafts, for redevelopment by covering residue disposal sites or was left as a muck pile. Around 2 million tonnes of mine waste, representing 1% to 2% of the quantity extracted, could be used for backfill, earthworks or as road foundations in places near mining sites;
- uranium mine processing residues, meaning products remaining after extraction of the uranium contained in the ore by static or dynamic processing. The residues correspond to process waste, with an estimated volume of 50 million tonnes. These residues are defined as process waste under the French Environmental Code, which is why the disposal facilities for these residues are subject to the nomenclature of environmentally regulated facilities and are classified under Section 1735.

The processing residues are disposed of on 17 sites, all close to uranium ore processing facilities, and correspond to VLLW or LLW-LL, characterised by their particle size and specific activity:

- processing residues from low-content ore (of the order of 300 to 600 ppm uranium) with a total average specific activity of 44 Bq/g (including about 4 Bq/g of radium-226). These residues from static leaching (about 20 million tonnes) are either disposed of in muck piles or open-cast mines, or used as a first covering layer for dynamic leaching residue disposal sites;
- processing residues from high average content ore (of the order of 1,000 to 10,000 ppm uranium or 0.1% to 1% uranium) with a total average specific activity of 312 Bq/g (including about 29 Bq/g of radium-226). These residues from dynamic leaching (about 30 million tonnes) are either disposed of in former open-cast mines, sometimes with an additional dyke, or in basins enclosed by an encircling dyke or behind a dyke damming a thalweg.

The seventeen disposal sites are:

- Bauzot;
- Bellezane;
- Bessines-sur-Gartempe - Brugeaud;
- Bessines-sur-Gartempe - Lavaugrasse;
- Bertholène;
- Gueugnon;
- Jouac;
- La Commanderie;
- La Ribière;
- Le Cellier;
- L'Escarpière;
- Les-Bois-Noirs-Limouzat;
- Lodève;
- Montmassacrot;
- Rophin;
- Saint-Pierre-du-Cantal;
- Teufelsloch.

Very low-level waste linked to the use or dismantling of ore processing facilities or other front-end facilities in the cycle was also disposed of in situ at some of these sites. The sites in question are Bauzot, Saint-Pierre-du-Cantal, Bessines-sur-Gartempe, Gueugnon, Lodève, Jouac, L'Escarpière, Les-Bois-Noirs-Limouzat and Le Cellier.

Moreover, three sites managed under the La Crouzille mining division (Orano, formerly Cogema and then Areva) were used in the 1970s and 1980s as dumps for very low-level waste from various front-end facilities in the cycle: Fanay, Margnac and Peny.

Under the French National Radioactive Materials and Waste Management Plan (PNGMDR), Orano submitted studies on the assessment of the long-term impact on health and the environment of the disposal facilities for mine processing residues (physicochemical characterisation of residues, geomechanical strength of dykes and the long-term radiological impact of the disposal facilities) and former mining extraction sites (management of diffuse discharges and water treatment, long-term impact of mine waste).

The studies submitted under the PNGMDR 2013 - 2015:

- provided information on modelling the impact of mining residue disposal facilities;
- improved understanding of uranium transport phenomena from muck piles into the environment;
- improved understanding of mechanisms governing uranium and radium mobility in uraniferous mining residues.

Furthermore, in 2010, the interdisciplinary expert group for the Limousin submitted a report on the current and long-term impact of these mining operations. This report proposes monitoring management options[1].

Finally, pursuant to the circular of 22 July 2009[2], environmental assessments are being carried out for all mining sites under Orano's responsibility, including the disposal facilities for processing residues. Assessment of "orphan" sites (for whom the body responsible is unknown or insolvent) is also in progress.

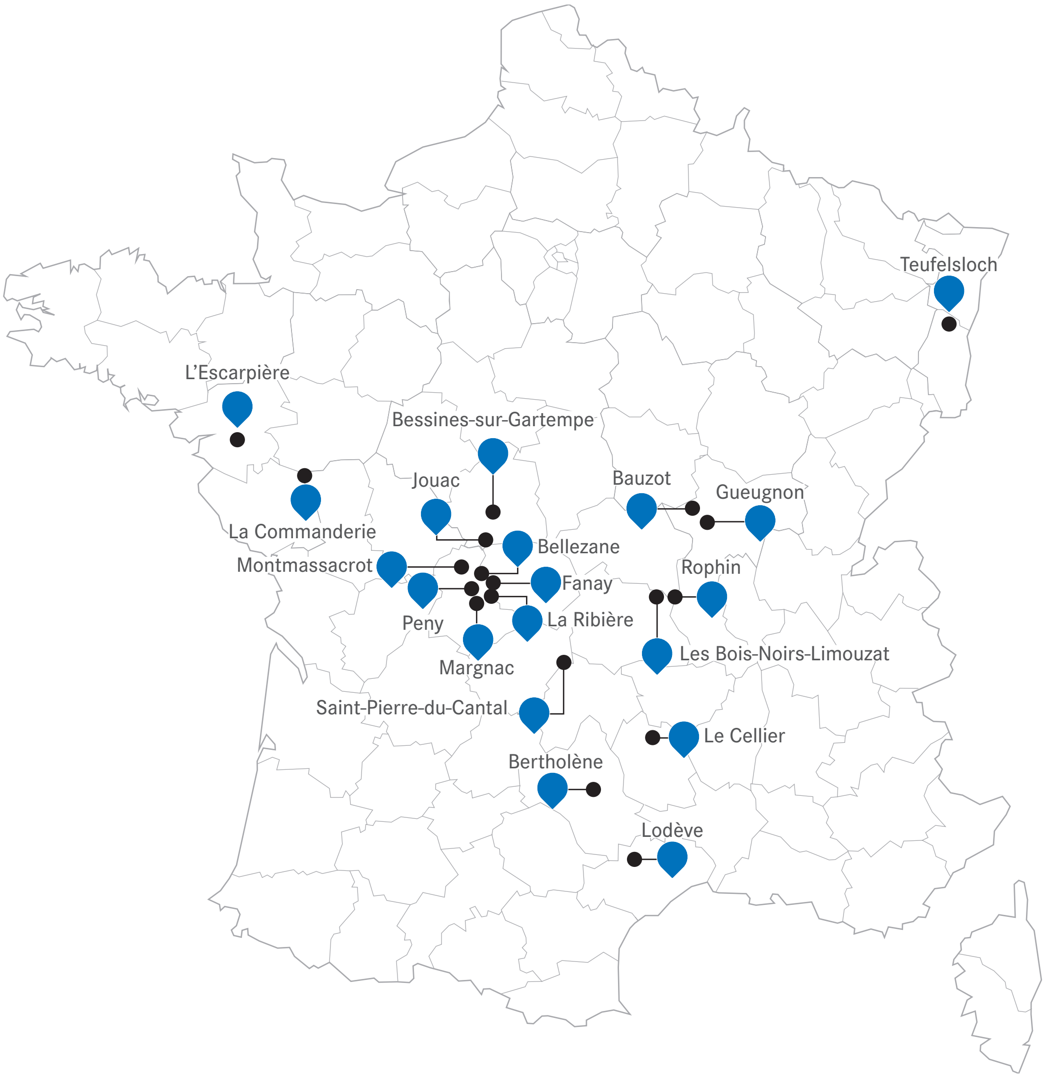
The former uranium mine at Bellezane while still in operation...

... and after remediation

1 *Recommandations pour la gestion des anciens sites miniers d'uranium en France. Des sites du Limousin aux autres sites, du court aux moyen et long termes*, Final Report prepared by the interdisciplinary expert group on uranium mines in Limousin, September 2010.

2 Circular of 22 July 2009 on the management of former uranium mines.

MINING SITES



CURRENT MANAGEMENT OF WASTE CONTAINING NATURALLY OCCURRING RADIOACTIVE MATERIAL

Waste containing naturally occurring radioactive material (NORM) is generated by the use or processing of raw materials that contain naturally occurring radionuclides but are not used for their radioactive properties. This waste is categorised as low-level long-lived or very low-level waste.

Since the Order of 25 May 2005[1], NORM waste has been subject to specific management procedures. Depending on the radiological characteristics of NORM waste, it can be:

- managed in situ;
- recovered for its physicochemical properties, particularly for use in the manufacture of construction products;
- disposed of in conventional waste disposal facilities. Regulations allow for the possibility of disposing of NORM waste in hazardous waste disposal facilities, non-hazardous waste disposal facilities, and inert waste disposal facilities. Four facilities are now licensed to handle NORM waste, in accordance with the regulations in force.

1 Order of 25 May 2005 concerning professional activities using raw materials naturally containing radionuclides not used for their radioactive properties.

These are the hazardous waste disposal facilities of Villeparisis, Bellegarde, Champteussé-sur-Baconne and Argences. In order to accept this type of waste, these hazardous waste disposal facilities followed the measures set out in the Circular of 25 July 2006[1]. This circular specifies acceptance and inspection methods for waste in waste disposal facilities, conditions for monitoring the radiological impact of admitting this waste on the environment, and procedures for informing the inspection body for regulated facilities through the annual activity report. The quantities of NORM waste received in these facilities are far below the authorised capacities (less than 10% of the authorised capacity);

- disposed of at Andra disposal facilities. Very low-level NORM waste that cannot be accepted in conventional waste disposal facilities is disposed of at Cires. Approximately 1,400 m^3 of waste in this category has been recorded (excluding waste generated by coal-fired plants, paper mills and biomass combustion). Furthermore, there are around 21,000 m^3 of NORM waste in the LLW-LL category.

The management of NORM waste has been completely overhauled by French Decree 2018-434 of 4 June 2018[2], which took effect on 1 July 2018. It transposes the provisions of Council Directive 2013/59/EURATOM of 5 December 2013, laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation.

THE ORFLAM-PLAST SITE AT PARGNY-SUR-SAULX

The former Orflam site before...

In the 1930s, the monazite processing plant, which later became the Orflam-Plast plant, was set up in Pargny-sur-Saulx to manufacture lighter flint from monazite. The plant operated until 1967, with final shutdown in 1997. The extraction of monazite, an ore rich in thorium, led to the production of low radioactive residues, which initially concentrated the radioactivity present in monazite. These residues led to site pollution, which was subsequently remediated.

The vast majority of this waste and earth produced during cleanup was disposed of at Cires. The rest, mainly consisting of rubble with very low radioactivity was contained on site (3,000 m^3).

... and after remediation

1 Circular of 25 July 2006 on conditions for the acceptance of waste containing technologically enhanced naturally occurring radioactive materials in waste disposal facilities.
2 Decree no. 2018-434 of 4 June 2018 concerning various nuclear-related measures.

05

SPECIAL REPORTS

REPORT

01

Existing and planned solutions in France for long-term management of radioactive waste

INTRODUCTION

Like many other countries, France has chosen to set up a long-term solution for managing radioactive waste. This solution is based on definitive disposal (surface, near-surface or deep geological disposal), which is the only viable solution for confining waste for the period needed for its radioactive elements to decay to a level that no longer presents a risk to man or the environment.

Confinement involves isolating contaminants to prevent their propagation in the long term and to ensure that the measures taken on design of each disposal facility are monitored and maintained over time. This design is adapted to the types of waste received in the basis of three components.

There are currently three French surface disposal facilities (two in operation and one in the closure phase[1]) that dispose of most volumes of radioactive waste produced each year in France (VLLW and LILW-SL). For other types of waste (LLW-LL, ILW-LL and HLW), suitable disposal facilities are currently being developed. In the mean time, the waste is stored in specific facilities, generally at the production sites.

DISPOSAL FACILITY COMPONENTS

Historically, the safety of any kind of nuclear facility is based on the concept of redundancy of protection equipment and measures. This concept involves the implementation of successive barriers between the radionuclides and the biosphere. Their role is to delay, and if possible prevent, the dispersion of radionuclides in the ecosystem by:

- limiting water influxes;
- delaying the release of radionuclides in the aqueous phase;
- retaining any radionuclides released.

For nuclear waste disposal facilities, the confinement system consists of three components:

- the packages containing the waste;
- the disposal vaults containing the packages;
- the site geology which forms a natural barrier.

DEEP GEOLOGICAL DISPOSAL FOR HLW AND ILW-LL

After 15 years of research on HLW and ILW-LL management and after a public debate, Planning Act 2006-739 of 28 June 2006, now codified in the French Environmental Code, established deep geological disposal as the only safe long-term solution for managing waste that, for safety or radiation protection reasons, cannot be disposed of in surface or near-surface facilities. This approach is aimed at reducing the burden on future generations. For the implementation of this solution, the Planning Act tasked Andra with conducting studies and research to choose the site and design a reversible deep disposal facility for HLW and ILW-LL.

Andra is therefore managing the Industrial Centre for Geological Disposal (Cigeo) project for the disposal of all HLW and ILW-LL produced at all current nuclear facilities, including waste from facility dismantling and the processing of spent fuel used in nuclear power plants.

If approved, Cigeo will be built along the borders of the Meuse and Haute-Marne *départements* in eastern France.

Cigeo will consist of surface facilities that will be used to receive waste packages and to excavate and build the necessary underground vaults. The waste will be disposed of some 500 metres below ground in an impermeable argillaceous rock formation able to contain radioactivity over very long periods.

Cigeo is designed to operate for at least 100 years and to be flexible over time to give future generations as many adaptation options as possible.

1 Formerly known as the monitoring phase.

In April 2016, Andra sent a series of documents to the ASN for assessment, including a proposed Cigeo Master Plan for Operations, a Safety Options Report and a Retrievability Technical Options Report.

The ASN issued its opinion on these reports in January 2018[1].

This was an important step in the Cigeo design process, prior to submission of the construction licence application. Construction work on Cigeo could start following the ASN assessment of this application and a public inquiry and, providing a decree is issued granting the construction licence.

After an industrial pilot phase, operation of the waste repository is scheduled to last for over one century.

Pending waste disposal at Cigeo, storage on the waste production sites is vital for the management of HLW and ILW-LL.

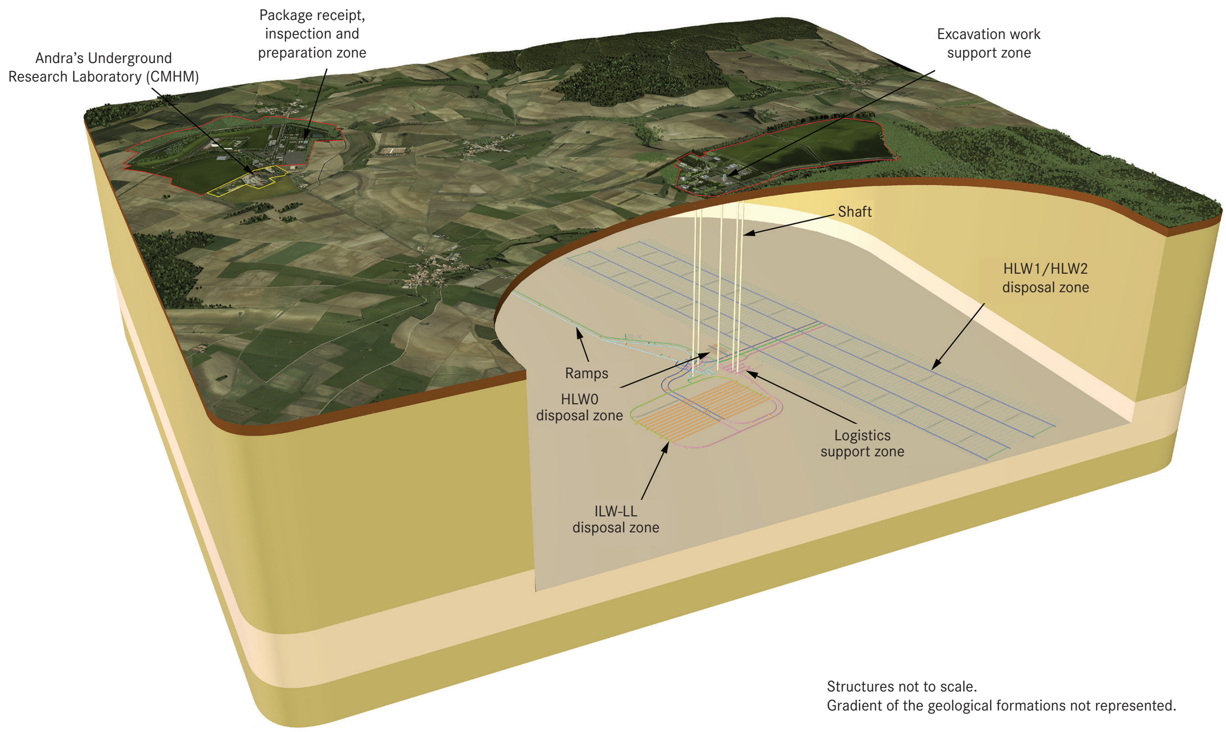


Diagram of Cigeo project surface and underground facilities

1 Opinion no. 2018-AV-0300 of the French Nuclear Safety Authority of 11 January 2018 on the Safety Options Report presented by Andra for the Cigeo Project to build a deep geological radioactive waste disposal facility.

PRE-DISPOSAL STORAGE

Before disposal, waste is generally stored on site in dedicated facilities. This consists of:

- for waste to be taken to existing disposal facilities:
  - buffer storage of conditioned waste in the form of packages, of a logistical nature, for management of flows to Andra facilities,
  - storage of waste, especially older waste, awaiting treatment, conditioning and subsequent shipment;
- for waste to be taken to disposal facilities under development:
  - storage of waste, especially older waste, awaiting recovery and transfer to other storage facilities or Andra facilities under development,
  - storage until disposal solutions are available,
  - storage of high-level waste, which has to be stored for several decades to decay, before it can be placed in deep disposal facilities.

Unlike a disposal facility, a storage facility is by definition temporary.

Storage can also be used for the purposes of radioactive decay for the short-lived radionuclides contained in waste, for removal to the CSA, for example.

NEAR-SURFACE DISPOSAL FOR LLW-LL

Programme Act no. 2006-739 of 28 June 2006 on the sustainable management of radioactive materials and waste, now codified in the French Environmental Code, tasked Andra with developing disposal solutions for graphite waste, generated primarily by the operation and dismantling of first-generation gas-cooled graphite-moderated reactors (GCR), and radium-bearing waste. The French government also asked Andra to examine the possibility of including other low-level long-lived waste (LLW-LL) in the studies.

A national campaign to find a disposal facility site for LLW-LL was launched in 2008 at the government's request. Andra contacted 3,115 municipalities located on lands whose geological characteristics appeared favourable for a near-surface facility and presented them with the project. In late 2008, Andra provided the government with a report analysing the geological, environmental and socio-economic aspects of the forty-odd municipalities that expressed an interest in the project.

After consulting with the French Nuclear Safety Authority (ASN), the National Assessment Board (CNE) and the relevant elected officials, in 2009 the government asked Andra to conduct in-depth geological investigations in two municipalities. However, these two municipalities then rescinded their candidacy.

In response, the government decided to push back the deadlines to allow time for consultation, and also asked Andra to explore other potential scenarios for managing this waste, in particular the separate management of radium-bearing and graphite waste.

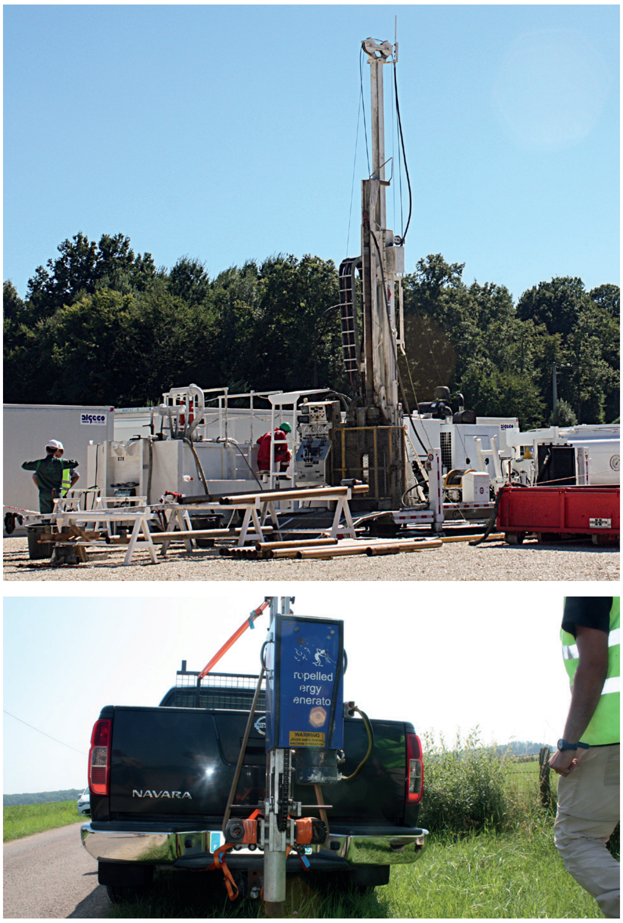
In addition, the government tasked the High Committee for Transparency and Information on Nuclear Safety (HCTISN) with compiling experience feedback on the site search. The HCTISN submitted its recommendations to the government in September 2011. They cover selection of a site, a schedule, responsibilities, local stakeholders, public information, consultation and project support. In particular, the High Committee recommended selecting areas that already have nuclear facilities. At the same time, in 2012, Andra submitted a report on the long-term management scenarios for LLW-LL. This report pointed to the need to initiate geological investigations and to continue the waste characterisation and R&D work to move forward with the design of a near-surface disposal facility project.

In response to this report, the French ministry responsible for the environment asked Andra to continue its work to locate a disposal site, contacting existing nuclear facility sites as well as focusing on areas where municipalities had submitted a candidacy in 2008, as recommended by the HCTISN.

The Soulaines community of municipalities in the Aube *département*, where surface disposal facilities operated by Andra are already located, agreed to geological investigations in 2013. A consultation took place prior to any work in the field, as requested by local elected officials. The geological investigations conducted in the Aube *département* in north-eastern France between mid-2013 and mid-2015 were aimed at improving knowledge of the local geology, in order to determine whether the subsurface characteristics are suitable for a low-level long-lived waste disposal facility.

In compliance with the 2013-2015 PNGMDR, Andra submitted a status report on LLW-LL management in 2015. This report set out the lessons learned from the initial geological investigations carried out, and described the progress made on the studies and research on waste conducted by Andra and the waste producers (EDF, CEA, Orano and Solvay). Preliminary design studies were carried out and a first safety assessment completed. The 2015 status report identified a geographical area for continuation of the project. It also identified topics to be studied in greater depth in the forthcoming study programme. The ASN was consulted on this report and presented its recommendations in opinion no. 2016-AV-264[1].

Pending Andra's construction of a suitable disposal facility, LLW-LL is most often stored on production sites or, particularly for waste from industries outside the nuclear power sector, at Andra's industrial facility for grouping, storage and disposal (Cires).



Additional LLW-LL geological investigations campaign in 2017

CIRES STORAGE FACILITY

In 2012, Andra commissioned a long-lived radioactive waste storage building at Cires, especially intended for waste from industries outside the nuclear power sector. The building has a surface area of 2,000 m^2.

This waste, mostly LLW-LL with some ILW-LL, is stored in different halls, depending on its radiological characteristics. The waste will be gradually recovered for disposal as the disposal facilities are commissioned.

The main types of waste stored at Cires at the end of 2016 were:

- radioactive lightning rods;
- radioactive objects from private owners (radium fountains, radioluminescent objects, etc.);
- radioactive medical artefacts used between the two world wars (collector's items such as radium needles, tubes and compresses);
- waste (e.g. soil, rubble) resulting from the cleanup of sites contaminated by radioactivity containing long-lived radioactive elements (radium, thorium).

1 Opinion no. 2016-AV-264 of the French Nuclear Safety Authority of 29 March 2016 on the studies on management solutions for low-level long-lived waste (LLW-LL) submitted in application of the National Radioactive Materials and Waste Management Plan for 2013-2015, with a view to drawing up the National Radioactive Materials and Waste Management Plan for 2016-2018;

SURFACE DISPOSAL FOR LILW-SL AND VLLW

LILW-SL

Low- and intermediate-level short-lived waste (LILW-SL) has been disposed of at surface facilities in France since 1969. There are two facilities in France for waste in this category: the Manche disposal facility (CSM) and Aube disposal facility (CSA).

Around 527,000 m^3 of waste was disposed of at the Manche disposal facility between 1969 and 1994. This facility has been closed since 1994 and therefore no longer accepts waste.

The CSA facility has been in operation since 1992 and is located in the municipalities of Soulaines-Dhuys, Epothémont and La Ville-aux-Bois. It covers a surface area of 95 ha, including 30 ha for disposal, with an authorised capacity of one million cubic metres of radioactive waste packages.

Waste disposed of at CSA is conditioned in concrete or metal packages. These packages are disposed of in reinforced concrete vaults 25 metres long and 8 metres high, built in a geological area consisting of a clay layer overlain with a sandy layer. The clay layer is impermeable and acts as a natural barrier in case of accidental dispersal of radioactive elements in the subsoil. Above the clay, the sandy layer drains rainwater towards a single outlet, which simplifies environmental monitoring.

The space between the packages in a vault are filled with concrete or gravel, depending on whether the packages are metal or concrete. The vault is then sealed with a concrete slab and covered with an impermeable polyurethane layer. When the facility ceases operation, the vaults will be covered with a multi-layer cap primarily made of clay to ensure long-term waste confinement and the site will be monitored for at least 300 years.

The impermeability of the vaults is verified via a network of underground galleries, which are inspected on a regular basis.

Disposal of a LILW-SL package

VLLW

As requested by the public authorities, Andra has developed a specific solution for very low-level waste.

In many countries, below a certain level of radioactivity known as the “clearance level”, waste is managed as conventional waste. In France, all waste produced by regulated nuclear facilities, environmentally regulated facilities or facilities authorised under the French Public Health Code, which contain or could contain radioactive elements, are managed using dedicated waste solutions.

Since 2003, this waste has been disposed of at the industrial facility for grouping, storage and disposal (Cires) in the municipalities of Morvilliers and La Chaise. This facility is an environmentally regulated facility (ICPE) and covers a surface area of 46 ha, including 18 for disposal.

It is designed to accommodate 650,000 m^3 of waste, mainly from the dismantling of French nuclear facilities. Its design is based on the hazardous waste disposal facilities in the chemical industry.

Waste packages are inspected upon arrival and placed in cells excavated in clay, with a base engineered to collect seepage water. They are isolated from the environment by:

- a synthetic membrane around the waste cells and a leaktightness monitoring system;
- the layer of clay underneath and on the sides of the disposal cells.

During operation, the cells are protected by a mobile roof system and are equipped with monitoring devices. Once filled, the cells are covered with a layer of clay linked to a system for inspection and leach solution collection.

VLLW disposal cell

SPECIAL CASES

In addition to waste subject to specific disposal solutions (see Chapter 4), some cases require special management solutions due to their physicochemical characteristics.

TRITIATED WASTE

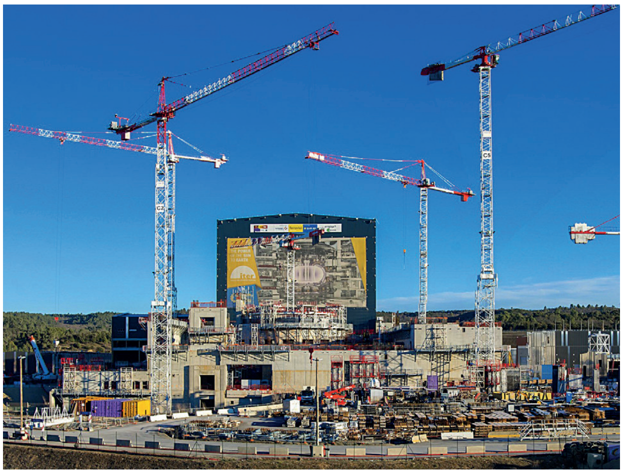
Tritium is a short-lived radionuclide (half-life of around 13 years) which is difficult to confine and may easily migrate into the environment. Waste containing tritium ("tritiated" waste) is therefore managed in a specific way: it is stored for long enough, generally around fifty years, to allow for the decay of tritium activity in the packages, which are then sent to one of the Andra disposal facilities, depending on their level of radioactivity and residual gas release rate. Tritiated waste with an activity or tritium gas release rate that is too high, may receive thermal treatment to reduce their activity or gas release before storage.

At the end of 2016, the volume of tritiated waste stored was around 5,640 m^3. This waste is generally in solid form. However, there are small quantities of liquid and gaseous tritiated waste.

The vast majority of tritiated waste (around 99%, i.e. around 5,580 m^3 at the end of 2016) comes from the national defence sector, and almost entirely from nuclear deterrence activities. Industry and medical and pharmaceutical research laboratories have used tritium in the past and continue to do so today, which generates tritiated waste. At the end of 2016, the corresponding volume was 60 m^3. Finally, the ITER facility will also generate tritiated waste (after 2030) and will become its leading producer, first in its operation phase and then, in around 2060, in its dismantling phase. Tritiated waste is currently stored on production sites. In 2012, the CEA commissioned a storage facility in Valduc for its own very low-level tritiated waste. Similarly, the ITER project includes the construction of a storage facility for waste produced by its operation and dismantling. The first storage modules will be available in 2027.

There are also plans to use the ITER storage facility for storing tritiated waste from research (except CEA), industries outside the nuclear power sector, and medicine.

Pending the commissioning of this facility, in case of an emergency impacting the environment or human health, this waste could be temporarily stored on the Valduc site, after authorisation on a case-by-case basis by the competent safety authority (ASND, the French Nuclear Safety Authority for Defence-related Facilities and Activities).



ITER facility under construction

VERY SHORT-LIVED WASTE

The majority of very short-lived waste comes from hospitals and contains radionuclides with a half-life under 100 days, which have been used for diagnosis or therapeutic purposes (see Special Report 5).

The decay of this waste is managed at the production sites. It is stored for a period ten times greater than the longest half-life for the radionuclides it contains.

This allows the radioactivity to decrease by a factor of 1,000, at which point the waste can be removed via conventional disposal solutions, following checks.

Decay tanks

WASTE FROM MALVÉSI

Since 1960, the Malvési Orano industrial site has performed the first step for converting the uranium required for the nuclear fuel cycle. The process used for uranium conversion produces solid waste stored in settling ponds on the Malvési site.

Because of the specific nature of this so-called legacy waste (in high volumes), it is not incorporated into existing or planned disposal solutions. This waste is part of the uranium conversion treatment residues waste stream in the National Inventory. Studies are underway to define a final disposal solution for this waste.

For waste produced from 1 January 2019, Orano is currently working on two projects that aim, firstly, to reduce the volume of solid waste produced and promote existing disposal solutions, and secondly, to use a thermal process to treat future liquid effluents from this process, in addition to those already stored in the evaporation pans. These future changes to the process will lead to the creation of two distinct waste streams:

- solid waste, formed of fluorides and gypsums, which will be produced by the plant in the future in the form of dense sludges stored in on-site cells;
- solid waste from the thermal treatment of nitrated liquid effluents produced by future operation of the conversion facilities and recovery of the inventory already stored in the evaporation pans.

Waste produced after 1 January 2019 will no longer be managed alongside legacy uranium conversion treatment residues, and will have to be directed towards VLLW and LLW-LL management solutions after treatment and conditioning.

Aerial view of the Orano Malvési site

WASTE WITHOUT A DISPOSAL SOLUTION

Most radioactive waste has an existing or planned disposal solution. Nevertheless, a small quantity of waste, estimated at 1,800 m^3 at the end of 2016, compared to 3,800 m^3 at the end of 2013, has no corresponding solution. This waste is said to have no management or disposal solution. It is defined as waste for which none of the existing or planned elimination solutions can be used in the current state of our knowledge, mainly on account of its specific physical or chemical characteristics. It is subject to studies that seek to define suitable management solutions for each type of waste.

In this context, a working group was implemented under PNGMDR 2010-2012. This working group helped consolidate the inventory of waste without a disposal solution and identify three categories of waste considered “priority” in the search for a common solution.

This includes:

- waste containing loose asbestos, which is not accepted for disposal, given its strong capacity for resuspension and requirements for operational conditions and long-term safety scenarios;
- waste containing mercury which could become volatile or leach, depending on the physicochemical conditions;
- certain organic liquids and oils that are incompatible with the acceptance specifications of the Cyclife Centraco incineration facility in Codolet.

Studies carried out in 2013-2015 achieved the following:

- discovery of management solutions for waste containing loose asbestos. Since Andra has revised its specifications for acceptance of asbestos waste in disposal facilities, it is now mainly declared in the VLLW category;
- development of a stabilising process for mercury contained in radioactive waste to produce stabilised solid waste that meets disposal specifications for Cires or CSA. However, for some mercury-containing waste, the insolubilisation process may require pre-treatment. Developments are under way for roll-out in a nuclear context;
- identification of various treatments for organic liquids and oils, depending on their characteristics, at varying levels of technological maturity. In particular, a treatment process using a polymer mix has been considered. This process produces stabilised waste, which is currently not accepted by Cyclife Centraco and Andra disposal facilities due to insufficient characterisation. The preferred strategy is an assembly with other organic liquids and oils collected by Andra from producers outside the nuclear power sector in order to reduce the radiological activity and concentration of toxic elements in order to comply with acceptance criteria.

Other waste produced in nuclear facilities with no disposal solution, which does not fall under one of the above categories, is subject to studies that seek to develop treatment processes with a view to being accepted in disposal facilities. In particular, these are presented under the operators’ waste management strategies, which are periodically examined by the ASN and ASND.

REPORT

02

Radioactive waste treatment and conditioning

GENERAL INFORMATION ABOUT RADIOACTIVE WASTE TREATMENT AND CONDITIONING

When radioactive waste is produced, it occurs in a raw form that can be a gas, liquid or solid. For management purposes, this waste usually needs to be conditioned, which entails producing "waste packages" that can be handled, and ensuring the confinement of radionuclides. Depending on the physicochemical nature of the waste, conditioning may be preceded by treatment to produce waste with characteristics that are suitable for long-term management.

Conditioning can be defined as all operations by which waste (previously treated in some cases) is placed in a container, to which an embedding or immobilisation material may or may not be added, to create a waste package.

The choice of treatment, use of an embedding or immobilisation matrix, and the container primarily depends on the radiological and physicochemical characteristics of the raw waste. It also aims to optimise the volume of conditioned waste, particularly by increasing the waste incorporation rate in the dedicated matrix and/or by reducing the container dimensions.

The main matrices used to condition liquid or powder waste are as follows:

- cement matrix for sludges, evaporation concentrates, incineration ashes, etc.;
- bitumen, particularly for embedding sludges and evaporation concentrates resulting from the treatment of liquid effluents;
- vitreous matrix, particularly for fission product solutions;
- polymer matrix (using epoxy resin) for ion exchange resins (IER).

For solid waste, two processes are commonly used:

- embedding or immobilisation of compacted or non-compacted waste in a hydraulic binder after being placed in a container;
- stacking of compacted pucks directly in a container without adding a hydraulic binder.

Containers come in various shapes (cylindrical or parallelepiped) to suit their content and storage and disposal sites. Various materials are used for these containers. Currently, the most common materials are concrete, which may be fibre-reinforced, and stainless steel.

To be integrated into a storage or disposal facility, the waste package must comply with acceptance specifications defined for that facility. These specifications are established based on the characteristics of the expected waste packages and the facility in question, and define the expected performance levels for the package, depending on the waste contained. For example, they may prohibit the presence of putrescible waste, or liquids, or limit the quantity of gas released by a waste package.

- ***Conditioned waste*** *is waste that:*
  - *is accepted without additional treatment in an operational disposal facility;*
  - *or complies with the disposal acceptance specifications for the operational facility to which it will be sent;*
  - *or for which no additional treatment is planned by its producer before disposal if there is no operational disposal facility for this waste.*
- ***Preconditioned waste*** *is waste that is not in bulk form and for which additional treatment (decontamination, immobilisation, compaction, vitrification, melting, injection, incineration, etc.) is planned by its producer before disposal.*
- ***Non-conditioned waste*** *is waste in bulk form; it is usually found in tanks, pits or silos.*

These definitions were taken from the Order of 9 October 2008, as amended by the Orders of 4 April 2014 and 16 March 2017.

MAIN INDUSTRIAL PROCESSES FOR TREATMENT AND CONDITIONING

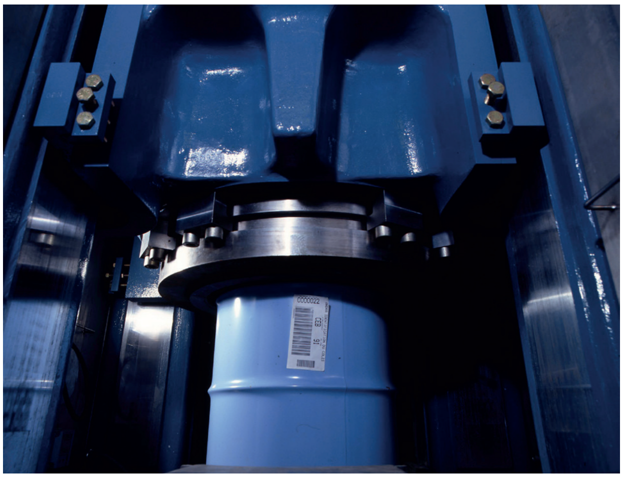
Since the 1950s and the commissioning of the first nuclear reactors in France, many treatment and conditioning processes have been studied and developed for managing the waste produced by the various nuclear facilities. The main processes involved in treatment and conditioning are presented below.

TREATMENT PROCESSES

COMPACTION

Compaction aims to reduce the volume of certain types of solid waste, in particular metal or plastic waste. This process uses various press technologies with capacities ranging from a few hundred tonnes to a few thousand tonnes, depending on the type of waste to be compacted. After compaction, the waste is placed in containers and may be immobilised using a hydraulic binder.

Compaction is generally used by waste producers (on the La Hague and Cadarache sites, etc.), but also by Andra in its operating disposal facilities [Industrial facility for grouping, storage and disposal (Cires) for very low-level waste and the Aube disposal facility (CSA) for low- and intermediate-level short-lived waste].



Compaction press at the Aube disposal facility (CSA)

COMPACTED WASTE PACKAGES

The structural components of spent fuel assemblies for light water reactors (cladding tubes, end caps, spacer grids, springs, etc.) are compacted and conditioned in the hull compaction facility (ACC) in La Hague, which was commissioned in 2002. The packages also contain solid metal operating waste that has been compacted.

These waste packages for intermediate-level long-lived waste (ILW-LL) are in the F2-3-02 stream and take the form of a stainless steel container measuring around 1.4 metres high and 43 cm in diameter, containing around 600 kg of compacted waste.

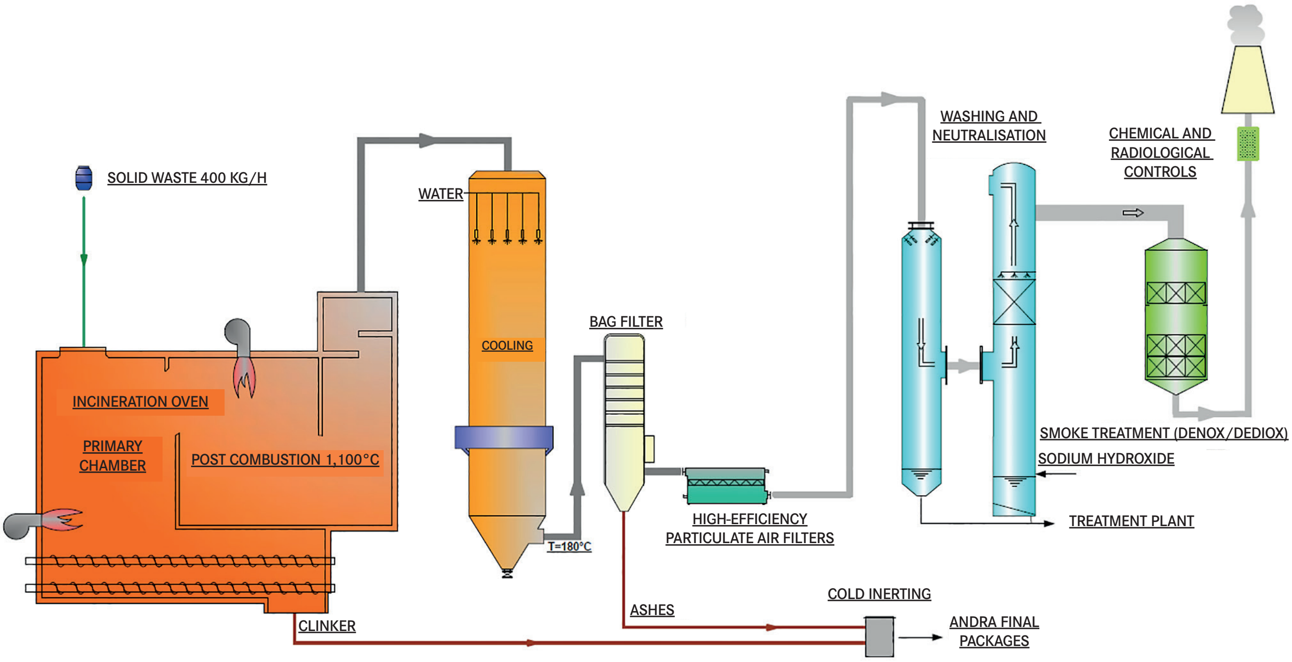
EVAPORATION

Before conditioning, liquid waste is sometimes concentrated by heating and evaporation, if its chemical characteristics allow, in order to reduce its volume. The concentrates obtained are conditioned directly via cementation or bituminisation, for example.

Evaporation is generally carried out on producers' sites, in the facility in which the concentrates are conditioned.

INCINERATION

Incineration significantly reduces the mass and volume of waste and concentrates its radioactivity in the ashes. It is particularly suited to aqueous liquid and organic waste, solvents, scintillation liquids or organic solid waste that is very low-level waste (VLLW) or low- and intermediate-level short-lived waste (LILW-SL). The Cyclife Centraco facility in Codolet was commissioned in 1999 and can incinerate both liquid and solid waste.



Schematic diagram of the incineration process © Cyclife Centraco

WASTE PACKAGES OF CEMENTED INCINERATED RESIDUES

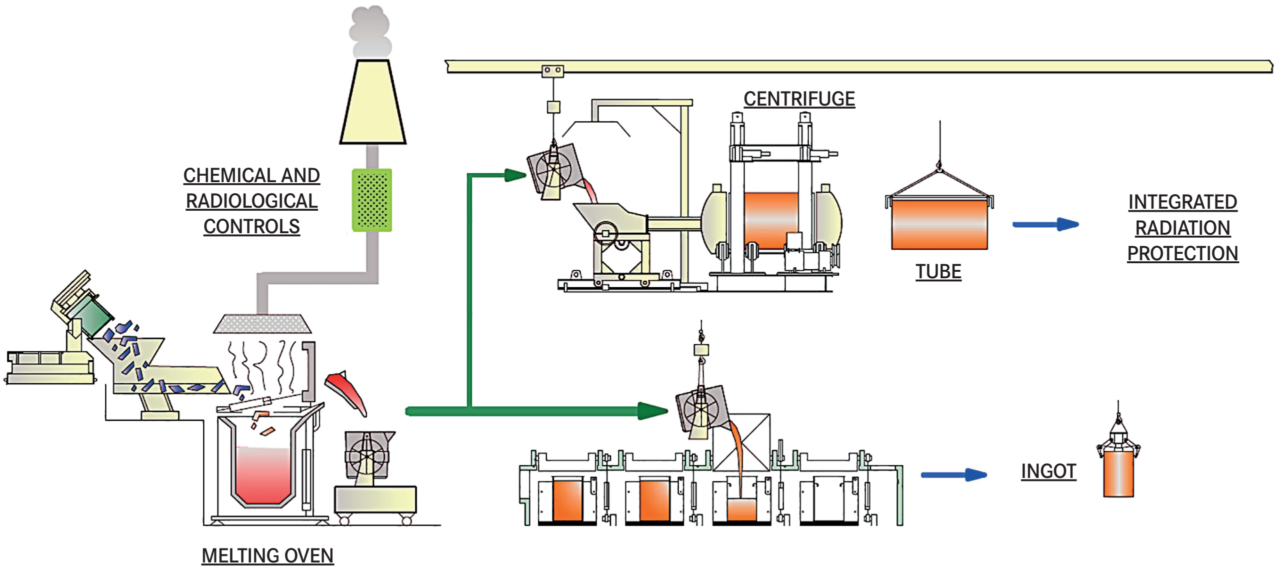
The incineration residues take the form of clinker, slag and ash. These raw residues are crushed and mixed with a cement-based material, which is then poured into an unalloyed steel drum and the cover is welded on. This forms low- and intermediate-level short-lived waste (LILW-SL) packages, categorised under the F3-7-01 stream.

The package mass is around 1.5 tonnes for a volume of 450 litres. One package contains around 370 kg of raw incineration residues.

MELTING

Like incineration, melting reduces waste volume and partially decontaminates it, so it can then be recycled within the nuclear power sector. Melting is used for the treatment of metal waste.

For example, melting is carried out at the Cyclife Centraco facility to treat steel or non-ferrous metal waste from maintenance or dismantling operations in nuclear facilities.



Schematic diagram of the melting process © Cyclife Centraco

CONDITIONING PROCESSES

CEMENTATION

Cementation is used to:

- immobilise solid waste such as technological waste, activated waste or structural waste. In this case, it results in what are called heterogeneous waste packages;
- embed waste in a solution or powder form: evaporation concentrates, chemical treatment sludges, ion exchange resins, etc. The resulting waste packages are referred to as homogeneous.

This is the most widely used conditioning process. Cement matrices combine several favourable factors: availability, low cost, simplicity of use, good mechanical strength, and, in general, stability over time.

Cementation is widely used on the sites of waste producers (La Hague, Cadarache and Marcoule sites, etc.). This process is also used on the Andra Cires and CSA sites.

CEMENTED WASTE PACKAGES

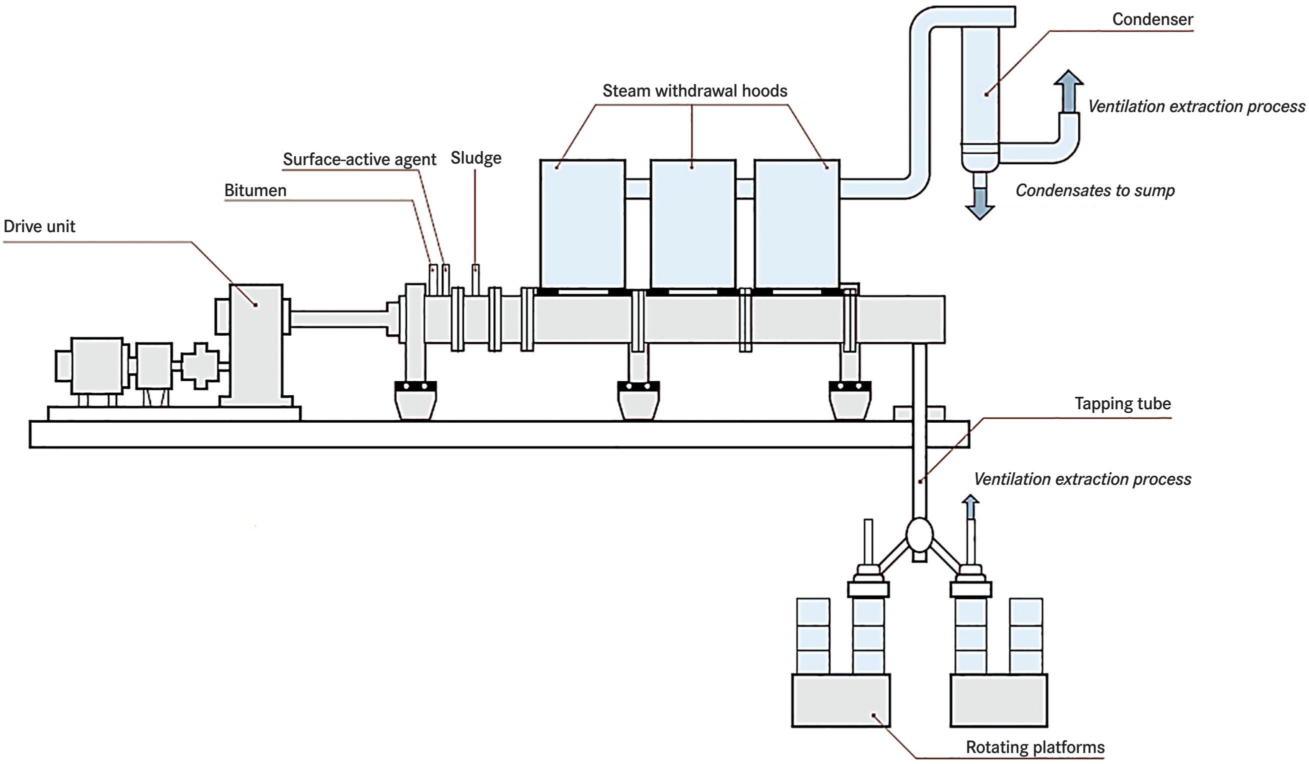
The waste generated by everyday operation of various workshops and laboratories and by maintenance and dismantling operations at the La Hague site is conditioned in fibre-reinforced concrete cylindrical containers. Depending on the activity of the waste, these packages are either disposed of at the CSA (for low- and intermediate-level short-lived waste – LILW-SL – categorised under the F3-3-11 stream) or stored until a suitable disposal facility becomes available (for intermediate-level long-lived waste – ILW-LL – and low-level long-lived waste – LLW-LL – categorised under the F2-3-08 and F9-3-03 stream respectively).

The package mass is approximately 2.5 t for a volume of 1.18 m^3. One package contains approximately 450 kg of waste.

BITUMINISATION

The process of embedding in bitumen involves mixing the heated waste, in the form of sludges, with bitumen. The resulting mixture is dehydrated and poured into a container where it is cooled. Bitumen has interesting properties with its high binding capacity, chemical inertia, impermeability, low solubility in water, high confinement capacity, low cost and availability.

This process is mainly used at the waste producers' sites for conditioning the precipitation sludges that result from liquid effluent treatment. It has now been largely replaced by cementation or vitrification, depending on the types of waste to be treated.

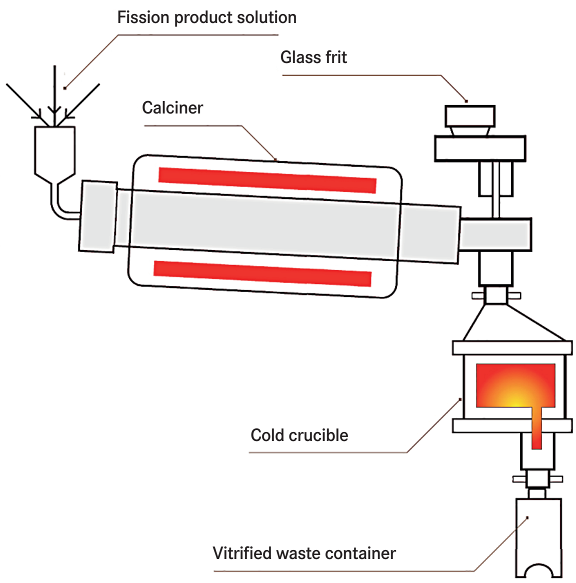


Schematic diagram of the bituminisation process

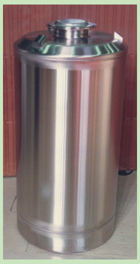
VITRIFICATION

Vitrification consists of using a crucible heated to high temperatures to mix previously calcined radioactive waste (generally liquid) with glass frit whose composition is adjusted to the chemical nature of the waste in order to homogeneously integrate, at the atomic scale, all the radionuclides present in the waste into the vitreous network. The resulting mixture is then poured into a stainless steel container. Due to its chemical composition and amorphous structure, glass is particularly resistant to heating and irradiation, and offers good chemical durability over long time periods.

This process has been used in the Marcoule and La Hague plants for several decades, and has become the industry standard for conditioning fission product solutions produced by spent fuel reprocessing. Technological developments, for instance the use of a cold crucible, have made it possible to reduce the waste produced by the process and to widen the field of application to other types of waste.



Schematic diagram of the vitrification process



VITRIFIED WASTE PACKAGES

The first industrial use of vitrification took place at the Marcoule site in 1978. Prior to its shutdown in 2012, the vitrification facility produced packages of high-level vitrified waste categorised under the F1-4-01 stream.

These waste packages take the form of a stainless steel container measuring around 1 metre high and 50 cm in diameter and containing around 360 kg of vitrified waste.

POLYMER RESIN EMBEDDING

Depending on its radiological and physicochemical characteristics, solid waste can be also be embedded using a polymer resin. This process is used to condition the ion exchange resins (IER) used in the chemical and volume control systems for the reactor coolant systems in nuclear reactors. These resins are also used for the treatment and purification of pool waters and the treatment of spent effluents.

The process consists of mixing the ion exchange resins with an epoxy matrix, then conditioning them in cylindrical concrete containers.

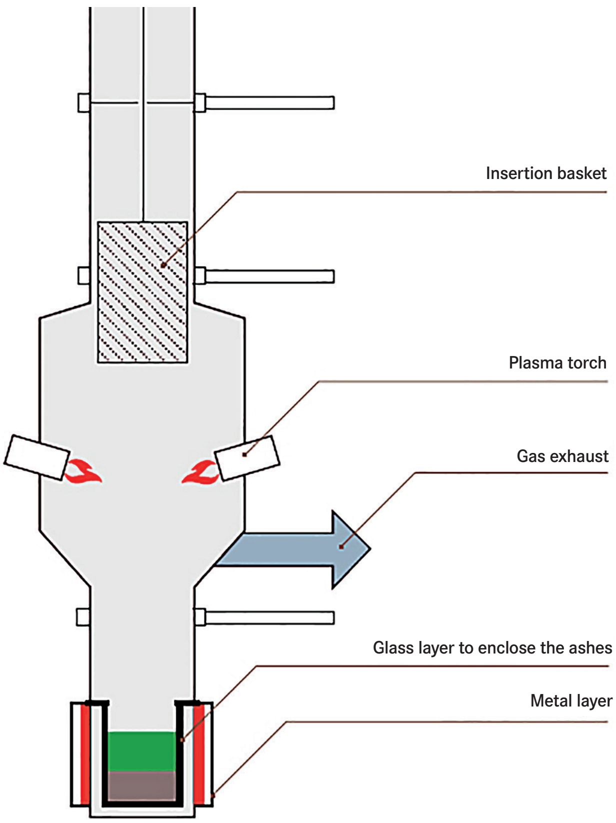
Certain IERs are not very transportable due to their radiological or physicochemical characteristics. It is therefore preferable to move the treatment process rather than the waste itself. The mobile machines designed by the Cyclife Centraco can condition waste in compliance with Andra specifications.

TREATMENT AND CONDITIONING RESEARCH AND DEVELOPMENT

PIVIC: TOWARDS A NEW PROCESS FOR TREATING WASTE CONTAMINATED BY ALPHA EMITTERS

Orano and the CEA are working with Andra to develop a new process for treating waste contaminated with alpha emitters. This project focuses on the treatment and conditioning of solid technological waste, a mix of metals and organic materials (vinyl, polyethylene, polymer gloves) that mostly come from operation of the Melox plant, which produces MOX or mixed-oxide fuel (from uranium and plutonium).

This waste is much less radioactive than waste from spent fuel reprocessing, but must nonetheless be disposed of in suitable packages. This is where an innovative process known as Pivic (in-can incineration vitrification) comes in. Its aim is to treat and condition the waste in a single step.



Schematic diagram of the Pivic process

The principle is to insert the waste into a combustion chamber and incinerate it using a plasma torch placed over the melting-vitrification module. The resulting ashes are therefore incorporated into the glass, and the waste container will contain a metal phase at the bottom and a glass phase at the top. This package will then be placed in a suitable container for disposal.

This process is currently being studied and brings together several processes, in particular plasma torch incineration, vitrification, melting using induction heating, and gas treatment.

If it is shown to be feasible, industrial commissioning of the Pivic process could take place around 2035.

DEVELOPMENT OF A SPECIFIC HYDRAULIC BINDER FOR MAGNESIUM WASTE

The magnesium waste stored on the Marcoule site is metal magnesium cladding in bulk, crushed or compacted form. A specific hydraulic binder ("geopolymer") is currently being developed to control the physicochemical interactions between the embedding material and the waste.

The CEA is working with Andra to study this conditioning solution. If it is shown to be feasible, and approved for use in disposal, the CEA aims to roll out this process in the short term for older and less radioactive magnesium waste (low- and intermediate-level short-lived waste).

REPORT

03

Dismantling and cleanup of nuclear facilities

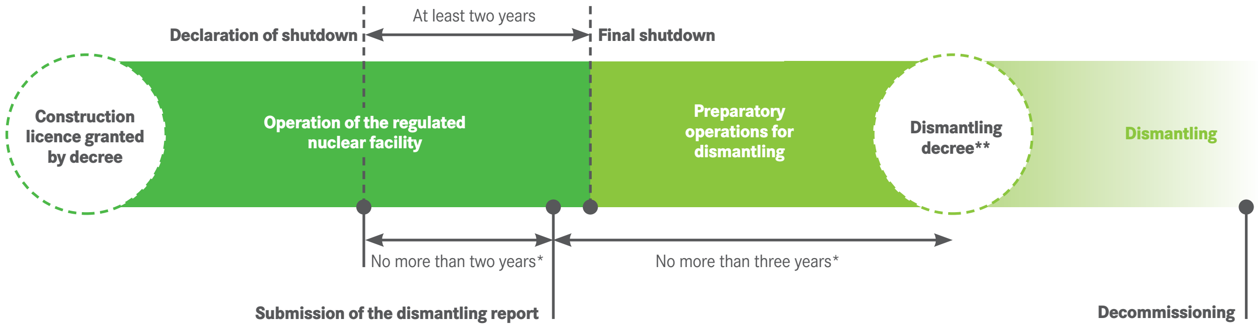
Like all industrial activities, operation of a nuclear facility is for a finite period. When the authorised nuclear operator decides on final shutdown, it launches an operational process to place the facility in a state where any impact or residual risk to the public, workers or the environment will be as low as reasonably possible, such that it can be decommissioned and therefore removed from the regulatory control of nuclear facilities.

This final phase is referred to as nuclear facility dismantling.

There are three major phases in the life of a nuclear facility:

- the facility construction phase after obtaining a construction licence;
- the facility operating phase after obtaining an industrial operating licence;
- the dismantling phase, which follows final shutdown or termination of facility activity.

PHASES IN THE LIFE OF A NUCLEAR FACILITY



** May be extended by two years in some cases.*
*** The dismantling decree becomes effective on the date on which the ASN approves revision of the general operating rules, and no later than one year after publication of the decree.*

REGULATORY PROCESS

The dismantling of nuclear facilities in France is a process that starts before the final shutdown date scheduled by the nuclear operator, and continues until the facility is decommissionned by the relevant nuclear safety authority.

This process has been regulated since 2006 and Act 2006-686 of 13 June 2006 on Transparency and Security in the Nuclear Field, later supplemented by the Decree of 2 November 2007, as amended, and the Order of 7 February 2012. It is also governed by the French Environmental Code and the Decree of 28 June 2016 related to the modification, to the final shutdown and dismantling of basic nuclear installations, as well as to subcontracting. For any facility, it requires:

- declaration of final shutdown to the Minister responsible for nuclear safety and the ASN, as soon as the operator plans for final shutdown of its facility;
- a dismantling decree, issued following the opinion of the ASN and a public inquiry. This decree sets out the main stages of dismantling, the dismantling end date and final state to achieve;
- key meetings with the ASN, required under a safety reference framework for decommissioning and dismantling operations;
- an internal authorisation process for the operator with a view to launching certain work within the limits of the authorised reference framework;
- preliminary phases prior to obtaining the dismantling decree, during which:
    - the operator must provide, at least two years prior to final shutdown, a declaration of the date on which shutdown will occur, and must specify and justify the operations it intends to carry out to reduce the risks or inconvenience for the public, workers and the environment, taking into account the shutdown and while awaiting launch of dismantling operations,
    - consultations and public inquiries must be organised.

Except in cases of serious risk or serious and imminent risk, the operator of a nuclear facility decides when to shut it down and informs the ASN of this decision.

DIFFERENCE BETWEEN “DISMANTLING” AND “DECOMMISSIONING”

“Dismantling” refers to all technical operations, which, after a nuclear facility has been shut down, are intended to clean up and eliminate residual radioactive and hazardous substances and the structures or equipment in which they were contained. These operations are carried out in order to reach a final state defined ahead of time, particularly with regard to future use: disassembly of equipment, cleaning rooms, soil cleanup or remediation, potential destruction of civil works, conditioning, removal and elimination of the waste generated (both radioactive and non-radioactive).

“Decommissioning” on the other hand is a purely administrative operation to remove the facility from the list of regulated facilities. The facility is then no longer under the same legal and administrative regime. Decommissioning removes the obligation of regulatory inspections that a regulated facility must undergo. Decommissioning may be accompanied by usage restrictions for land located near or next to a decommissioned facility.

The standard approach recommended by the ASN for dismantling of a facility with a view to decommissioning is to conduct full cleanup. This approach consists in, “when technically possible, fully cleaning up contaminated radioactive sites, even if the exposure of individuals caused by radioactive pollution appears limited”, i.e. returning to the initial state before activation or contamination of the structures.

DISMANTLING STRATEGY

There are two different potential strategies for the dismantling of nuclear facilities:

- dismantling immediately after final shutdown of the facility. This strategy means that future generations will not have to bear the technical or financial burden of dismantling. It also makes it possible to draw on the skills and knowledge of the teams involved in facility operation, which is vital for the first dismantling operations. In addition, it avoids the significant costs of monitoring and maintaining a satisfactory safety level, or even facility regeneration;
- deferred dismantling, several decades after facility shutdown, which is primarily justified by the radioactive decay of the components to be dismantled, allowing for simpler dismantling operations and optimised exposure to ionising radiation for individuals carrying out dismantling operations. It can also spread costs over time in line with sound financial management.

The choice depends on national regulations, socio-economic factors, funding capacity and methods for operations, the availability of dismantling techniques, qualified personnel and waste elimination solutions.

The strategy adopted in France, as set out in Article L. 593-25 of the Environmental Code is dismantling in as short a timeframe as possible after final shutdown of the facility, under acceptable economic conditions and in line with the principles of prevention of health risks associated with the environment and the workplace.

DISMANTLING WORK

PREPARING DISMANTLING WORK

As soon as the decision has been made for final shutdown of a nuclear facility or part of a nuclear facility, a dismantling preparatory phase begins. This transitional step gives nuclear facility operational teams the opportunity to perform preparatory operations for final shutdown while the operating licence is still valid. This includes conditioning and removing as many radioactive and hazardous substances from the facility as possible, shutting down processes and preparing for dismantling operations, including site preparation, radiological and chemical research and investigations in various zones, adaptation or renovation work on the facility or equipment, if required, definition of operating procedures, training of teams, etc.

For example, in the case of a nuclear reactor, the fuel is removed from the facility. In the case of a waste reprocessing plant or treatment facility, the process equipment is drained and rinsed.

During this stage, the safety and security functions required during the operating phase are maintained.

DECLARATION OF FINAL SHUTDOWN

Pursuant to Article L. 593-26 of the French Environmental Code, the operator of a regulated nuclear facility planning final shutdown of operations at its facility, or part of its facility, must make a declaration to this effect to the Minister responsible for nuclear safety and the ASN. This declaration must state the date on which shutdown will occur, and specify and justify the operations it intends to carry out to reduce the risks or inconvenience for the protected interests mentioned in Article L. 593-1, taking into account the shutdown and while awaiting launch of dismantling operations.

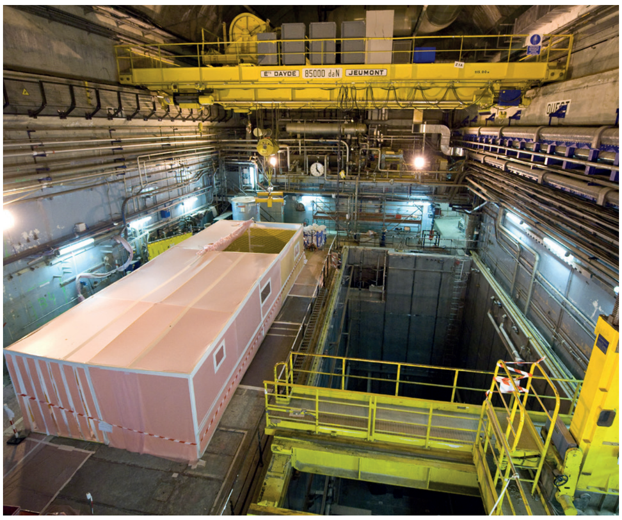
It must be made at least two years before the planned shutdown date or as soon as possible if this shutdown is to carried out within a shorter timeframe due to reasons substantiated by the operator. The declaration must be accompanied by an updated dismantling plan that presents and justifies the dismantling strategy adopted, the principles and measures taken by the nuclear operator for facility dismantling, the dismantling schedule and the final state to be achieved.

CONDUCTING DISMANTLING WORK

After the final shutdown preparatory phase, the operator launches the dismantling phase, which can last several years and requires an administrative licence.

Dismantling work is carried out in line with the facility's reference framework and regulatory requirements set out in the dismantling decree, in addition to any requirements issued by the nuclear safety authority.

The procedures are specific to each facility, depending on its history, available characterisations and investigations, and zone accessibility, etc. Scenarios are developed according to the specific features of the facilities or equipment, especially with regard to the nature of materials and type of contamination for the definition of containment methods, tools, protocols, treatment solutions, conditioning and removal of any waste produced, etc.



Dismantling of the EDF Chooz A plant

Cleanup of a shielded cell from the Cyrano line at the CEA Fontenay-aux-Roses facility

FINALISING DISMANTLING WORK

In France, the final state after dismantling of a nuclear facility must be such as to prevent any risks or inconvenience posed by the site with regard to safety, public health and protection of nature and the environment.

The demolition of buildings from the nuclear facility is not always required to achieve this final state. The operator may wish to reuse the buildings or areas that have been cleaned.

The ASN recommends that operators implement cleanup and dismantling practices that seek to achieve a final state where all hazardous and radioactive substances have been removed from the facility.

Depending on the characteristics of the pollution, should this approach be difficult to implement, the operator must still go as far as reasonably possible in the cleanup process, and provide technical and economic information to demonstrate that the standard approach cannot be implemented and that the cleanup operations cannot be taken any further using the best cleanup and dismantling methods and techniques available under acceptable economic conditions. This substantiating information from the operator must include, among other things, the volume of waste generated for each of the scenarios and their respective costs.

If the operator is not able to demonstrate that there is no risk to public health and safety or the protection of nature and the environment for all uses, public service easements are applied. In this case, the decommissioning application will be one of the documents subject to a public inquiry for the implementation of these easements. Public service easements can be applied at the request of the operator or administration (ASN, prefecture, local council). These can contain a certain number of usage restrictions (e.g. limited to industrial use) or precautionary measures (preservation of records, radiological measures for excavation, etc.). The ASN can make the decommissioning of a regulated nuclear facility dependent on these kinds of easements.

Furthermore, in the event of a threat to the interests mentioned in Article L. 593-1 of the Environmental Code, the ASN may, at any time, even after facility decommissioning, order assessments and the implementation of any necessary provisions.

Dismantling of a prototype facility for pulsed column solvent extraction (INB57) at the CEA Fontenay-aux-Roses facility

R&D FOR DISMANTLING

Nuclear dismantling operations are complex and require various types of expertise and specific technologies. Although the majority of operations use common techniques adapted to the nuclear environment, some fields require the development of specific methods, processes and tools.

France has acquired recognised skills in this area and continues to develop R&D in the following fields:

- measurement of radioactivity to support initial and waste characterisation;
- structure and soil decontamination (lasers, foams, gels, etc.);
- cutting (especially laser processes);
- robotics to support operations in hostile environments;
- simulation and virtual reality tools to support the definition of dismantling scenarios;
- treatment and conditioning of waste and specific effluents generated by these operations.

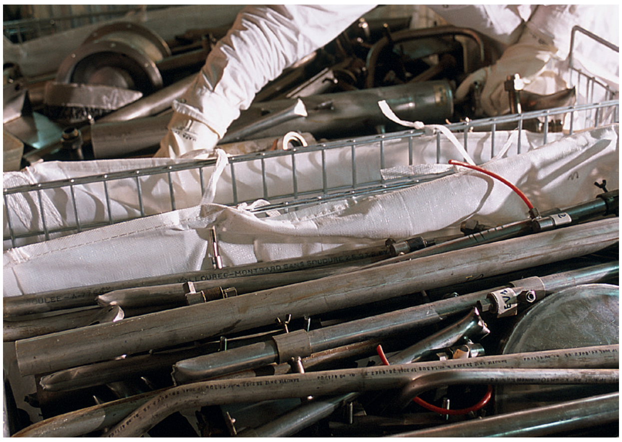
WASTE FROM DISMANTLING OPERATIONS

Waste from dismantling operations can either be conventional or radioactive. To identify which of these two categories the waste falls into, facilities are divided into zones based on the history of the facility and the operations conducted there:

- waste from conventional waste zones is not radioactive and is therefore inspected and then eliminated through approved conventional waste solutions;
- waste from potential nuclear waste production zones is all managed as if it were radioactive, even if measurement devices fail to detect radioactivity. This waste is conditioned and characterised for treatment by the French National Radioactive Waste Management Agency with a view to long-term management.

Waste zoning can be revised between operation and dismantling to take into account specific characteristics of various operating phases and thereby optimise waste management.

Storage of very low-level waste (VLLW) from dismantling of the Triton research reactor



Metal containers with very low-level waste (VLLW)

PRINCIPLES FOR THE MANAGEMENT OF WASTE FROM DISMANTLING OPERATIONS

The policy for the management of radioactive waste from dismantling operations is, like that of other waste, based on:

- ensuring traceability of waste from nuclear facilities (waste zoning, characterisation, inspections);
- minimising the volume of waste produced;
- optimising categorisation;
- sending waste to existing waste disposal facilities immediately after production. If waste has no available disposal solution, it is stored in dedicated facilities.

Radioactive waste is therefore sorted and may require treatment before conditioning (See Special Report 2). It is then transported to existing waste disposal facilities adapted to its level of radioactivity (Cires for VLLW and CSA for LILW-SL) or stored until adequate disposal solutions become available.

NATURE OF WASTE FROM DISMANTLING OPERATIONS

Most waste from dismantling is conventional waste, especially rubble and metal. For example, during dismantling of the Chooz A nuclear power plant, 80% of the 40,000 tonnes of waste produced was conventional and 20% radioactive.

The radioactive waste from dismantling was mostly (> 99%) very low-level waste (VLLW) and low- and intermediate-level short-lived waste (LILW-SL). This included:

- materials from facility demolition work (concrete, rubble, scrap metal, glove box walls, piping, etc.);
- process equipment (e.g. metal parts);
- tools and protective clothing (gloves, vinyl overalls, etc.);
- effluents used for rinsing equipment.

There may also be low-level long-lived waste (LLW-LL), particularly graphite waste from the first French reactor system (graphite-moderated gas-cooled reactors - GCR) and intermediate-level long-lived waste (ILW-LL) in low quantities (primarily activated waste, including metal parts from the reactor core).

ESTIMATED QUANTITIES OF DISMANTLING WASTE

During the preparation of dismantling operations, the quantity and type of waste to be produced, and the treatment and conditioning methods to use are estimated. The estimates take into account all the waste resulting from the operation, including secondary waste, such as the volumes of effluents generated by decontamination.

This starts with drawing up an exact inventory of the facilities to be cleaned, including the equipment they contain and their residual contamination level, which requires good knowledge of the history of facility operation.

The quantities of waste produced will be estimated using this operational history and on the basis of feedback from previous dismantling operations.

DISMANTLING OPERATIONS IN FRANCE

Since the early 1980s, dismantling operations in R&D facilities, research reactors, or fuel cycle facilities have been carried out on various sites. Over thirty nuclear facilities have been dismantled and decommissioned.

There are currently over fifty facilities in the process of being dismantled or which will be dismantled in the medium term. These include:

- around ten nuclear reactors, most with different technologies and designs than those currently in operation in France;
- around forty facilities belonging to the CEA (research reactors or prototypes, research facilities and laboratories), EDF (irradiated materials workshop) and Orano (fuel cycle).

The examples below illustrate the diversity of nuclear facilities to be dismantled, the difficulties encountered, the timeframe between facility shutdown and industrial redevelopment of the site, and the capacity of the French nuclear industry to successfully see nuclear facilities through to the end of their life cycle, while complying with safety and security requirements.

ILLUSTRATION NO. 1: SICN SITES

SICN is a French nuclear fuel company, belonging to the Orano group. It originally specialised in the production of nuclear fuel for research reactors, GCR reactors and fast neutron reactors, before branching out into the manufacture of uranium metal munitions and parts.

SICN had facilities (production workshops, laboratory, etc.) in Annecy from 1954 and Veurey-Voroize from November 1960.

DISMANTLING OF ANNECY SITE

In 2002, the decision was made to stop all nuclear activities at the facilities and launch dismantling and cleanup operations, which began in 2008.

Orano still owns all of the site, which has undergone complete industrial redevelopment, particularly in 2015 with the installation of a 12 MW biomass boiler, operated by Idex.

DISMANTLING OF THE VEUREY-VOROIZE SITE

In 2006, two regulated nuclear facilities (INB) located on the Veurey-Voroize site were put in final shutdown:

- nuclear fuel production site, INB no. 65, licensed in 1967;
- pelleting workshop, INB no. 90, licensed in 1977.

Between 2006 and 2011, Areva (now Orano) began nuclear dismantling of equipment and then building cleanup.

Since the end of dismantling work in 2013, all site utilities have been leased to Sofradir (French infra-red company), which occupies around 60% of the site.

ILLUSTRATION NO. 2: CEA GRENOBLE SITE

The CEA Grenoble facility was created in 1956 to support development of the French nuclear power industry, but saw nuclear research activities decline in the late 1990s. In 2001, the CEA Grenoble site launched cleanup and dismantling of six of its regulated nuclear facilities:

- INB 19 (Mélusine), nuclear reactor shut down since 1988;
- INB 20 (Siloé), nuclear reactor shut down since 1997;
- INB 21 (Siloëtte), nuclear reactor shut down since 2002;
- INB 61 Radioactive materials control and analysis laboratory (Lama);
- INB 36 and 79 Waste and effluent treatment facility (Sted), former decay storage facilities.

These nuclear facilities conducted significant cleanup and dismantling work, which enabled the decommissioning of four of them (INBs 19, 20, 21 and 61) and the reuse of areas for R&D activities in micro- and nano-electronics and technologies for health and renewable energies.

Dismantling of the Siloé reactor at the CEA Grenoble facility

Dismantling of Lama at the CEA Grenoble facility

ILLUSTRATION NO. 3: CHOOZ A NUCLEAR POWER PLANT

The Chooz power plant is located in the Ardennes *département* in north-eastern France on the Meuse River, and has two operational reactors (Chooz B1 and B2) and a reactor undergoing dismantling (Chooz A). Chooz A was commissioned in 1967, and operated until 1991. It is one of nine reactors in France currently being deconstructed.

Chooz A was the first power plant built in France with a pressurised water reactor (PWR). This was a French-Belgian project, led by SENA (*Société d'énergie nucléaire des Ardennes*), consisting of EDF and a group of Belgian power companies. It was unique in that its reactor and nuclear auxiliaries (pumps, exchangers, cooling systems, etc.) were installed in two rocky caverns inside a hillside in a loop in the Meuse Valley.

From 2001 to 2004, the main operations consisted of removing fuel, draining systems, dismantling, cleaning and demolishing the turbine hall, pumping station and nuclear buildings located outside the hill. Following these operations, 99.9% of the plant's radioactivity had been cleared from the site.

After a public inquiry organised in August and September 2006, the decree authorising full dismantling was signed on 27 September 2007. From this date, operations were carried out according to the reference scenario:

- 2008 - 2010, preparation for dismantling operations (creation of waste storage zones and dressing rooms, restoration of ventilation systems and lifting equipment, etc.);
- 2010 - 2014, cleanup and dismantling of auxiliary systems and the reactor coolant system (excluding reactor vessel) and removal to appropriate disposal solutions;
- 2015 - 2016, installation of facilities required for dismantling the reactor vessel, creation of a system for filtering and filling the pool with water, and launch of the dismantling of residual buildings in the auxiliary cavern using remote-controlled equipment;
- 2017, filling of the reactor pool with water, dismantling of the reactor vessel head with a view to removal in 2018.

The final dismantling operations, such as cutting, conditioning and removal of the reactor vessel are scheduled for up to 2022.

Disposal of a steam generator from the Chooz A power plant in Cires.

Deconstruction site at the Chooz A power plant: deconstruction of the cavern

INTERNATIONAL DISMANTLING OPERATIONS

Within the next twenty years, dozens of nuclear power reactors, research facilities (experimental reactors, laboratories, etc.), and fuel production and reprocessing plants will have to be dismantled all around the world.

The biggest international markets are on the American continent, especially in the United States, but also in Europe.

French companies have honed skills and knowledge in all the relevant fields, in an integrated manner, through the dismantling operations conducted in research or production facilities over the past 30 years. This clearly positions them to respond effectively to the challenges that these major international projects entail.

IMPORTANCE OF OPERATING FEEDBACK FOR FUTURE DISMANTLING PROJECTS

Operating feedback from dismantling projects in France and worldwide has fed and continued to feed into future dismantling projects. The main lessons learned include:

- the importance of taking into account intrinsic difficulties in dismantling operations such as working in irradiating environments, the disrepair of some facilities, regulatory changes, and the availability of disposal solutions for the waste produced;
- precise definition of the initial state (type and quantity of waste to be generated, characterisation of the radiological state, etc.) and the final state in order to better estimate the resources required to achieve these objectives.

REPORT

04

Sites contaminated by radioactivity

Sites contaminated by radioactive substances represent a very small proportion of all polluted sites in France.

This contamination may result from industrial, medical or research activities that involve radioactive substances. The contamination may affect the place where these activities were carried out and their immediate or more distant vicinity. Most sites contaminated by radioactive substances are related to past industrial or artisanal activities, from a time when the perception of risks associated with radioactivity was different from today.

Sites contaminated by radioactive substances require preventive or curative action from the public authorities.

"Site contaminated by radioactive substances: a site which, due to old deposits of radioactive substances or waste, the use or infiltration of radioactive substances or radiological activation of materials, has radioactive contamination that may cause harmful effects or an ongoing risk for people or the environment[1]."

The contamination found must be attributable to one or more radioactive substances as defined in Article L. 542-1-1 of the French Environmental Code, i.e. any "substance that contains natural or artificial radionuclides whose activity or concentration justifies radiation protection monitoring".

SOURCES OF RADIOACTIVE CONTAMINATION

Most sites contaminated by radioactivity are legacy sites where activities unrelated to the nuclear power industry took place. The substances contributing to contamination of these sites are:

- radium: its extraction, storage, handling and marketing for various applications such as medicine, health and beauty, and luminescent paints, are responsible for much of the radioactive contamination in France;
- tritium: used in the manufacture of luminescent paints as a replacement for radium;
- monazite, a naturally radioactive ore used, among other things, for the manufacture of lighter flints (former Orflam-Plast plant in Pargny-sur-Saulx);
- natural sands rich in zircons, naturally weakly radioactive minerals used in the manufacture of zirconia (zirconium dioxide).

Because the risks for health and the environment were poorly understood, these radioactive substances were usually handled with minimal or no precautions.

Advert from the radium craze years

1 Appendix 13-7 of the French public health code

RADIUM

Radium is present in very small quantities on earth, in the form of several isotopes, the most common of which is radium-226, an alpha and gamma emitter with a half-life of 1,600 years. Radium-226 is extracted from uranium ores, where it is present in trace amounts. Radium extraction factories developed in France leading to many contaminated industrial sites.

In the early twentieth century, the therapeutic benefits of radium in destroying diseased tissue were discovered. Thanks to some spectacular results, radium became very fashionable in the 1920s and 1930s.

In those days, many radium-bearing health and beauty products and industrial products (such as powders, cosmetics, wools, animal feed, spark plugs for cars, fountains, luminescent paints for clock-making and aircraft, etc.) were sold in France.

The manufacture, production and sale of radium-bearing items were banned in the late 1950s due to the radioactive hazards involved.

Radium, which was also used at the time for its radio-luminescent properties, was replaced by artificial radionuclides such as tritium.

This craze came to an end when the dangers of radioactivity were recognised and the use of radium was prohibited. Most of the industrial sites that had developed during the radium craze simply faded into oblivion. Some sites, mostly in urban areas, were redeveloped despite their radioactive contamination or left as industrial wasteland.

However, the contamination on these sites may require cleanup to reduce the risks for health and the environment.

Bayard clockmaker's - Woman at work

IDENTIFICATION OF SITES CONTAMINATED BY RADIOACTIVITY

It is not easy to identify contaminated sites as records have not always been kept. Various sources of information are used to identify these sites. The survey and inventory work is ongoing, updated as new sites are identified.

The historical survey performed in 1996 by Andra's Observatory, in close collaboration with Institut Curie, identified such sites, leading to radioactivity monitoring operations on dozens of them, followed by direct actions for making them safe and/or cleanup.

The Observatory's role in the monitoring and actions was to alert government services, not to take any on-site action. A national operation for collecting medical radium objects was also launched.

KEEPING THE PUBLIC INFORMED

The management policy for contaminated or potentially contaminated sites and soils is primarily based on large-scale survey work. In the late 1990s, following advances in this area by other countries, site remediation and treatment policy moved to a risk management policy based on use. This policy is based on risk assessment and management, rather than the intrinsic level of contamination and requires keeping records of the contamination and the remediation actions implemented, and assignment of soil uses that are compatible with the residual contamination after site treatment.

Soil Information Sectors (SIS) are a French legal instrument created to better inform the public regarding sites contaminated by radioactivity and to manage construction on such sites to ensure there are no health risks (see Article L. 556-1 of the Environmental Code).

For construction or land allocation projects, the SIS involves performance of a soil survey as detailed in Article R. 556-2 of the Environmental Code.

The following two databases, which can be accessed via the government's GéoRisques website, list sites contaminated by radioactivity:

- **Basias** on the GéoRisques website (georisques.gouv.fr/dossiers/basias), created in 1998, lists all current or former industrial sites which may cause environmental contamination, keeping a record of these sites and providing useful information for those involved in urban planning, property development and protection of the environment;
- **Basol** (basol.developpement-durable.gouv.fr/home.htm) lists contaminated (or potentially contaminated) sites which require preventive or curative action from the public authorities.

Finally, with regard to monitoring population exposure and keeping the public informed, the mean individual doses received by the population as a result of nuclear activities are made public. These are estimated at least every five years by the French Institute for Radiological Protection and Nuclear Safety (IRSN), and published as a report on the IRSN website (Article R. 1333-27 of the French public health code).

Although there was never a statutory obligation to do so, the National Inventory provided a survey and record of sites contaminated by radioactivity in France up to 2015. Andra made an annual inventory of all sites contaminated by radioactivity, in collaboration with the French Nuclear Safety Authority (ASN), and the Directorate-General for Risk Prevention (DGPR). From now on, in agreement with the Minister responsible for the Environment, information regarding polluted sites will no longer be provided in the National Inventory but on the GéoRisques site.

The National Inventory will focus exclusively on radioactive materials and waste. This means that waste from cleanup of contaminated sites will still be listed.

MANAGEMENT OF SITES CONTAMINATED BY RADIOACTIVITY

The management of sites contaminated by radioactive substances is covered by the general framework of the national policy on the management of contaminated sites and soils (Articles L. 556-1 to L. 556-3 and R. 556-1 to R. 556-5 of the French Environmental Code), whose application is detailed at the end of the government memo dated 19 April 2017 on contaminated sites and soils.

The polluter-pays principle established by the Environmental Code defines the general principle for management of contaminated sites. When the entity responsible for a contaminated site is identified, this entity is responsible for taking the necessary measures to ensure cleanup. Andra may also intervene on these sites to assist the owner. If the polluter of a site is solvent, it must finance the cleanup and redevelopment operations for the contaminated site until all waste is eliminated.

When the polluter is defaulting (in which case the site is referred to as an "orphan" site), the public authorities take responsibility for site cleanup and remediation via IRSN and Andra. Most legacy polluted sites are orphan sites.

A PUBLIC SERVICE MISSION

The Planning Act of 28 June 2006 defines Andra's missions, which include "(...) collecting, transporting and managing radioactive waste and cleanup, and if necessary management, of sites contaminated by radioactive substances at the request and expense of those responsible for the sites" (Article L. 542-12 of the French Environmental Code).

Andra's "contaminated sites" department is responsible for promoting and coordinating the collection and management of radioactive objects for domestic use and the cleanup of sites contaminated by radioactivity when the entity responsible is defaulting. Acting on behalf of the owner, the "contaminated sites" department draws up remediation scenarios, obtains the necessary funding and permits, specifies the work and carries it out, relying on a network of specialist companies.

Several players intervene and collaborate to manage the contaminated sites:

- IRSN performs initial diagnostics for contaminated sites and assesses the risks for the public and the environment.
- the ASN sets the technical rules which must be complied with for elimination of radioactive waste and ensures that sites identified as contaminated are made safe for the public and the environment. It also monitors application of radiation protection rules for workers on cleanup sites;
- the National Advisory Committee for Public Funding in the Field of Radioactivity (CNAR), created by Andra in 2007 to give advice on the use of public subsidies for orphan sites only, on whether or not a site needs to be decontaminated, and on fund granting priorities, contaminated site remediation strategies and waste management policies. The CNAR is chaired by the CEO of Andra and includes:
  - representatives of the authorities,
  - representatives of public technical bodies,
  - representatives of associations,
  - an elected official designated by the Association of French Mayors;
- Andra may also take the role of owner or provide project owner assistance, supplementing the detailed characterisation of the site where necessary, in particular regarding deeper contamination, then drawing up the cleanup project, presenting it to stakeholders (with validation by the CNAR depending on the scenario). It is also responsible for managing the resulting waste;
- the Prefecture orders and supervises the cleanup work from a legal perspective by Prefectural Order, and provides monitoring through the DREALs (Regional Directorates for the Environment, Town and Country Planning and Housing) for legacy industrial sites and the ASN for radiation protection issues.

Site diagnostics are performed if there is any suspicion of contamination. This is a knowledge gathering phase which must be performed in a detailed manner, including a historical documentation survey and a vulnerability study.

Site characterisation is used to confirm if suspected radioactive contamination is present or not, and then, if necessary, to determine its location, type and level so that cleanup objectives can be defined.

If exposure is discovered, it must be decided if the contamination observed is compatible with the actual or planned use of the site and suitable actions that are proportionate with the situation encountered must be sought to reduce exposure.

The management objectives must be defined in compliance with the principle of optimisation applicable concerning radiation protection, taking into account the characteristics of the contamination, the type of existing or planned uses, and the redevelopment project.

Demolition site for a contaminated house in Gif-sur-Yvette

In compliance with the radiation protection principles set out in Article L.1333-2 of the French Public Health Code, the cost/benefit statement that is to be drawn up if the situation involves a management plan, must be aimed mainly at reducing to as low as reasonably achievable any exposure of persons to the ionising radiation resulting from use of the site and remediation operations.

Depending on the specifics of each contaminated site and the future use of the site, the site may either be completely decontaminated to make it suitable for all uses without constraint, or maintained in a state of residual contamination, managing the impact by restricting possible uses and installing barriers. These precautions are made permanent via usage restrictions incorporated into town planning documents. For example, construction or crops could be prohibited.

After site remediation, a record of past contamination and remediation is kept, in particular thanks to the Basias and Basol databases and the Soil Information Sectors (SIS).

In practice, once contamination is found, the site is secured by fences, barriers and suitable signage. When Andra is responsible for site cleanup, it is carried out in several steps:

1. preparation: protective covers are installed (for example: PVC covers, tenting, dust extraction, etc.) to prevent any dispersal of contaminated substances into the environment;
2. remediation work: contaminated materials are removed and conditioned by qualified specialist staff;
3. management: the radioactive waste produced by cleanup (soil, rubble, objects, etc.) is sent to the appropriate management solution (disposal or storage centre).
4. renovation-redevelopment: work is carried out as needed.

Cleanup work at Institut Curie

RADIOACTIVE WASTE MANAGEMENT

Cleanup of contaminated sites produces radioactive waste.

The volumes and characteristics of the radioactive waste that may be produced during contaminated site cleanup is assessed when the cleanup scenarios are drawn up. Given the typology of contaminated sites, the waste produced is mainly rubble, soil, wood and technological waste (work clothing, tools, etc.).

Waste sorting operations are planned and carried out to reduce the quantity of radioactive waste produced and to comply with the acceptance criteria and conditioning methods of the disposal and storage centres. Waste must be characterised before shipment to allow for its management by the appropriate solution.

Waste produced during cleanup of a contaminated site is mainly VLLW, which is therefore sent to Andra's industrial facility for grouping, storage and disposal (Cires) or disposed of on site if the quantity of waste is too great. In rarer cases, LLW-LL can also be produced. This waste is also sent to Cires, for temporary storage, pending the opening of a suitable disposal facility.

Special attention must be paid to chemical pollutants which have specific acceptance conditions in the various elimination facilities.

This waste is conditioned in big bags or injectable metal containers, sometimes after having been temporarily placed in smaller drums. Since some of the sites are located in urban areas (most of these sites are in Paris and the surrounding area), it may be necessary to first use 120 litre drums, which are easy to handle. These drums are transported on a storage platform, and then emptied and the waste is conditioned in its definitive packaging.

Cleanup site in a Parisian home (sitting room).

EXAMPLES OF CLEANUP ACTIVITIES CARRIED OUT BY ANDRA

PLOTS OF THE FORMER SOCIÉTÉ NOUVELLE DU RADIUM SITE IN GIF-SUR-YVETTE

In the early 1900s, the Société Nouvelle du Radium was created in the town of Gif-sur-Yvette.

Its sites included:

- a radioactive substances testing laboratory (LESR) located in the Coudraies neighbourhood;
- a radium extraction plant located in the adjacent Clos-Rose neighbourhood.

The plant operated from 1913 to 1935 and the laboratory until the late 1950s. When it closed, the buildings were demolished to make room for a housing development; the soil had some contaminated areas.

Andra performed cleanup work on two residential plots of this neighbourhood. Each of these plots had a house built in the 1960s on soil that was already contaminated, resulting in a radon level in the houses above the public health recommendations.

The preliminary technical and economic studies showed that it was not possible to remove the contaminated soil under the houses without demolishing them. The government therefore decided to buy the two plots from their owners and convert them to "green space" use.

The remediation work began in September 2013 and lasted a year. After the houses were demolished, the most contaminated soil was extracted and eliminated, and the low residual pollution present at the bottom was confined under a thickness of clean soil varying from 50 cm to several metres. Use restrictions are in force in the neighbourhood to prevent digging below this layer of clean soil (recorded in town planning and land registry documents).

In total, 339 m^3 of VLLW and 0.2 m^3 of LLW-LL were produced and sent to Cires for disposal in the first case and storage in the second.

Worksite 1: before cleanup

Worksite 1: after cleanup

FORMER ORFLAM-PLAST PLANT IN PARGNY-SUR-SAULX

Orflam-Plast manufactured lighters until February 1997, when it ceased activity due to a compulsory wind-up order.

In particular, between 1932 and 1967, these activities involved the processing of a thorium-rich ore, monazite, from which the cerium was extracted for the manufacture of lighter flints. Extraction produced residues of thorium-232, a long-lived weakly radioactive material, concentrating the radioactivity initially present in the monazite. These residues contaminated the plant site and the banks of the Saulx river which borders the site. The French government took over the orphan site in 2009. In 1997, the most urgent safety work was carried out. This consisted of covering the contaminated banks with an impermeable screen, to protect the public who might linger on these banks (fishermen). In 2008 and 2009, two contaminated areas outside the site were found several hundred metres from the site in a poplar grove. A former employee attested that thorium-232 rich processing waste was buried in this area and near Gravière lake. These areas were immediately made safe using markers and fencing. To complete the research, a large-scale radiological survey was carried out in June 2009. This survey did not find any other contaminated areas. In December 2009, the CNAR agreed to the remediation of Gravière lake, making safe the poplar grove, demolition of the plant buildings and on-site confinement of the demolition rubble, with long-term development.

The contaminated soil around the lake was partially removed and taken away. The treated area is now open to the public and fishermen. The trees in the poplar grove were cut down, chipped on site and covered with a layer of clay. Finally, the former plant buildings were demolished. The very weakly radioactive rubble from the demolition was gathered on site, under thousands of tonnes of clay and soil, to provide durable confinement that is safe for local people. The hydraulic structures were rebuilt and the banks of the Saulx were locally strengthened.

Orflam-Plast plant

Aerial photograph of the former Orflam-Plast site in Pargny-sur-Saulx after remediation.

REPORT

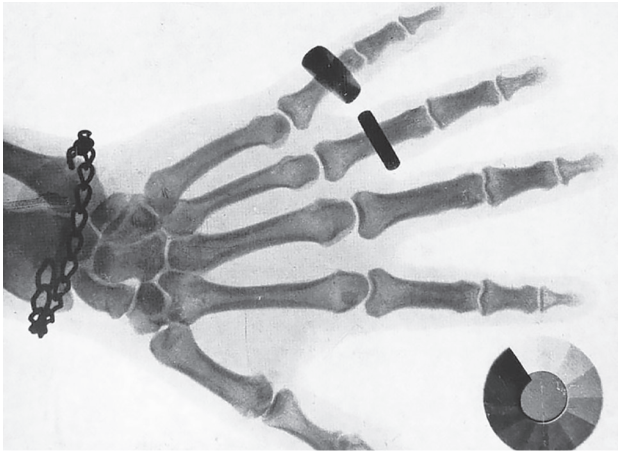
05

Radioactive waste from the medical sector

HISTORY

RADIOTHERAPY

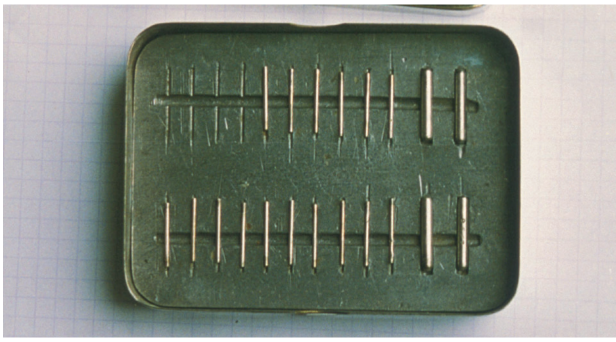
The discovery of X-rays by Röntgen in 1895 marks the beginning of radiotherapy. Just one year later doctors first used these rays to treat a tumour. Following the discovery of radioactivity in 1896 and radium in 1898, Pierre Curie and Henri Becquerel published a paper[1] in 1901 describing the energy effect of radium rays on the skin, causing cutaneous lesions. This paper was the starting point for the use of radium in medicine to heal skin infections and cancers. Initial X-ray and radium treatments developed rapidly.



X-ray image of a hand

Doctors first used X-ray tubes, devices comprising a cathode and an anode emitting X-rays, to treat tumours. However, the X-rays from these tubes only had low energy and did not penetrate deeply under the skin. They were therefore mainly used to treat skin cancers. It was a little later, with the use of radium (an extremely rare element), that treatments for other types of cancer began to be developed. Radium emits higher energy radiation that can reach deeper tumours.

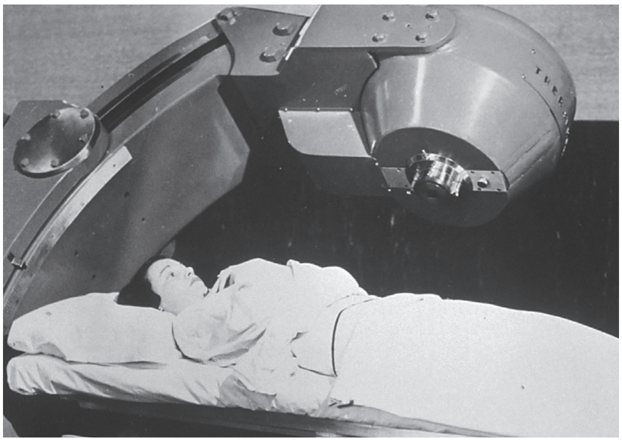
Doctors initially used small plastic packets containing radium powder which they put in contact with the skin to treat tumours and skin lesions. Then, in 1920, radium was packaged into small tubes and needles. This was the start of brachytherapy, a technique that treats cancers with radioactive sources placed in contact with tumours or inserted directly into tumours.



Radium needles

With the discovery of artificial radioactivity in 1934, use of radium gradually declined in favour of artificial radionuclides that were both cheaper and more suitable for treatments. New radioactive sources were made available to radiotherapists who replaced radium with caesium-137, iridium-192 and iodine-125.

From 1955, cobalt sources producing more penetrating high-energy radiation were used in “cobalt bombs” enabling better irradiation of tumours while minimising the impact on healthy tissue. In the late 1960s, “cobalt bombs” were replaced by more effective particle accelerators, which are still used today.



Cobalt bomb

1 *Physiology – Action physiologique des rayons du radium (Physiological action of radium rays).* Paper by Henri Becquerel and Pierre Curie

DIAGNOSTICS USING NUCLEAR MEDICINE

In 1913, Georg von Hevsey pioneered use of the radioactive tracer method: he watered plants with water containing a radionuclide, lead-210, and tracked its movement in the plants by measuring the radioactivity in the roots, stems and then leaves. Eleven years later, in 1924, two doctors injected patients with bismuth-214 as a tracer to determine the speed of blood circulation by measuring the radioactivity in the patient's body: this was the start of nuclear medicine. Radiodiagnostics did not really develop until the discovery of artificial radionuclides in 1934, and the discovery of technetium-99m in 1937, which is still the radionuclide most used in nuclear medicine due to its short half-life (6 hours), cost, availability and ability to be combined with many molecules.

USE OF IONISING RADIATION

IN NUCLEAR MEDICINE

Nuclear medicine covers all uses of radionuclides in unsealed sources[1] for diagnostic or therapeutic ends. Diagnostic uses break down into in vivo techniques based on administering radionuclides to a patient and in vitro techniques where the radionuclides are not injected into the patient but used in samples from the patient.

IN VIVO DIAGNOSTICS

SCINTIGRAPHY

Scintigraphy is a functional medical imaging technique for observing the structure and functioning of an organ and thereby detecting various ailments and pathological processes such as inflammation, a tumour or infection, etc. It complements morphological imaging such as MRI or CT scans, which take an image of the organism without giving functional information.

RADIOGRAPHY AND CT SCANS

Radiography and CT scans use X-rays, high frequency electromagnetic radiation made up of photons. Unlike gamma rays, these X-rays do not come from atomic nuclei and are not due to radioactivity.

They are produced by electrical X-ray generators. Electrons are emitted by a cathode, made of a filament (usually tungsten) heated by an electric current. They are accelerated between the cathode and the metal anode (usually tungsten) by a potential difference.

The anode is thereby bombarded by electrons, which emit X-rays via the following interactions:

- the electron is slowed by the anode and emits a photon;
- the electron excites the atoms of the anode, which emit photons to return to their fundamental state.

The X-rays thus formed pass through the human body and are attenuated to varying degrees depending on the tissues crossed. They then reach the photosensitive film (radiography) or a sensor (CT scan) placed behind the body and this produces an image of the tissues analysed. As radiation passes through the body of the patient, a dose of radiation is received, as with scintigraphy examinations or radiotherapy. The dose depends in particular on the organ being observed.

These techniques are called morphological imaging and are sometimes complementary to functional imaging such as scintigraphy.

1 Unsealed radioactive sources are sources whose presentation and normal conditions of use mean that dispersion of radioactive substances cannot be prevented.

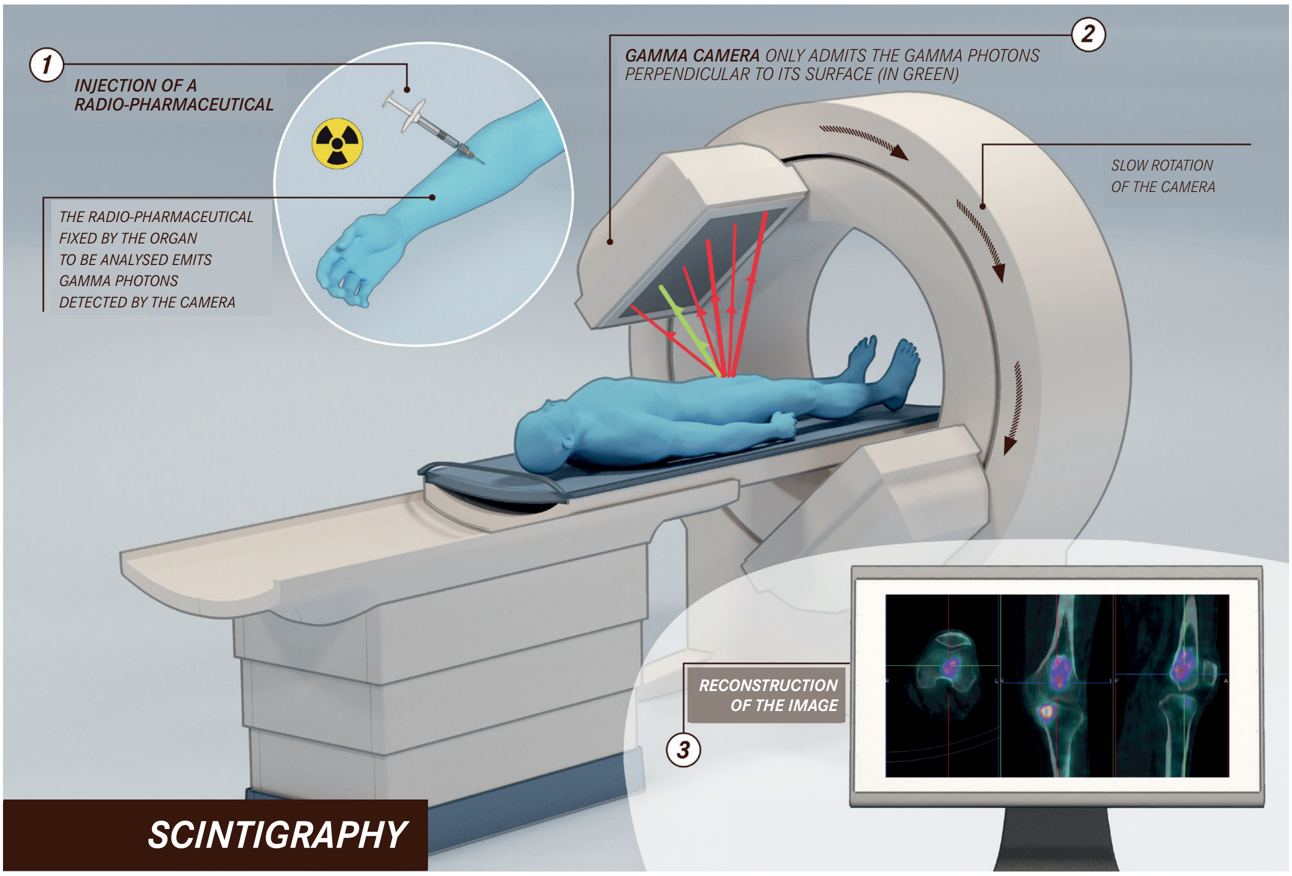
Scintigraphy works via the administration (intravenously, by inhalation or by ingestion) of a small quantity of a radioactive substance called a radio-pharmaceutical, which selectively fixes onto the organ or tissue to be examined. The radio-pharmaceutical is a gamma-emitter selected based on the function of the organ or the pathology to be observed. It may be a free radionuclide or fixed onto a molecule or cell (hormone, antibody). Usually radionuclides with very short half-lives are used, which are rapidly evacuated from the body. For example, technetium-99m, which is widely used in scintigraphy, has a half-live of six hours and is very quickly excreted in urine.

The level of activity injected into the patient depends on the examination.

The gamma radiation emitted by the radio-pharmaceutical fixed by the organ or tissue to be analysed is detected using a special camera called a gamma camera. A series of images is taken to enable visualisation of the functioning of the organ or tissue analysed. The imaging may take place immediately after injection, after several hours or several days and takes between 5 and 30 minutes. Injection of a radio-pharmaceutical has no effect on the body due to the low quantity administered.

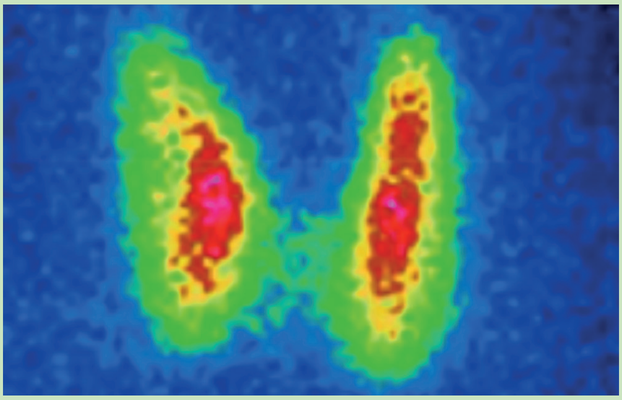
Principle of the gamma camera

A gamma camera has a collimator, a thick lead or tungsten plate with narrow parallel piercings, a crystal and a photomultiplier in the form of an electronic tube that detects light signals. The collimator selects the gamma photons emitted by the radio-pharmaceutical whose direction is perpendicular to the crystal surface. The thallium-doped sodium iodide crystal stops gamma photons and converts part of their energy into a luminous scintillation detected by the photomultipliers which convert the light signal into an electric signal. This determines the energy and position of the gamma ray that has interacted with the crystal.



EXAMPLES OF SCINTIGRAPHIC EXAMINATIONS

Thyroid scintigraphy is used to observe iodine metabolism in the thyroid gland. Iodine-123 or technetium-99m are injected into the patient and are selectively fixed by the thyroid. Scintigraphy is used to visualise the regions of the thyroid that fix the least radio-pharmaceuticals (cold nodules) or those that fix the most.



Thyroid scintigraphy

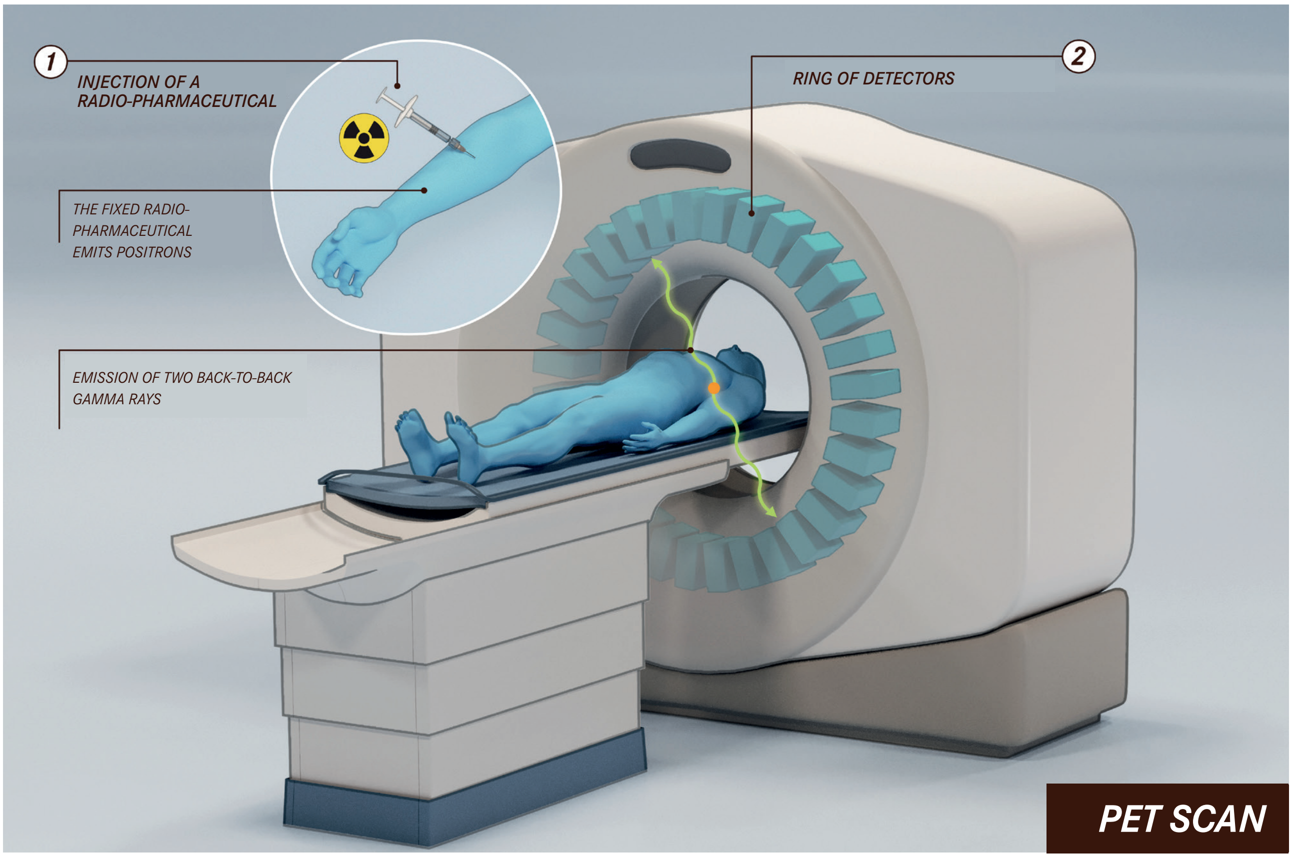
Lung scintigraphy is used to study lung function: lung ventilation (air flow) and perfusion (blood flow). Ventilation scintigraphy involves administering the patient with an aerosol inhalation containing a known quantity of radioactive product (xenon-133, krypton-81m or technetium-99m). The images produced by the gamma camera can highlight an absence of radio-pharmaceutical fixation, which corresponds to an area of lung that is not receiving air. Perfusion scintigraphy involves intravenously injecting the radio-pharmaceutical which diffuses through the body. When lung perfusion is normal, the radio-pharmaceuticals are uniformly distributed across the two lungs. When an artery is blocked by a clot, the particles cannot get past and are not detected by the gamma camera. This is what happens with a pulmonary embolism.

POSITRON EMISSION TOMOGRAPHY (PET)

Positron emission tomography (PET) is a scintigraphy technique that uses positron-emitting radionuclides, such as fluorine-18, bromine-76 or oxygen-15. In contrast to the photon-emitting radionuclides used in classic scintigraphy, positron emitters are light, abundant and easier to use. After a short range in the body, positrons vanish emitting two back-to-back gamma rays. The simultaneous detection of this gamma pair makes it possible to locate the emission zone and construct a map of the fixation of the radioactive atoms in cells. PET requires a special scintillation camera. This imaging technique can be used for the early detection of cancers and monitoring treatment and cancers. It is also used to diagnose degenerative brain conditions such as Alzheimer’s disease, and inflammatory or infectious illnesses.

The main radio-pharmaceutical used for cancer diagnosis is fluorine-18 in the form of a glucose-like sugar, 18F-FDG (fluorodeoxyglucose with fluorine-18). It is injected intravenously and is fixed by the cancer cells. Cancer cells are continuously dividing and require a lot of energy, and therefore a lot of glucose. They therefore consume an abnormally large amount of glucose compared to healthy cells. The radio-pharmaceutical is fixed in large quantities by cancer cells, which can then be detected by the PET camera.

PET scan



IN VITRO DIAGNOSTICS: RADIO-IMMUNOLOGY

Radio-immunology is a medical biology analysis technique. In contrast to in vivo diagnostics, the radionuclide is not injected into the patient. This technique is used to measure the quantity of compounds (hormones, drugs, enzymes, etc.) in biological fluids taken from a patient (blood, urine, saliva, etc.). However, radio-immunology is now facing strong competition from analysis techniques that do not use radionuclides and are easier to implement.

Radio-immunology is a dosing technique usually based on immunological reactions (specific antibody-antigen reactions). To determine the quantity of antigens in a sample from the patient, a known quantity of antigens marked with a radionuclide and a small quantity of specific antibody are added to the medium. The marked antigen is used to determine the quantity of antigen in the sample.

The antigens, marked and unmarked, are fixed by the antibodies. Since they are in excess in the sample compared to the antibody, a fraction of the antigens are fixed by the antibody and the rest remain free.

The free antigens are separated from the fixed antigens, and the quantities of marked free and fixed antigens are measured to determine the quantity of unmarked antigens present in the patient's sample.

PRODUCTION OF RADIOISOTOPES

Radioisotopes are atoms with an unstable nucleus. This instability is due to an excess of protons and/or neutrons. They stabilise by releasing energy in the form of radiation.

90% of radioisotopes are used for diagnostics and 10% for treatments. The radionuclides used in medicine are produced using particle accelerators (cyclotrons and linear accelerators) or by nuclear reactors.

Technetium-99m (^{99m}Tc), used in 75% of scintigraphic examinations, is obtained by ß decay of molybdenum-99 (^{99}Mo), itself produced in a nuclear reactor from uranium enriched to nearly 20%. After irradiation, the molybdenum is removed from the reactor then placed in a generator, from which ^{99m}Tc can be extracted. Due to its longer half-life (66 hours for ^{99}Mo, compared with 6 hours for ^{99m}Tc), molybdenum can be stored for much longer than technetium. Generators are distributed to hospitals once or twice a week. Technetium can be extracted from this generator and mixed with injectable molecules. Most fission ^{99}Mo is produced by just six research reactors worldwide.

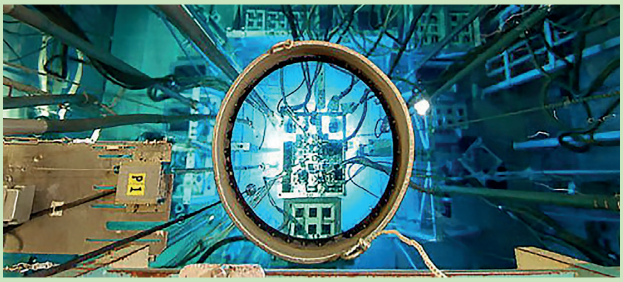
Some radioisotopes are produced in particle accelerators called cyclotrons. These comprise two metal half cylinders facing each other with a gap between them, all enclosed in a high vacuum. A magnetic field is applied perpendicular to the plane of the half cylinders and an electric field in the space between them. A source, located near the centre of the cyclotron, emits charged particles. These particles are subject to the magnetic field that curves their trajectory and the electric field which accelerates them. The particles therefore have an accelerated spiral trajectory until they are expelled from the cyclotron and propelled onto their target.

For example, the source used in proton therapy is a system that ionises hydrogen gas by heating it. The hydrogen nucleus is a single proton, which is separated from its electron by an electric field, then the proton is extracted to be accelerated in the cyclotron before being directed towards the patient's tumour.

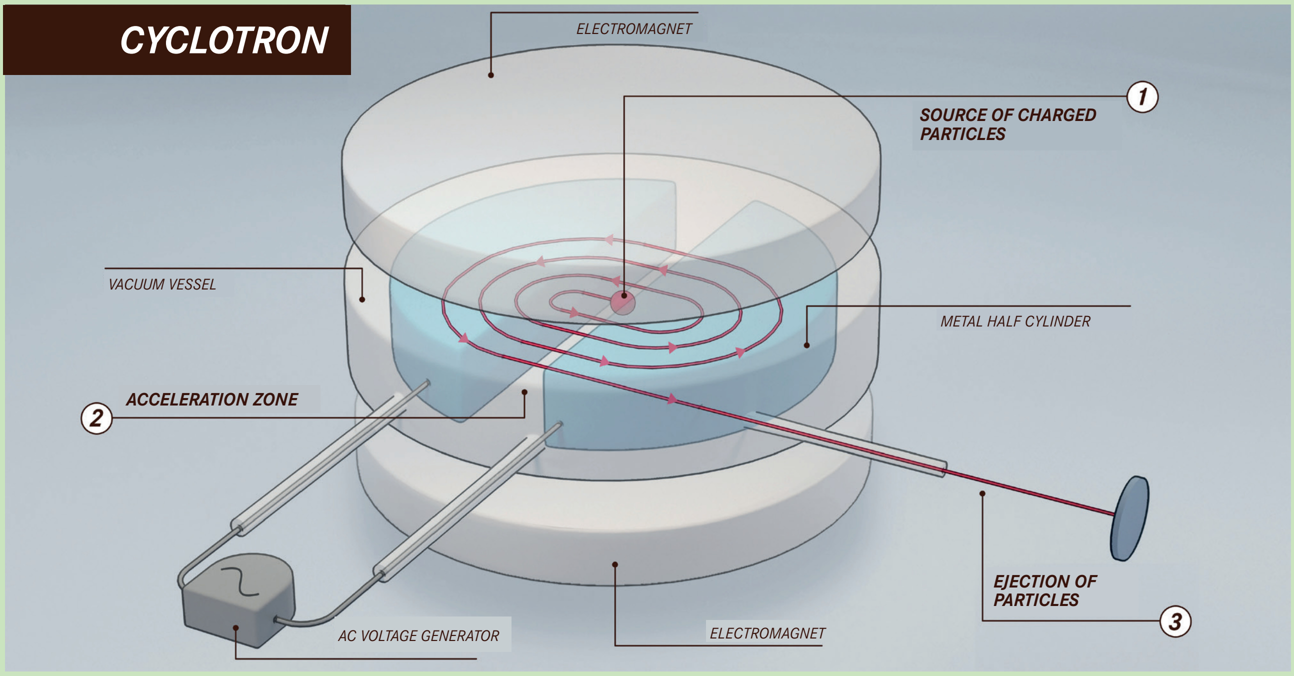
The fluorine-18 used in positron emission tomography is produced in a cyclotron by bombarding oxygen-18 nuclei with protons accelerated in the cyclotron. A nuclear reaction takes place and transforms the oxygen nuclei into fluorine-18. Due to the short half-life of fluorine-18 (110 minutes), it must be produced near the hospital.

Another type of particle accelerator is also used to manufacture radioisotopes: a linear particle accelerator. This is made of a series of open-ended cylindrical electrodes separated by spaces in which an alternating electric field is applied. The particles are accelerated in this space.

In nuclear medicine, the radioisotopes formed may be bound to molecules to form the radio-pharmaceuticals. These are prepared in an isolated room called a "hot" laboratory, fitted with leaded bins, leaded refrigerators, and glove boxes in which the radio-pharmaceuticals are prepared. The syringes are placed in shielded containers to protect workers. The radioactive product is injected into the patient in an injection room next to the hot laboratory.



Osiris experimental reactor



RADIATION STERILISATION OF EQUIPMENT

Radiation is also used in the medical sector to sterilise the equipment used in operating theatres and for general treatment: syringes, needles, surgical gloves, compresses, implants, IV-bags, etc. Radiation damages DNA molecules and thereby destroys various organisms (fungi, insects, parasites, moulds, microbes and bacteria). Sterilisation takes a few seconds and is performed in a sterilisation unit, generally using cobalt-60 or caesium-137 sources, which are high-energy gamma emitters. This type of sterilisation is ideal for heat-sensitive materials. Equipment can be sterilised in its packaging.

For blood transfusions, blood bags are irradiated in hospitals to eliminate potentially lethal cells.

For both sterilisation of medical equipment or the treatment of blood bags, the radiation has no effect on the product itself.

Blood irradiator

METABOLIC RADIOTHERAPY

Metabolic radiotherapy is a radiotherapy technique used in nuclear medicine (use of unsealed sources) where radionuclides are directly injected into patients. It consists of locally irradiating tumours that are small or disseminated in the body using a radio-pharmaceutical.

The radio-pharmaceutical, a molecule with a radioactive beta-minus emitter and selectively fixed by the cells to be treated, is injected into the patient. This is the same principle as for scintigraphy, but with much greater quantities (the dose delivered is over 50 Gy). The radio-pharmaceutical is given orally or intravenously. It is selectively fixed by the cells to be treated and the beta particle emitted when it decays transfers its energy within the cell via ionisation, which leads to its destruction. Due to the limited path of beta particles in matter, the radiation is confined to the tissues to be treated.

Iodine-131 is used for the treatment of over-active thyroids and thyroid cancers. The administered dose is very high and requires hospitalisation in a room with leaded walls and windows to protect staff from ionising radiation. Iodine-131 is fixed preferentially by the thyroid and thus destroys thyroid cells, while minimising irradiation of neighbouring cells.

The use of alpha-emitting radio-pharmaceuticals is currently increasing rapidly. Compared with beta particles, they have the advantage of delivering a larger quantity of energy over a shorter path and thereby irradiating the tumour while minimising the exposure of healthy cells. For example, radium-223 dichloride (also called Xofigo®) for the treatment of bone metastases of prostate cancer, is fixed by new bone growth (it mimics calcium) and there destroys cancer cells while minimising irradiation of healthy tissue.

ASN oversight in the medical sector

Nuclear activities relating to the manufacture, possession and use of radionuclides and products or devices containing them, and to the use of particle accelerators are subject to permits. Permit requests must be made to the French Nuclear Safety Authority (ASN). The ASN is responsible for overseeing radiation protection in the medical field. Every two years, it inspects radiotherapy centres (for compliance with the rules regarding radiation protection for staff and patients, management of facilities, equipment and sources and quality assurance). The ASN also inspects nuclear medicine departments. Summaries of the inspection reports are available on the ASN website (asn.fr). A radiation protection officer is designated in each establishment to ensure radiation protection for staff by: assessing risks, promoting good practices, implementing zoning, training staff and monitoring dosimetry. Radiation protection for patients is also implemented.

IN RADIOTHERAPY

Radiotherapy is a method of cancer treatment that uses ionising radiation from radioactive sources. Alongside surgery and chemotherapy, it is one of the main techniques used for the treatment of cancer cells.

There are several radiotherapy techniques depending on the radiation used and the location of the radioactive sources. They are all based on the same principle: irradiating cancer cells destroys them or stops them dividing while sparing healthy tissues and neighbouring organs as far as possible. Radiation of cancer cells damages the cells and their DNA. This stops them from proliferating, which leads to cell death.

Various radiotherapy techniques are described below.

EXTERNAL RADIOTHERAPY

External radiotherapy consists of irradiating cancer cells with radiation from a source located away from the patient which penetrates the skin to reach the tumour. In external radiotherapy, the radiation used is high-energy photons (or X-rays) and electrons produced by particle accelerators. Protons may also be used; this is called proton therapy.

External radiotherapy is used to treat a wide range of cancers, such as breast, lung and blood cancer.

There are several external radiotherapy techniques, which are continually being modernised to improve treatments and reduce secondary effects, which are mainly due to irradiation of healthy cells near the cancer cells. These techniques include the following:

- **three-dimensional conformal radiotherapy (3D-CRT)** is the most commonly used today. It sculpts radiation beams to the shape of a tumour, thereby sparing neighbouring healthy tissue as far as possible;
- **intensity-modulated radiotherapy (IMRT)** is based on the same principle as 3D-CRT, but works by modulating the dose rate delivered;
- **respiratory-gated radiotherapy** takes into account the patient's breathing and its effect on the position of the organs. In this radiotherapy technique the radiation is controlled based on the movement of the organs, thereby improving the precision of treatments;
- **stereotactic radiotherapy (SRT)** is a high precision technique that uses micro-beams of photons or protons to irradiate small volumes at high doses. It is used for brain tumours in particular;
- **tomotherapy** uses irradiation adapted to the tumour while sparing neighbouring organs as far as possible. The particle accelerator rotates around the patient while the patient is moved longways;

Tomotherapy machine

- the **CyberKnife** is a technique where a large number of beams converge with great precision on the tumour, thereby minimising the impact on healthy tissue.

CyberKnife System

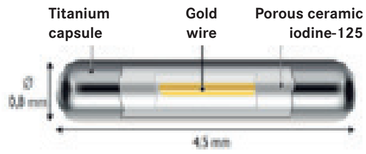
These last two techniques are used for treating tumours whose location makes more conventional conformal radiotherapy unsuitable.

BRACHYTHERAPY

Brachytherapy is an irradiation technique that involves placing radioactive sources inside or in direct contact with the tumour.

There are three types of brachytherapy:

- **low-dose rate (LDR) brachytherapy:** this requires the patient to stay in hospital for several days. It delivers dose rates of 0.4 à 2 Gy/h. The iridium-192 sources are in the form of wires (0.3 to 0.5 mm diameter and up to 14 cm long). They are installed on the patient in a shielded room and left in place during the stay in hospital. LDR brachytherapy can be used to treat eye, ENT, breast or gynaecological cancers. It is also used for prostate cancers: sealed iodine-125 sources a few millimetres long are permanently implanted into the prostate due to the rapid decay of their radioactivity. The radioactive sources emit radiation that destroys the cancer cells;



Iodine-125 seeds for prostate brachytherapy

Prostate X-ray showing the iodine-125 seeds

- **Pulsed-dose rate (PDR) brachytherapy:** this delivers the same doses as LDR brachytherapy but in a shorter time using a small iridium source. In contrast to LDR brachytherapy, the sources do not stay on the patient all the time. This technique should replace LDR brachytherapy because it offers better radiation protection for staff, who can intervene without being exposed, and is more comfortable for the patient. It can be used to treat ENT, breast or gynaecological cancers;
- **High-dose rate (HDR) brachytherapy:** here, the dose rate is high, around 12 Gy/h and the treatment time is short. A small iridium source is used. It is mainly used to treat cancers of the oesophagus, bronchi and breast, etc.

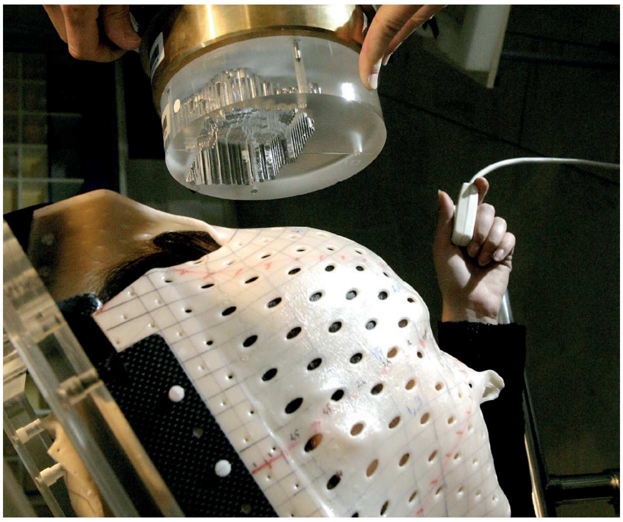
The radionuclides used in brachytherapy are different from those used in nuclear medicine. They are higher energy and emit beta and gamma radiation. The doses administered to patients are higher, and vary depending on the type of cancer, its stage, the organ to be treated, the age of the patient, etc.

PROTON THERAPY

This technique involves treating tumours using accelerated protons, unlike conventional radiotherapy which uses beams of photons or electrons. It is a precise technique that spares healthy tissue, which is why it is used for tumours located near critical organs that are sensitive to radiation such as the eye or brain. It is also used in paediatrics.

The basic principle of proton therapy is to direct a beam of accelerated protons from the particle accelerator onto the patient's tumour. The energy of the protons is modulated so that they reach the tumour and release as much of their energy as possible into the tumour. Tissues beyond the tumour are not reached.

This technique is very expensive because it uses large, sophisticated equipment. There are currently only two proton therapy centres in France.



Proton therapy

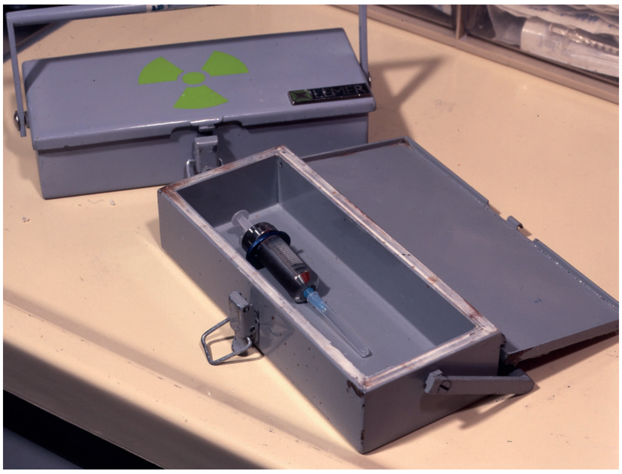
RADIOACTIVE WASTE FROM THE MEDICAL SECTOR

TYPES

Radioactive waste from the medical sector produced following in vitro/in vivo analyses or radiotherapies may be liquid or gaseous effluents, or contaminated solid or liquid waste.

Radioactive liquid effluents are mainly from:

- rinsing, in "hot sinks" reserved for radioactive effluents, of reusable instruments such as those used for preparations and injections (syringe shields, plates, etc.);

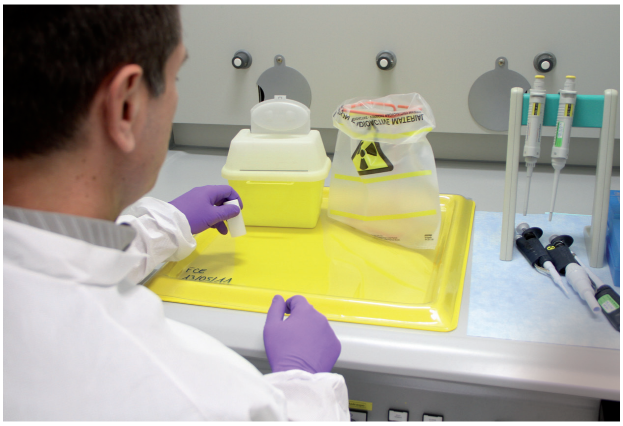


Syringe shield

- washroom facilities for patients having received radionuclide injections (scintigraphy, PET), and for the shielded rooms for iodine-131 treatments.

Radioactive gaseous effluents are from radionuclides that may become volatile during the preparation and handling of unsealed sources or from pulmonary ventilation examinations.

Contaminated waste is of two types: sharps (razors, needles, etc.) and other waste (gloves, compresses, cotton swabs, tubes, test tubes, pipette ends, etc.). This waste has the particularity of risks other than radioactivity: infectious, chemical or toxic risks.



Use of radioactive products in the medical sector

Other waste: some waste may be generated. For example, lead containers transporting radio-pharmaceuticals which, after checking for non-contamination, have a special disposal solution.

Medical waste in the National Inventory

Every year, establishments that use radionuclides for medical diagnostic or therapy are required to send Andra an inventory of the radioactive waste that they possessed on the 31 December of the previous year, indicating the management solution used.
At the end of 2016, the volume of waste produced by medical activities was around 10,500m^3 of which 1,950 m^3 was managed by decay and 8,400 m^3 sent for disposal at the Manche disposal facility (CSM).

WASTE MANAGEMENT

The management of medical waste is governed by law. The Order of 23 July 2008 approved ASN Decision 2008-DC-0095 in application of Article R.1333-12 of the French public health code, which "sets the technical rules applicable to the elimination of effluents and waste contaminated by radionuclides, or liable to have been contaminated owing to a nuclear activity".

In healthcare establishments, a "waste zoning" system is implemented to distinguish zones where the waste and effluents produced are or may be contaminated, from zones where the waste and effluents produced are conventional. This may be a single workstation (a hot sink for example), or part or all of a room.

For each establishment, the management methods for contaminated waste and effluents are described in a document: the contaminated waste and effluent management plan.

This plan includes:

- the ways that radioactive effluents and waste are produced and managed (sorting methods, conditioning, storage);
- provisions to ensure the elimination of waste and effluents and the associated monitoring methods;
- identification of the zones where effluents and waste are produced and stored;
- identification and location of effluent discharge points;
- monitoring of the system for recovering effluents and of the environment.

Contaminated waste and radioactive effluents are managed independently.

ARTICLE R.1333-16 OF THE FRENCH PUBLIC HEALTH CODE

"Effluents and waste contaminated by radionuclides or liable to have been contaminated or activated owing to a nuclear activity shall be collected and managed, taking into account the characteristics and quantities of said radionuclides, the exposure risks involved and the disposal solutions adopted. The methods for the collection, management and elimination of effluents and waste shall be recorded by the person responsible for a nuclear activity in a waste and effluent management plan made available to the relevant authority."

MANAGEMENT OF CONTAMINATED WASTE

Waste contaminated by radionuclides presents a risk of exposure and contamination for staff, patients and the environment. It must therefore be eliminated using specific solutions while ensuring that exposure and contamination risks are managed.

Healthcare establishments that possess or produce contaminated waste are responsible for it until final elimination. Waste elimination involves sorting, conditioning, characterisation, storage, collection, transport and any treatment.

Categorised waste bins used in hospitals

Contaminated waste is separated from non-contaminated waste then sorted based on its type, the radionuclides it contains and specific risks (infectious, carcinogenic, reprotoxic, etc.). It is conditioned into suitable containers that protect from radiological risks (lead bins) and other risks (infectious, chemical or toxic). Lead bins may therefore contain packaging for infection risk material (DASRI[1]).
Contaminated waste is managed based on the radioactive half-life of the radionuclides it contains.

Contaminated waste may be managed by decay:
- if it contains or is contaminated by radionuclides with a radioactive half-life of less than 100 days;
- if the daughter products of these radionuclides, from successive decays of radionuclides, are not themselves radionuclides with a period of more than 100 days. In the case where the daughter products are radionuclides with a half-life of more than 100 days, the waste may be managed by radioactive decay if the ratio of the half-life of the mother radionuclide to that of the daughter radionuclide is less than the coefficient 10^{-7}.

DASRI packaging

Most radionuclides used for in vivo applications have a half-life of less than 100 days: ^{99m}Tc, ^{123}I, ^{131}I, ^{18}F.

The waste is stored in a closed space reserved for this type of waste. After a storage period of at least 10 half-lives of the radionuclide with the longest half-life, the waste can be eliminated of as non-radioactive waste once it has been checked that there is no contamination. After decay, the waste can therefore be directed:
- to non-hazardous waste disposal systems, if there is no infection or chemical risk;
- to DASRI waste disposal systems, if there is an infection risk;
- to suitable waste disposal systems, if there is a chemical or toxic risk.

To ensure that there is no contamination of conventional waste systems, detection systems (monitoring stations, radiation portal monitors) are installed in establishments with a nuclear medicine facility.

Radioactive waste storeroom

Technetium generators, used in nuclear medicine and regularly delivered to healthcare establishments, have a limited operating life. Due to radioactive decay, after about a week the generator no longer produces enough technetium. It is stored for decay for a further 3 weeks. Then, once the activity level is sufficiently low, it is returned to the supplier.

Waste that cannot be managed by decay, with a half-life of more than 100 days, is managed via disposal systems licensed for the management of radioactive waste. It is directed to disposal facilities run by Andra.

Technetium generator transport container

Technetium generator

1 DASRI is a French acronym for medical waste containing viable micro-organisms or their toxins, which due to their type, quantity or metabolism, are reasonably believed to cause illness in humans or other living organisms. Even where there is no infection risk, the following are also considered DASRI: sharp equipment or materials and blood products.

MANAGEMENT OF RADIOACTIVE LIQUID EFFLUENTS

Liquid effluents may be managed by radioactive decay if they meet the criteria described above for contaminated waste.

Liquid effluents are directed to and stored in tanks before discharge to avoid direct discharge into the wastewater system. At least two tanks are used to collect effluents: when one is in the filling phase, the other is in the storage phase for decay. The liquid effluents contained in the storage tanks are discharged into the wastewater system if the activity is less than 10 Bq/L, except for the rooms of patients treated with iodine-131 where the limit is 100 Bq/L. Note that deliberate dilution of radioactive liquids before discharge is strictly prohibited.

Decay tanks

After decay for a period of at least 10 half-lives of the radionuclide with the longest half-life, the effluents can be discharged into the environment. However, it should be noted that “any discharge of wastewater other than domestic wastewater into the public network is subject to prior authorisation by the network operator”.

Discharge of liquid effluents containing radionuclides with a half-life of more than 100 days is subject to ASN approval. The establishment must perform a technical and economic study and an impact assessment of the effect of the discharges on the population, the environment and workers, and must define the methods implemented to monitor discharges and suspend them if necessary. Based on this information, the ASN may either authorise the discharge of effluents by setting conditions for discharge into the environment, or impose their removal to Andra disposal facilities if the impact on the environment, the population and workers is too great.

MANAGEMENT OF RADIOACTIVE GASEOUS EFFLUENTS

The discharge of gaseous effluents must be as low as reasonably achievable. Filters, such as active carbon filters must be installed. These filters are eliminated with contaminated waste. If the gaseous effluents contain a radionuclide with a half-life of more than 100 days, the ASN sets the conditions for discharge into the environment (monitoring the activity discharged, environmental monitoring plan, etc.) as for radioactive liquid effluents.

SPECIAL CASE OF LINEAR PARTICLE ACCELERATORS

The dismantling of linear particle accelerators also produces waste. Some parts of the accelerator may be activated under the particle flux. These parts must be identified, characterised and their activity assessed with a view to specifying their management solution and the potential need for them to be managed by Andra. However, as the characterisation of long-lived pure beta emitters is difficult and expensive, the waste is usually stored in situ awaiting characterisation. Studies are underway to help in the characterisation of these metal parts.

PLUTONIUM-238 PACEMAKERS

The first generation of pacemakers operated on a battery with a limited service life, and needed changing regularly (about every 10 years). To avoid this problem, plutonium-238 pacemakers were developed in the 1970s. Their service life is much longer (about 40 years), so they can operate for the lifetime of the patient. These pacemakers use the thermal energy from plutonium alpha decay to make electricity to power themselves. The plutonium-238 is enclosed in a housing with several metal layers to protect the patient from radiation. Plutonium-238 pacemakers were later abandoned in favour of pacemakers with a lithium/iodine battery due to the risk of irradiation if the sealed housing were to fail. However, some patients still have plutonium pacemakers. When the patient dies, it is removed and returned to the supplier, as it is considered to be a sealed source.

Plutonium pacemaker

REPORT

06

Sealed sources

PRESENTATION OF SEALED SOURCES

DEFINITION

A sealed source is a source made up of radioactive material that is permanently bonded or fixed into an inactive capsule or matrix designed to prevent release and dispersal of the radioactive material under normal conditions of use and handling.

MANAGEMENT OF SEALED SOURCES BY IRSN

Sealed sources contain radioactivity and can be dangerous in the event of prolonged contact or ingestion.

To ensure safety for users, the public and the environment, regulations impose monitoring of the conditions for possession, use and transfer of sources from manufacture to disposal or recycling.

In France, monitoring for compliance with these regulations is provided by the Institute for Radiological Protection and Nuclear Safety (IRSN - irsn.fr).

Applications for permits to possess and use ionising radiation are assessed and granted by the various relevant authorities for radioactive sources (ASN, prefectures, DSND, etc.). Assessment of permit applications to manufacture and distribute sources is centralised at the national level. IRSN is the central authority responsible for these permits and for the movement of sources in France (acquisition, transfer, export, import, recovery, replacement, etc.). IRSN uses the computerised data it holds to produce the National Inventory of Ionising Radiation Sources.

IRSN is therefore the reference point for everything regarding the practical methods for all movement of sources: obtaining forms for purchasing sources, recovery of sources, annual inventory, etc.

PLACE OF SEALED SOURCES IN THE NATIONAL INVENTORY OF RADIOACTIVE MATERIALS AND WASTE

Not all sealed sources in France are covered by Andra's National Inventory. Only disused or spent sources (see "Management of spent radioactive sources" in page 139) are considered waste and included by Andra in the inventory.

SEALED SOURCES IN THE NATIONAL INVENTORY

Spent sealed sources account for several waste streams in the National Inventory:

- CEA packages with core source elements (LLW-LL F2-9-01 stream), which groups packages made up of spent sealed (solid, liquid or gaseous) sources, collected from small waste producers (hospitals, food processing industry, paper mills, petrochemical industry, etc.);
- CEA packages of sealed radioactive sources, with a half-life less than or equal to that of cobalt-60 (LILW-SL F3-9-02 stream). These sources were used in the past in medicine, research and industry;
- spent sealed sources (S01 stream). The majority of these sources are from ionisation smoke detectors. These sources also include primary and secondary source rods from EDF pressurised water reactors. The remainder are disused sealed sources recovered and stored by the main source suppliers or manufacturers;
- radio-luminescent objects (S02 stream). This waste stream mainly includes decommissioned military equipment, grouping radium- and tritium-bearing radio-luminescent objects (compasses, dials, sights, etc.);
- contaminated spent sealed sources (S03 stream) and radioactive surge protectors (S04 stream).

For historical reasons, sources that were previously under a specific waiver programme are not inventoried by IRSN but by Andra, as they are disused and considered as waste. These include:

- radioactive lightning rods;
- ionisation smoke detectors (current detectors do not contain radioactive sources);
- radio-luminescent sources;
- surge protectors (legacy electronic components used in particular for electrical protection of the telephone system).

All these objects may have been manufactured using radium, a radionuclide whose use was not regulated for a long period; after that, other radionuclides may have been used.

LEGACY RADIO-LUMINESCENT OBJECTS

Radio-luminescent alarm clocks

When legacy models of watches, alarm clocks, compasses, aircraft dials and night sights have needles and dials that remain luminescent after two days in complete darkness, they are radioactive and considered as sealed sources. The luminescent effect was obtained by adding radium or tritium to the paint. The quantities of radioactive substances involved are extremely small and confined in the housing by the glass. They present a problem if the glass or housing are no longer sealed. These legacy models are often owned by collectors, in particular collectors of military memorabilia, and by clockmakers or their inheritors. They cannot be sold or given away, they must be managed as radioactive waste by Andra.

FIELDS OF USE OF SEALED SOURCES

The justification principle (see box below) means that radionuclides may only be used when there is no other solution. Current use of sealed sources in industry or medicine complies with this principle.

Justification principle (Article L. 1333-2 of the French Public Health Code)

Any activity that may expose people to ionising radiation may only be undertaken or performed if it is justified by its benefits, in particular health, social, economic or scientific benefits, with respect to the inherent risk of this exposure. Any unjustified activity is prohibited. When several techniques can achieve the same result, the one with the lowest dose of ionising radiation and the most favourable risk assessment shall be chosen.

INDUSTRIAL USES

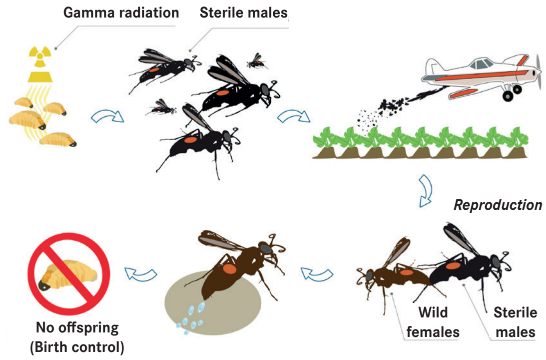
The radioactive properties of sealed sources are used in various industrial processes described below.

STERILISATION BY IRRADIATION

This involves exposing things to ionising radiation in order to destroy all living organisms without altering the composition of organic matter. This process is used in several applications:

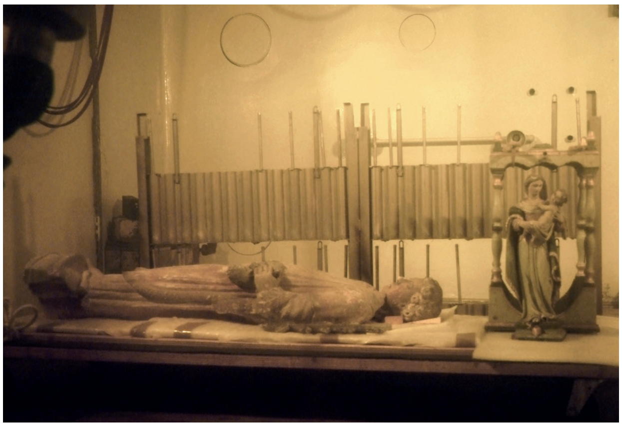
- **treatment of foodstuffs:** irradiation can prevent germination, kill insects, delay ripening (of fruit and vegetables), prevent illnesses (poultry) or reduce the quantity of micro-organisms (herbs). Following treatment, these products have no residual radioactivity.
  There are several foodstuff irradiation centres in France. They may use a sealed source (cobalt-60) or an electron accelerator;
- **eradication of insect pests:** for example, male tsetse flies are bred in laboratories and sterilised by brief exposure to gamma rays from a cobalt-60 sealed source. These sterile flies are then released in the target area to compete with the native male flies for mates;

INSECT PEST CONTROL USING THE STERILE INSECT TECHNIQUE (SIT)



Insect pest control using the Sterile Insect Technique (SIT)

- **protection of certain heritage items** against fungi or prevention of any contamination risk for researchers and the public. The mummy of Ramesses II was exposed to ionising radiation for this reason;



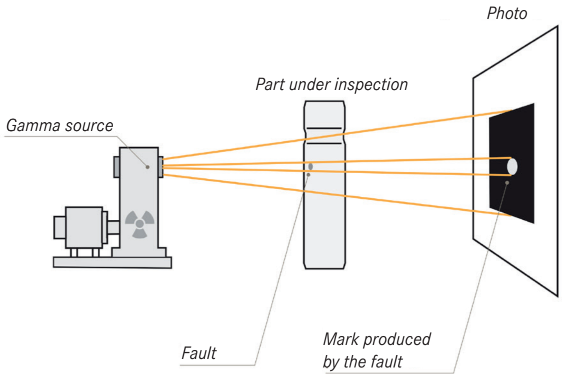
Disinfection of a mummy by (cobalt-60) irradiation. Source rods can be seen in the background

- **sterilisation of medical equipment,** pharmaceutical products and cosmetics. Gamma-ray treatment enables quick processing of products already in sealed packaging.

CHECKS AND ANALYSES ON MATERIALS

Sealed sources are used in several types of device for physical or chemical analysis of materials:

- **non-destructive testing using gammagraphy:** these checks are performed without damaging the objects tested. It works like an X-ray to identify internal faults.
  The techniques and procedures provide information on the condition of a part or structure, without causing damage that could jeopardise its later use;



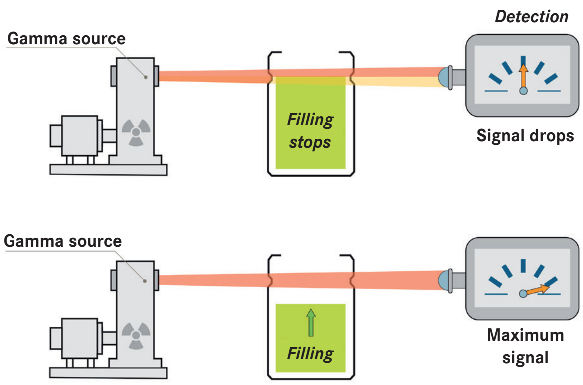
Schematic diagram of non-destructive testing using gammagraphy

- **checking for lead:** portable devices containing a sealed source are used to detect the presence of lead in paints. They are widely used in property condition assessments. These detectors use X-ray fluorescence: when the material is bombarded by radiation (emitted by a cadmium-109 or cobalt-57 source), the matter emits energy characteristic of the composition of the sample.

PARAMETER CHECKS

Sealed sources are used in various industrial sensors:

- to monitor the grammage or thickness of paper, fabric, plastic or metal. Attenuation of the radiation produced by the source depends on the thickness of materials crossed;
- to monitor vessel levels: a gamma ray beam crosses the container being filled, with a detector located opposite. When the rising liquid intercepts the gamma ray beam, the signal received by the detector suddenly falls. This detected signal is used to automatically stop filling. The radionuclides used depend on the characteristics of the container and its contents.

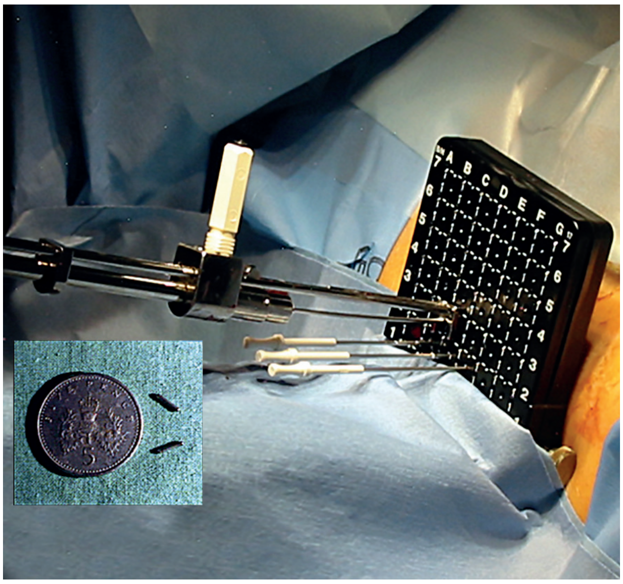


Schematic diagram of a vessel filling control system

MEDICAL USES

Sealed sources are used in medicine for:

- **brachytherapy** which involves placing radioactive sources in the body, in direct contact with the lesion to be treated. This concentrates the doses on a small volume without harming surrounding tissue. The gamma rays are delivered by a sealed source, implanted in the body, often in a natural cavity. Radium was originally used, but has been replaced by artificial radionuclides (caesium-137 and iridium-192 for example);
- **checking and calibrating equipment** used in nuclear medicine: standard sources are used to check correct operation of the measuring equipment used in diagnostics or treatment;
- **sterilisation:** as well as the examples mentioned above, this method is widely used to sterilise human blood before transfusion. Irradiators comprise a shielded vessel which contains a high-activity cobalt-60 or caesium-137 source.



Brachytherapy using iodine-125

MANAGEMENT OF SPENT RADIOACTIVE SOURCES

LEGISLATION CONCERNING SOURCES

French legislation concerning sources is grouped in the Public Health Code, in Articles L. 1333-1 and following, and Articles R. 1333-152 and following.

In particular, Article R. 1333-161 specifies that:

I. A sealed radioactive source is considered to have expired ten years at the latest after the date of first registration marked on the supply form or, if none, after the date of its initial market introduction, unless an extension is granted by the competent authority.

II. Any holder of sealed radioactive sources that are expired or at end-of-life must have them retrieved, irrespective of their condition, by a supplier authorised to do so under the terms of Article L. 1333-8. Sealed radioactive sources that are not recyclable under the technical and economic conditions of the time may be retrieved, as a last resort, by the French National Radioactive Waste Management Agency (Andra). The holder is responsible for costs related to retrieval of these sources.

If the holder has its sealed radioactive sources retrieved by a supplier other than the original one, or if they are retrieved by Andra, the holder must send a copy of the retrieval certificate issued by the retrieval agent to the original supplier and to the Institute for Radiological Protection and Nuclear Safety (IRSN) within one month of its receipt.

III. The provisions of I and II do not apply to sealed radioactive sources whose activity, at the time of manufacture, or, if this time is not known, the time of their initial market introduction, does not exceed the exemption limits specified in Table 1 and in the second and third columns of Table 2 of Appendix 13-8.

IV. The supplier of sealed radioactive sources, or products or devices that contain such sources, is required to retrieve any sealed source it has distributed, when that source is expired or when its holder no longer needs it or is insolvent. The conditions for this retrieval, including associated costs, are specified between supplier and buyer when the source is sold, and retained by the holder and supplier until the source has been retrieved. These conditions may be updated based on technical or economic changes and shall be taken into account during implementation of the financial guarantee specified in Article R. 1333-162. When the source is supplied in a device or product, the suppler is also required to take it back in full if the holder so requests. If the holder is insolvent and is not the beneficiary of a guarantee covering retrieval costs as specified in Article R. 1333-163, the French Nuclear Safety Authority (ASN) shall hold the supplier unconditionally responsible for retrieval.

This retrieval obligation shall end when the supplier ceases all distribution of sealed radioactive source activities. However, it is maintained for a period of three years from the expiry date of distributed sources whose activity at the time of manufacture, or, if this time is not known, the time of their initial market introduction, exceeds the exemption limits specified in Table 1 and in the second and third columns of Table 2 of Appendix 13-8. The expiry date mentioned above takes into account any extensions granted in application of I, for which the supplier has confirmed maintenance of the financial guarantee.

V. Any supplier shall eliminate or arrange the elimination of the retrieved sealed radioactive sources in a facility authorised for said purpose, or return them to their supplier or the manufacturer. Suppliers must substantiate their storage capacity for receiving retrieved sources during the period prior to their elimination or recycling.

OBLIGATION OF RETRIEVAL

French law requires suppliers to retrieve, on holder request, all sealed sources it has supplied in France.

To ensure retrieval of sources, even in the event of insolvency of their manufacturer, suppliers have formed the association Ressources to share the burden of financial guarantees and to reimburse Andra, or any other accredited body, the costs of source retrieval.

This association with sixty member companies represents nearly 95% of the market for this activity.

Source management

RECYCLING OF SEALED SOURCES

The radionuclides present in some sources have a very long half-life (for example, americium-241 has a half-life of 432 years), so the activity is little diminished at the end of their service life and is very close to the original activity. After retrieval, some sources can be recycled: depending on the type of source (shape, matrix, etc.), it may be possible to recover the radioactive isotopes to include them in new packaging and thereby produce a new source. The old packaging would be treated as waste. However, currently sources are hardly ever recycled, in particular due to major technical constraints (radionuclides trapped in hard to recycle matrices, etc.) and significant recycling costs.

MANAGEMENT BY ANDRA

Andra's operating or planned disposal facilities can or could accept spent sealed sources providing that they meet acceptability criteria.

Most spent sealed sources are currently stored awaiting a disposal solution.

▸ CIRES

Cires is designed for disposal of very low level waste.

Since 2015, the acceptance specifications of this facility mean that spent sealed sources can be disposed of in compliance with the facility's safety demonstration.

The activity of each source conditioned at the time of its declaration for management by Cires must be such that the resulting activity after 30 years of decay is less than or equal to 1 Bq.

These sources contain short-lived radionuclides, such as cobalt-57 (half-life of 272 days), iron-55 (2.7 years) or zinc-65 (244 days), and are therefore not recyclable.

▸ CSA

Since 2006, an acceptance specification lays out the conditions for management of spent sealed source packages. Prior to 2006, sources could only be accepted at CSA via an ASN waiver.

Among other conditions, the sources in a single package must only contain a single type of radionuclide, with a half-life of less than 30 years. Sources containing cobalt-60 (half-life of 5.3 years) and radionuclides with shorter half-lives are currently disposed of at CSA.

The acceptance limit for sealed sources in surface disposal facilities is due to their concentrated activity and their potential attractiveness (sources are small manufactured objects that could be pocketed or kept as trinkets, destroyed or ingested). It is therefore important that the residual activity does not cause unacceptable effects at a time when memory of the site is assumed lost (300 years) and where human intrusion (road projects, construction, etc.) is possible.

LLW-LL

To date, there is no definitive disposal facility design for low-level long-lived waste (LLW-LL). The characteristics of sources acceptable in this type of disposal will depend on the design. Sources destined for this disposal are those unacceptable for CSA and for which disposal at the Cigeo facility is not justified from a safety perspective.

These sources will be conditioned into packages that comply with acceptance specifications set by Andra.

CIGEO

The Cigeo disposal facility is designed for the deep geological disposal of high-level waste and long-lived intermediate-level waste (HLW and ILW-LL).

In compliance with the provisions of Article L. 542-1-2 of the French Environmental Code, sealed sources which cannot be disposed of in surface or near-surface repositories will be subject to deep geological disposal at Cigeo.

These sources will be conditioned into packages that comply with acceptance specifications set by Andra.

CHANGES IN THE USE OF SEALED SOURCES FOR CERTAIN ACTIVITIES

To comply with the justification principle and because the use of sealed sources imposes various constraints, alternative non-radioactive solutions should be preferred.

For example:

- the sealed sources used for external radiotherapy have been replaced by particle accelerators which only emit radiation when they are powered up;
- surge protectors containing radioactivity have been replaced by surge protectors containing various electronic components that do not use radioactivity;
- the radium present in radio-luminescent objects was gradually replaced by tritium (with lower toxicity), which has itself been replaced by photo-luminescent paint wherever possible;
- pacemakers powered by a plutonium-238 thermal generator have been replaced by pacemakers powered by lithium/iodine batteries;
- ionisation smoke detectors (americium source) have been replaced by optical detectors containing an LED and a photoelectric receiver.

Depending on the type of source, legislation may require the immediate scrapping of these radioactive devices even though they are still operational, or may permit their use until the end of their service life.

Ionisation smoke detector

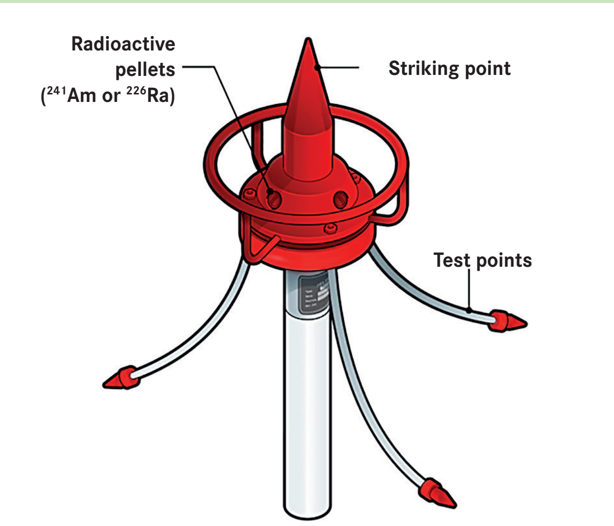
LIGHTNING RODS

In the early 20th century, radioactive sources were added to the tips of lightning rods to enhance the natural ionisation of the air and thereby improve the effectiveness of the lightning rod. Ionising lightning rods were manufactured in France from 1932 to 1986 by Helita, followed by Duval Messien, Franklin France, and Indelec. Because their additional effectiveness was not proven, the Order of 11 October 1983, applicable from 1 January 1987, prohibited their manufacture.

Their removal was not imposed by law, however, every time one is dismantled, it must be removed as radioactive waste to Andra.

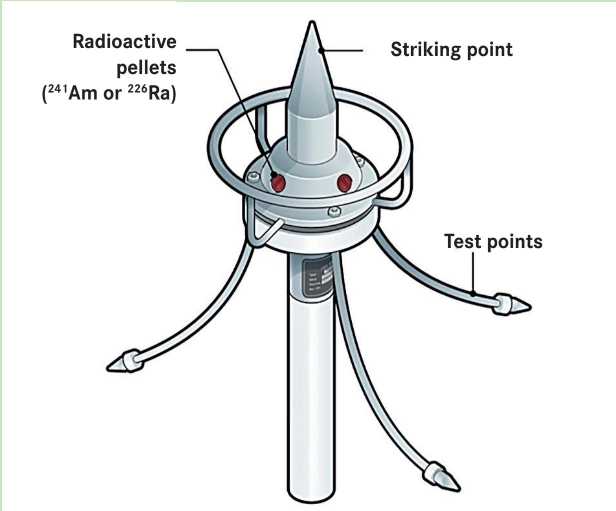
The total number of such lighting rods installed in France is estimated at 50,000, of which 30,000 are fitted with radium-226 sources (or both radium-226 and americium-241 sources: mixed lightning rods), and 20,000 are fitted with americium-241 sources.

The mean activity of a radium-226 lightning rod tip is around 50 MBq and that of an americium-241 lighting rod tip around 20 MBq.



Overall treatment of a lightning rod tip (Diagram 1)

The radioactive substances are in the form of sintered pellets, plates, sheets, or balls made of painted porcelain, which are generally small.



Local treatment of a lightning rod tip (pellets) (Diagram 2)

Initially, the lightning rod tip was processed as a whole.

The whole removed tip was considered as LLW-LL (see Diagram 1).

To optimise disposal space, Andra is planning to simply remove the pellets where all the activity is found (see Diagram 2). The pellets will be grouped in 870-litre drums, then stored awaiting disposal in Cigeo. As a precaution, the rest of the lightning rod tip will be considered VLLW. Awaiting implementation of this plan, these lightning rods will be sent to the Andra storage platform at Cires.

REPORT

07

Foreign inventories of radioactive waste

PURPOSE OF WASTE INVENTORIES

The first step in drawing up a radioactive waste inventory is to define a classification of radioactive waste. A working group at the Nuclear Energy Agency (NEA) is dedicated to the theme of the inventory of spent fuel and radioactive waste on an international level.

In 2016, this group published a report providing an assessment of the classification and inventory issues for radioactive waste[1], in particular the status of various current and planned international approaches, including those of the International Atomic Energy Agency (IAEA), the Net Enabled Waste Management Database (NEWMDB), the European Commission and the NEA itself.

INTERNATIONAL BODIES

The Nuclear Energy Agency (NEA) is a specialised agency of the Organisation for Economic Co-operation and Development (OECD). Its mission is to "assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes. It strives to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies [2]".

Created by the United Nations in 1957 as an independent body, **the International Atomic Energy Agency (IAEA)** has the mission of promoting the safe use of nuclear technologies for peaceful purposes. It has 168 Member States. One of the main missions of the IAEA is to prevent the proliferation of nuclear weapons[3]. The IAEA provides a joint database for all countries, the NEWMDB[4]. In particular, this database contains information on radioactive waste management programmes, waste inventories and legislation.

The **Joint Convention** on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management was ratified by France on 22 February 2000 and came into force on 18 June 2001. Under this convention, during the Review Meetings (every three years), each contracting party is required to present a report describing the way it is implementing its obligations under the convention. By 31 December 2016, 75 contracting parties had ratified the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

The **Euratom** treaty was signed in 1957 and aims to enable the development of EU countries' nuclear industry while ensuring the protection of workers and the general public from the harmful effects of ionising radiation. Under this treaty, the **European Commission** draws up directives that Member States must transpose into national law.

The inventory has several purposes, including the following:

- provide support to the definition of a radioactive waste management programme, and draw up an inventory to enable planning for the necessary facilities and the R&D programmes intended to provide a means of dealing with waste that has no available solution;
- ensure that the data concerning storage and disposal of waste is conserved in accordance with quality management requirements and is appropriate to the needs of future generations (Retrieval, Restoration and Maintenance of Old Radioactive Waste Inventory Records - IAEA-TECDOC-1548);
- draw up "an inventory of all spent fuel and radioactive waste and estimates for future quantities, including those from decommissioning, clearly indicating the location and amount of the radioactive waste and spent fuel in accordance with appropriate classification of the radioactive waste," according to Council Directive 2011/70/Euratom of 19 July 2011.

1 *National Inventories and Management Strategies for Spent Nuclear Fuel and Radioactive Waste. Methodology for Common Presentation of Data*. OECD 2016. NEA No. 7323.
2 oecd-nea.org; Strategic Plan of the Nuclear Energy Agency 2017-2022.
3 iaea.org.
4 newmdb.iaea.org.

Through these inventories, countries report on the volumes of radioactive waste produced and their situations (for example, whether disposal systems exist). They also provide information on the location, activity, conditioning, origins, destination, etc. of the waste.

The inventories are published regularly, in particular by the signatories of the IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

INTERNATIONAL CLASSIFICATION OF RADIOACTIVE WASTE

The classification of radioactive waste generally differs from one country to another. Encouraged by international bodies such as the IAEA, the OECD/NEA and for Europe, the Directive 2011/70/Euratom, convergence towards a joint international classification is underway. The table below compares the generally accepted names to the French classification.

French radioactive waste classification		Equivalent IAEA classification (GSG-1)
Déchets de très faible activité (TFA)	Very Low Level Waste (VLLW)	Very Low Level Waste (VLLW)
Déchets de faible et moyenne activité à vie courte (FMA-VC)	Low and Intermediate Level Short-Lived Waste (LILW-SL)	Low Level Waste (LLW)
Déchets de faible activité à vie longue (FA-VL)	Low Level Long-Lived Waste (LLW-LL)	Intermediate Level Waste (ILW)
Déchets de moyenne activité à vie longue (MA-VL)	Intermediate Level Long-Lived Waste (ILW-LL)	Intermediate Level Waste (ILW)
Déchets de haute activité (HA)	High Level Waste (HLW)	High Level Waste (HLW)[1]

In reports in English, the category Exempted Waste (EW) is also mentioned. This does not exist in France as there is no clearance level.

The boundaries between these categories must be listed to enable international comparisons and inventories (IAEA, GSG-1, see Section 3, Monitoring performed by the International Atomic Energy Agency (IAEA)).

Historically, the European Commission undertook an assessment of its member states published in 2009[2]. This assessment gave an overview of the national monitoring systems for data concerning waste implemented by EU Member States. It gave recommendations for future waste management systems. The study covered the collection, publication and management of data on radioactive waste and spent fuel in the EU Member States and Candidate Countries listed in the following table.

TYPE OF NATIONAL INVENTORY DATABASE OF RADIOACTIVE MATERIALS AND WASTE

Type of database	Country
Centralised computer database with electronic data submission	Belgium, Croatia, Estonia, Finland, Germany, Hungary, Italy, Latvia, Macedonia, Netherlands, Romania, Slovenia, Spain, United Kingdom
Computer database located at the nuclear power plant	Lithuania
Centralised computer database with data submission via network	Czech Republic, France[3]
Centralised computer database with data collection via paper forms	Bulgaria, Slovakia
Centralised paper archive data collection via paper forms	Greece
Not specified	Austria, Cyprus, Denmark, Ireland, Luxembourg, Malta, Poland, Sweden, Turkey

All of these countries have statutory specifications concerning the maintenance of a collection system for national data on waste and spent fuel.

The allocation of responsibilities for keeping an inventory is generally specified in the regulatory framework.

The national data collection system is organised in different ways according to the scale of the state's nuclear programme and the waste management system set up.

1 This category includes vitrified waste and spent fuel (SF).
2 Radioactive Waste and Spent Fuel Data Collection, Reporting, Record Keeping and Knowledge Transfer by EU Member States Final Report BS-Project No. 0707-03 Contract No. TREN/07/NUCL/S07.78807.
3 After publication of the study.

The following table shows national objectives regarding the creation of inventory databases for their radioactive waste. It shows that management of facility capacities (disposal volume available) constitutes one of the main concerns.

NATIONAL OBJECTIVES FOR INVENTORY DATABASES

Country	Political decision	Keeping the public informed	Management plan	Safety	Financial management	Technical management
Austria			X	X	X	X
Belgium	X	X	X			X
Bulgaria		X	X	X	X	X
Croatia	X	X	X	X	X	X
Cyprus	Non-public information					
Czech Republic	X	X	X	X	X	X
Denmark		X	X	X		X
Estonia	X		X			
Finland	"The main objectives of the database are: serve as a support to legislation on waste and associated inspections; provide ministers with a regular progress report; inform the public."					
France	X	X	X			
Germany	X	X	X		X	
Greece	Non-public information					
Hungary	X	X	X	X	X	X
Ireland						
Italy		X	X			
Latvia	X	X	X	X	X	X
Lithuania			X			X
Luxembourg						X
Macedonia		X	X	X	X	X
Malta	Non-public information					
Netherlands	Non-public information					
Poland	Non-public information					
Portugal	Non-public information					
Romania		X	X		X	X
Slovakia		X	X		X	X
Slovenia	X	X	X	X	X	X
Spain	X		X	X	X	X
Sweden	Non-public information					
Turkey	Non-public information					
United Kingdom	X	X	X			X

This inventory work within the European Commission was specified by the 2011 Directive described overleaf.

The following chapters present the work achieved on the theme of radioactive waste inventories by different international entities, specifically the IAEA and the European Union. The current trend is to harmonise schedules or use the same data in reports that the various countries must supply. This point is mentioned in the countries presented further.

EUROPEAN DIRECTIVE FOR THE RESPONSIBLE AND SAFE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE (2011/70/EURATOM)

BACKGROUND

In 2011, the EU Council adopted Directive 2011/70/Euratom, which establishes a community framework for the management of spent fuel and radioactive waste, from production to disposal. It thus supplements Euratom's legislative instruments, which did not yet cover this subject. It makes Member States and producers liable for the responsible and safe management of spent fuel and radioactive waste, and for the protection of persons and the environment from the dangers of ionising radiation.

It requires Member States to equip themselves with a legal framework for nuclear safety, with:

- a competent safety and monitoring authority, independent of the waste producers;
- licensees capable of demonstrating and maintaining the safety of their facilities in terms of the management of spent fuel and radioactive waste throughout their life.

It also obliges Member States to draw up a national programme for creating and implementing policy for the management of spent fuel and radioactive waste, including:

- general targets that the national policies of EU Member States must reach in terms of the management of spent fuel and radioactive waste;
- key deadlines in view of the targets to be reached for the national programmes;
- an inventory of all spent fuel and radioactive waste, and the estimates of future quantities, including those resulting from decommissioning, clearly indicating the location and amount of the radioactive waste and spent fuel in accordance with appropriate classification of the radioactive waste.

Moreover, Member States must:

- provide the necessary solutions for the management of spent fuel and radioactive waste;
- maintain adequate human resources;
- ensure the transparency of information and public participation;
- re-examine and regularly update their national programme to take developments and progress into account and to ensure that peer reviews are carried out;
- dispose of radioactive waste in the Member State where it was produced. However, the directive opens up the possibility for Member States of radioactive waste disposal in another country (Member State or, under certain conditions, a third-party state).

This directive came into force on 23 August 2011 and Member States had two years to transpose it into national law.

As one of its expectations, the directive notes that geological disposal represents the safest and most sustainable option as the end-point of high-level and intermediate-level long-lived waste management. In most countries, geological disposal has been selected as the long-term solution, following many studies examining various options.

EU Member States had to submit a report to the Commission on the implementation of the directive by 23 August 2015, and then once every three years, taking advantage of the reviews and reports written under the Joint Convention.

Finally, every three years, the European Commission is required to present the European Parliament and Council with:

- a progress report on implementation of the directive;
- an inventory of the spent fuel and radioactive waste present in the Community and forecasts for the future.

The first report was published in 2017[1].

1 European Commission report for the European Council and Parliament on progress in the implementation of Council Directive 2011/70/Euratom, an inventory of the radioactive waste and spent fuel present in the EU and future perspectives.

IMPLEMENTATION OF THE DIRECTIVE

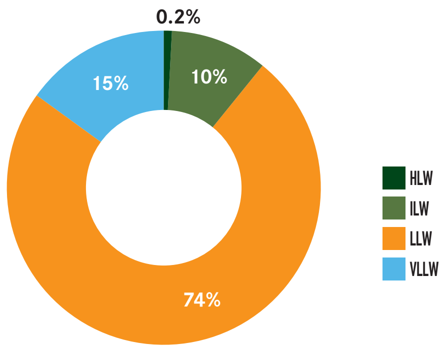
All EU Member States have now transposed the directive into national law and fulfilled their obligations: reports, national programmes or planned programmes. In 2017, on the basis of information available in these reports, the first European Commission report on application of the directive was submitted to the European Parliament and Council.

As mentioned above, this report[1] presents an inventory of radioactive waste and spent fuel in the European Union, and national policies and programmes with regard to the management of radioactive waste and spent fuel. The national frameworks and statutory background in all countries are also noted. The following diagram presents the consolidation, at the European level, of the volumes of radioactive waste and spent fuel.

CHANGES IN THE TOTAL QUANTITIES OF RADIOACTIVE WASTE AND SPENT FUEL OVER THE PERIOD 2004-2013[2]

Waste category	2004	2007	2010	2013
	Total volume (m³)			
VLLW	210,000	280,000	414,000	516,000
LLW	2,228,000	2,435,000	2,356,000	2,453,000
ILW	206,000	288,000	321,000	338,000
HLW	5,000	4,000	5,000	6,000
	Total mass (t)			
Spent fuel	38,100	44,900	53,300	54,300

DISTRIBUTION AMONG RADIOACTIVE WASTE CATEGORIES (END 2013)[2]



The report concludes on the subject of the support that the Commission will provide to Member States regarding the various aspects of the directive, in particular on the work that the Commission intends to perform to obtain an overview of the costs and funding of radioactive waste management. The Commission also undertakes to make a detailed analysis of the inventories of each country.

1 Report from the European Commission to the Council and Parliament, COM-2017 236 final.
2 Extract from the European inventory of radioactive waste and spent fuel. Source: COM-2017 236 final.

MONITORING CARRIED OUT BY THE INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)

The IAEA, a United Nations agency, publishes an international database called Net Enabled Waste Management Database (NEWMDB). This database is primarily an inventory of radioactive waste in various member countries. All data is updated on a regular basis and the trend is for harmonisation of presentation formats from one country to another.

Each country generally has its own radioactive waste classification and can transpose it into that of the IAEA, stipulated in the general safety guide GSG-1[1]. In the NEWMDB, waste quantities are given according to both national and international classifications, so the volumes can be summed and compared.

Moreover, the radioactive waste inventory volumes in each country can be drawn up in various ways: volumes of waste in raw, treated, conditioned, stored, or ready-for-disposal forms. However, the trend is towards harmonisation of reported volumes, which are increasingly given as ready-for-disposal volumes (conditioned equivalent volume).

Every three years, member countries publish a national report under the IAEA, within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The last conference took place in 2015 at IAEA headquarters in Vienna (Austria). A part of these reports is devoted to existing inventories of radioactive waste and spent fuel updated at the time of their publication.

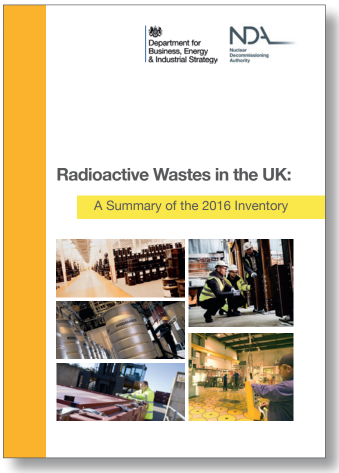
National reports published by Member States can be accessed from the IAEA website, if the Member State has authorised this. For the Sixth Review Meeting under the IAEA Joint Convention (May/June 2018), reports from the following countries were published:

- Argentina;
- Australia;
- Belgium;
- Brazil;
- Canada;
- Czech Republic;
- Denmark;
- Estonia;
- Euratom;
- Finland;
- France;
- Germany;
- Ireland;
- Japan;
- Lithuania;
- Norway;
- Russian Federation;
- Slovakia;
- Slovenia;
- South Korea;
- Spain;
- Sweden.
- United Arab Emirates;
- United Kingdom;
- USA;

1 IAEA Safety Standards series No. GSG-1, 2009.

A SELECTION OF NATIONAL INVENTORIES

UNITED KINGDOM



In the United Kingdom, a radioactive waste inventory is compiled every three years by the National Decommissioning Authority (NDA), in partnership with the Department of Energy and Climate Change (DECC).

The latest 2016 edition (published in March 2017) describes the status of existing waste on 1 April 2016 and presents all anticipated waste in the United Kingdom. All inventory documents are directly available on the dedicated website nda.gov.uk/ukinventory. This report, called 2016 UK Radioactive Waste & Materials Inventory (2016-UKRWMI), is made up of five documents:

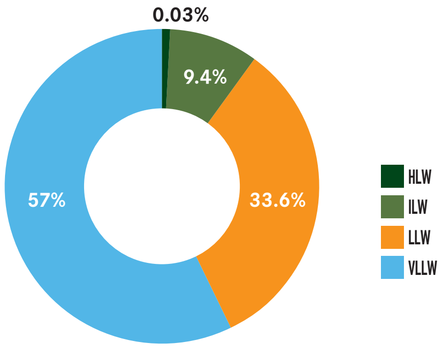
- Context and Methodology Report;
- A Summary of the 2016 Inventory;
- Radioactive Wastes and Materials not Reported in the 2016 Waste Inventory;
- Summary of Data for International Reporting;
- UK Radioactive Waste Inventory Report.

This set of documents includes information on the quantities, types, and characteristics of existing and future waste. Forecasts are based on assumptions regarding electricity production, decommissioning and choice of solution.

Except for the disposal facility for low- and intermediate-level short lived waste, the Low Level Waste Repository (LLWR) at Drigg (near Sellafield), no nuclear site lists radioactive waste other than that produced by the facility itself. The 2016 inventory lists 1,337 sites and waste management solutions that concern the activities of the nuclear industry, defence, and small producers. It counts the actual or forecast waste mainly located on the production site and not yet subject to final disposal.

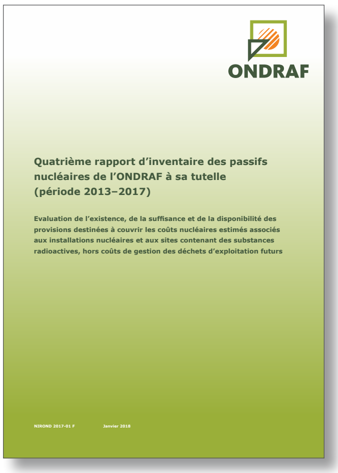
INVENTORY OF RADIOACTIVE WASTE IN THE UNITED KINGDOM[1]

Type	Total (m^3)
VLLW	2,720,000
LLW	1,600,000
ILW	449,000
HLW	1,500
Total	**4,770,000**



The summary UK inventory, intended for international publication, satisfies the needs for an inventory declaring radioactive waste to bodies such as the IAEA, the European Commission, and the NEA/OECD. It reviews the classification of both short-lived and long-lived waste in the United Kingdom.

BELGIUM



ONDRAF, the Belgian Agency for Radioactive Waste, is responsible for drawing up a two-part inventory: one part on the radioactive substances present on Belgian territory, and the other on "nuclear liabilities", which lists the various sites and producers of radioactive waste.

1 Source: Radioactive Wastes in the UK: A Summary of the 2016 Inventory.

This task was assigned to it by the Royal Order of 16 October 1991, and was extended to all sites and producers by the Act of 12 December 1997.

ONDRAF continually updates a quantitative and qualitative inventory of all present and forecast radioactive waste in Belgium, including unused fissile materials and future waste from the dismantling of nuclear facilities.

The inventory is published every five years, and the last one, which came out in 2018, covered the period 2013-2017.

It lists 608 sites with radioactive waste, radioactive materials obtained from dismantling, and nuclear materials. They are listed in three categories: I (nuclear power plants, former fuel cycle plants, research sites, etc.), II (laboratories, industrial sites, hospitals, teaching centres, etc.) and III (industrial sites and laboratories containing sealed sources). There is also one contaminated site and four special cases.

The inventory includes a forecast of waste volumes according to a scenario that assumes that all existing nuclear installations are dismantled and produce no more waste. This timeframe is highly dependent on the scenarios and management schedules considered: the management scenario for spent fuel, facility dismantling scenarios, disposal schedules, etc.

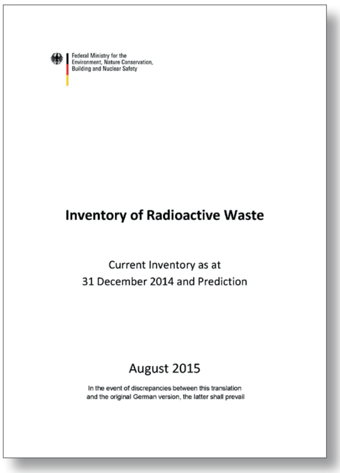
It includes non-nuclear sites containing radium-bearing waste from mineral processing (e.g. Olen plant), as well as facilities containing radioactive sources.

The inventory compiled in Belgium is intended to verify the availability of the financial resources necessary for waste producers to take all of their waste into account. The idea is to prevent the waste from becoming a liability, i.e. a burden on the community where resources are insufficient or absent. Following the 2013 edition, the 2018 edition of the Belgian inventory gives greater importance to assessment of financial resources, their associated provisions and their availability. The nuclear liability inventory task assigned to ONDRAF is defined by Article 9 of the Planning Act of 12 December 1997, (www.nirond.be) and involves:

- “drawing up a directory of the location and status of all nuclear facilities and all sites containing radioactive substances;
- estimating the associated decommissioning and cleanup costs;
- evaluating the availability and sufficiency of financial provisions for funding ongoing or future operations;
- updating this inventory every five years”.

The fourth inventory report has been published and is available on the ONDRAF/NIRAS website. A summary of the inventory is also available.

GERMANY


Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

Inventory of Radioactive Waste

Current Inventory as at
31 December 2014 and Prediction

August 2015

In the event of discrepancies between this translation and the original German version, the latter shall prevail

Since 1984, the Federal Office for Radiation Protection (BfS) has been responsible for collecting and updating the data in the radioactive waste inventory database. This data concerns the existing quantities and volumes as well as the forecasts for the next year, for each decade until 2080.

BfS conducted annual surveys with producers, by means of a questionnaire concerning the volumes of waste produced, treated and conditioned. This only concerned waste for disposal.

The 2016 reorganisation of the institutional framework for radioactive waste in Germany means that from now on the role of performing the inventory of radioactive waste is the responsibility of BGE, the federal company for radioactive waste disposal.

In Germany, waste likely to receive radiation protection clearance[1] is not counted in the inventory. This is mainly depleted uranium and uranium and plutonium from reprocessing used in the manufacture of fuel elements.

Recycled plutonium and uranium are, however, accounted for annually by the Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The present and future waste volumes are supplemented by chemical data stating the organic compositions of the waste and the inorganic hazardous substances in accordance with groundwater protection.

Forecasts for the production of radioactive waste are drawn up by the BfS according to a scenario modified by the 13th amendment of 6 August 2011 of the law on nuclear energy (Atomic Energy Act).

With this amendment, which was added following the events that took place in Japan in 2011, leading to a re-examination of the risks related to the use of nuclear power, eight operating permits for nuclear power stations were not renewed.

1 Pursuant to Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, Member States may implement clearance levels below which the materials in question are released from regulatory control. When the concept of clearance levels is used, national thresholds for a given radionuclide may either be universal (regardless of material, origin and destination) or dependent on the material, its origin and its destination.

The operating permits for remaining reactors will expire by 2022. The complete German National Radioactive Waste Inventory is not yet available to the public (not all aspects of its preparation are covered). It could constitute one of the sections of the future National Waste Management Programme, for which the future disposal site for exothermic waste remains to be defined. On the other hand, from a legal and regulatory standpoint, the decree of 2001 concerning radiation protection contains provisions concerning radioactive waste taken in application of the standards set forth in the Atomic Energy Act.

In accordance with that decree, the licensee is obliged to provide, in advance, annual forecasts of the quantity of radioactive waste that will result from its activities, and to describe their planned management and disposal. It must also draw up an inventory of radioactive waste in the forms specified in the appendix of that same decree.

The inventory of radioactive waste and spent fuel in Germany has therefore been regularly produced by the Federal Office for Radiation Protection (BfS), and the BGE since 2017. It is presented once every three years via the Federal Republic of Germany's report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste. This national report was published in 2014 in preparation for the fifth Review Meeting of the IAEA Joint Convention, in May 2015.

Finally, in connection with the National Waste Management Programme drawn up in response to Directive 2011/70/Euratom, information and data on the quantities of radioactive waste and spent fuel are presented to the European Commission.

SPAIN

ENRESA (Andra's Spanish counterpart) compiles and updates an inventory of radioactive waste produced in Spain, based on information supplied by waste producers. The first inventory studies were initiated in 1986, with the implementation of the first Spanish General Radioactive Waste Plan. Today, this information is compiled in a database used to produce a summary report.

Royal decree 102/2014 concerning the responsibility and safety of spent fuel and radioactive waste regulates the activities and funding of Enresa. This public body is responsible for drawing up an inventory of the radioactive waste in storage and disposal, as well as waste from dismantled or closed installations. In application of this decree, the *Plan General de Residuos Radiactivos* (Spanish General Radioactive Waste Plan, GRWP) includes an inventory of spent fuel and radioactive waste produced and to be produced, giving a precise indication of their quantities and locations according to a classification based on their final destination. The most recent Spanish GRWP dates from 2006. The report in application of Directive 2011/70/Euratom provides the latest data on the radioactive waste inventory. This report is the responsibility of the *Consejo de Seguridad Nuclear* (CSN, Spanish Nuclear Safety Council) but Enresa consolidates the data from waste producers.

The contract between the waste producers and Enresa requires producers to supply an initial inventory presenting the current situation at the time of signing the contract according to type and quantity of radioactive waste. In addition, the producer must provide the following information each year:

- five-year forecasts of operational radioactive waste to be produced, classified according to waste stream;
- ten-year forecasts of fuel;
- five-year forecasts of special and particular radioactive waste;
- inventory of waste produced in the previous year, by stream (operational, spent fuel, and special and particular waste);
- the timetable of upcoming facility closures.

A national database of radioactive waste and spent fuel is kept up to date by Enresa.

Its main objective is to contribute to the operational and strategic planning of waste management. This inventory is not published directly and publicly by Enresa. It is however described via the IAEA NEWMDB, and by the Spanish national report published for the Review Meetings under the IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste.

USA

Several systems for radioactive waste inventory and monitoring exist in the United States. They differ according to which body is responsible for regulating them:

- the Department of Energy (DOE) for the defence sector, under the aegis of the federal government;
- The Nuclear Regulatory Commission (NRC) for the commercial sector.

Disposal sites are often determined by the origin and nature of the waste.

The NRC draws up national inventories of spent fuel from the commercial sector and sealed sources.

For other categories of waste, there is no national inventory system that uniformly collects all the information from every facility and body (producers, brokers, processors or disposal managers).

However, the waste producers in the commercial power generation sector use a Manifest Information Management System to generate manifests when shipping waste to intermediaries. Radioactive waste is disposed of by both the DOE and private organisations. The disposal sites will ultimately be placed under the responsibility of the Federal or State governments. Spent fuel and high-level waste are currently stored.

Waste from several producers can thus be grouped before treatment and disposal. The operators of disposal facilities store the data throughout the lifetime of the facilities and arrange for it to be archived after closure.

The specifications of the inventories are defined by the laws of the states in which the disposal facilities are located, or the federal government.

The inventory must include a paper record of all waste, from the time it is produced and for as long as it remains at the disposal facility.

The NRC requires that waste producers in the private sector implement inventory systems for all waste at disposal sites.

For the defence sector, the DOE (www.em.doe.gov) also has its own specific inventory systems implemented on the sites and illustrated by the following examples:

- Solid Waste Information Tracking System (SWITS), used for solid waste, LILW and transuranic (TRU) waste stored at the Hanford site;
- Integrated Waste Tracking System (IWTS), implemented in the Idaho National Laboratory;
- Waste Isolation Pilot Plant (WIPP) Waste Information System (WWIS) which constitutes the inventory (transuranic waste) of the first geological disposal site in operation.

American inventories are often very comprehensive, covering all production that generates radioactive waste: mining waste, site cleanup activities, and so-called mixed low-level waste, containing both radioactivity and toxic chemical residue.

The information is generally freely accessible in the form of databases on the Internet, particularly the WIPP database used by the DOE.

In addition, the DOE prepares a summary of inventory data on nuclear facilities. This summary is published in the national report submitted to the International Atomic Energy Agency (IAEA) in accordance with the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. It is also updated in the database of the NEWMDB inventory operated by the IAEA. The American inventory published in this report lists the waste according to the DOE and NRC classifications. It includes mining residue and materials:

- the forecast inventory of spent fuel is updated annually. Spent fuel is not currently sent for disposal, but stored at the producers' facilities;
- the inventory of radioactive waste in disposal is published in summary and detailed by sector (DOE or NRC). Waste stored on the production sites is not listed in this inventory. It is covered in an operational and flow monitoring inventory drawn up by the operators.

SUMMARY TABLE OF INVENTORIES OF RADIOACTIVE WASTE ACCORDING TO SECTOR AND FACILITY (US 5TH NATIONAL REPORT FOR THE IAEA JOINT CONVENTION, SEPT. 2014)

Sector	Facility type	Type of waste	Number	Inventory	Unit
Government	Geologic Repository (WIPP)	TRU	1	9.10×10^4	m^3
	Greater Confinement Disposal (boreholes) at the Nevada National Security Site	TRU	1	2.00×10^2	m^3
	Surface disposal	LLW	18	1.51×10^7	m^3
				1.25×10^2	Reactor compartments
Commercial	Operating Near Surface Disposal	LLW (Class A, B, C)	4	4.63×10^6	m^3
		AEA Section 11e.(2)	1	1.40×10^6	m^3
	Closed Near Surface Disposal	LLW	4	4.38×10^5	m^3
Government/ Commercial	Title I UMTRCA Disposal	Residual Radioactive Material (tailings)	22	2.45×10^8	tonnes
Commercial	Title II UMTRCA Disposal	AEA Section 11e.(2)	44		
Government	Other disposal cells, after closure (Weldon Spring Site and Monticello)	Residual Radioactive Material (tailings)	2	3.03×10^6	m^3

CANADA

Canada publishes a three-yearly inventory specifying the location of radioactive waste and draws up a status report on production and the quantities accumulated. It also provides forecasts of waste production quantities until the end of life of the current reactor fleet, planned for 2050.

INVENTORY OF RADIOACTIVE WASTE IN CANADA[1]

Category	Inventory end of 2013	Inventory end of 2050
High-level waste (HLW, spent fuel)	10,021 m^3	20,660 m^3
Intermediate-level waste (ILW)	34,770 m^3	67,738 m^3
Low-level waste (LLW)	2,352,672 m^3	2,499,803 m^3
Uranium processing waste	216,000,000 tonnes	Unavailable

The data for the inventory of radioactive waste comes from several sources, especially the Nuclear Waste Management Organisation (NWMO/SGDN) in charge of drawing up the inventory of spent fuel.

The data comes from regulatory documents, reports, and bulletins supplied by the regulatory body, waste producers, and waste management facilities. Regulatory documents include annual or quarterly compliance reports, annual safety inspections, and decommissioning reports submitted to the Canadian Nuclear Safety Commission (CNSC).

Finally, every licensee must create and implement an accounting system that covers radioactive waste and spent fuel. This system and the resulting records are subject to regulatory monitoring.

Radioactive waste is presented according to three categories corresponding to the different waste management policies implemented in Canada:

- nuclear fuel waste;
- low-level and intermediate-level waste;
- waste from ore extraction and uranium concentration.

The first category concerns the fuel clusters of CANDU-type reactors. The second category is divided into common waste resulting from the operation and dismantling of facilities, and legacy waste resulting from past activities (e.g. Port Hope radium refinery). Finally, Canada lists the uranium processing waste in currently operating, inactive or decommissioned sites.

The inventory is compiled by the Historic Waste Program Management Office (HWPMO). This body is also responsible for current and legacy waste management programmes. The Office is administered by Atomic Energy of Canada Limited (AECL) on behalf of the Ministry of Natural Resources.

Four inventories were published between 2009 and 2012. One edition was published in 2014 by Canadian Nuclear Laboratories (CNL) on behalf of the HWPMO. Some of this information was taken from the fifth Canadian report for the IAEA Joint Convention.

Canada has been producing radioactive waste since the early 1930s, when the first uranium mine started operations in Port Radium, Northwest Territories. Radium was refined for medical purposes, and later, uranium was processed in Port Hope, Ontario. Research and development activities on the use of nuclear energy in electricity production began in the 1940s at the Chalk River Laboratories (CRL) of Atomic Energy Canada Limited (AECL). Today, the radioactive waste generated in Canada comes from uranium mines and concentration plants, refineries and conversion plants, nuclear fuel manufacture, the operation of nuclear reactors for power generation, nuclear research, and the production and use of radioisotopes.

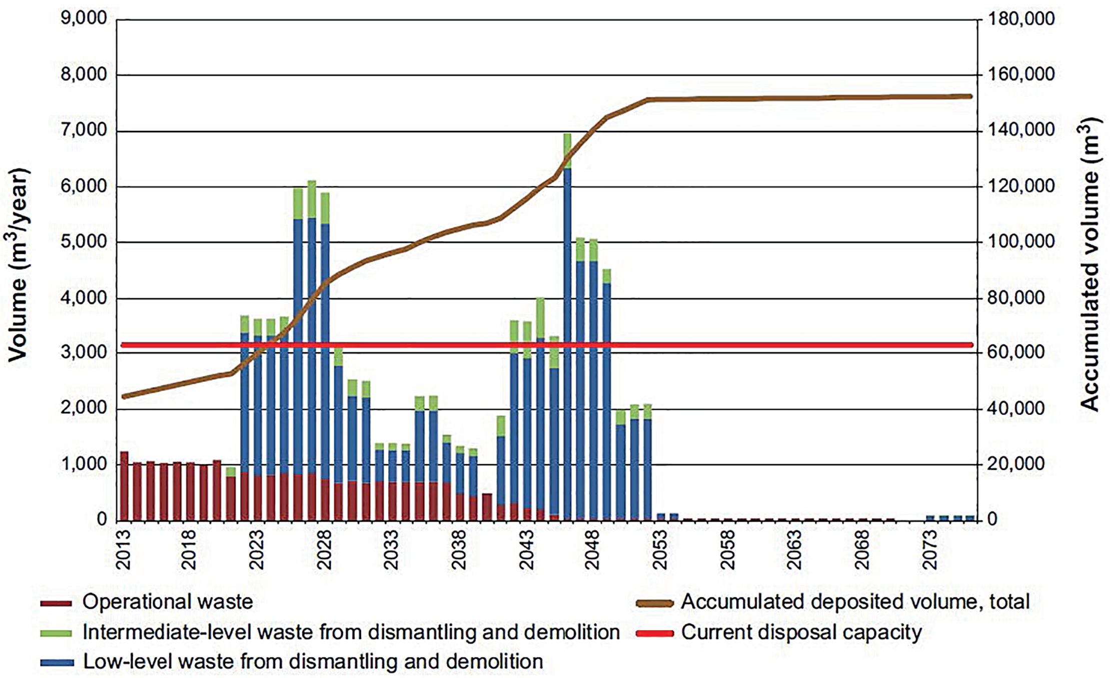
1 Source: Inventory Summary Report, CNL, 2013.

SWEDEN

In 2007, during an assessment of environmental objectives, the Swedish radiation protection authority of the time concluded that with regard to radiation from radioactive substances, the management and elimination of all radioactive waste should be the highest priority. It proposed that a new objective be entitled: “By 2020, there will be solutions for the safe management and elimination of all radioactive waste”. To meet this objective, the authority suggested that a National Management Plan be established for all radioactive waste. The government then tasked the Swedish radiation protection authority with drawing up the first Swedish Management Plan for all radioactive waste by 30 June 2009.

This document, of which the inventory is only one part, was then replaced by the national report under European Directive 2011/70/Euratom, in line with the report for the IAEA Joint Convention. The latest edition of this report was published in 2015.

There is no legally defined system of waste classification in Sweden for radioactive waste. However, there is a waste classification system established by the Swedish nuclear industry. In the 2015 report, therefore, there is a comparison between the various Swedish, EU and IAEA classifications. The classification scheme used in Sweden is based on existing and future waste management solutions (permanent disposal). For example, LILW-SL is disposed of in underground galleries in a granite mountain range: this disposal site, called SFR, is located 50 metres below the Baltic Sea and includes four 160-m-long rocky vaults and a chamber in the rocky substrate with a 50-m-high concrete silo for the most radioactive waste. The diagram below shows the development of disposal needs associated with the SFR, given that the current SFR disposal capacity is 63,000 m^3 [1].



Forecast of volumes of short-lived waste from dismantling and demolition to SFR. The volume per year can be seen on the left-hand axis. The brown curve shows the accumulated volume of waste and can be read on the right-hand axis (total about 155,000 m^3). Accumulated volume can be compared with current disposal capacity (red line, total 63,000 m^3).

1 skb.com.

06

APPENDICES & GLOSSARY

APPENDIX

01

Methodology used for the National Inventory

NATIONAL INVENTORY PRINCIPLES

REGULATIONS

Article L. 542-12 of the French Environmental Code assigns Andra the task of “establishing, updating every three years and publishing the inventory of radioactive materials and waste found in France or planned to be disposed of there, along with their locations”.

Articles R.542-67 to R.542-72 of the French Environmental Code and the Ministerial Order of 9 October 2008[1], as amended by the Ministerial Orders of 4 April 2014 and 16 March 2017[2], define the obligations of those producing and possessing radioactive materials and waste regarding declarations.

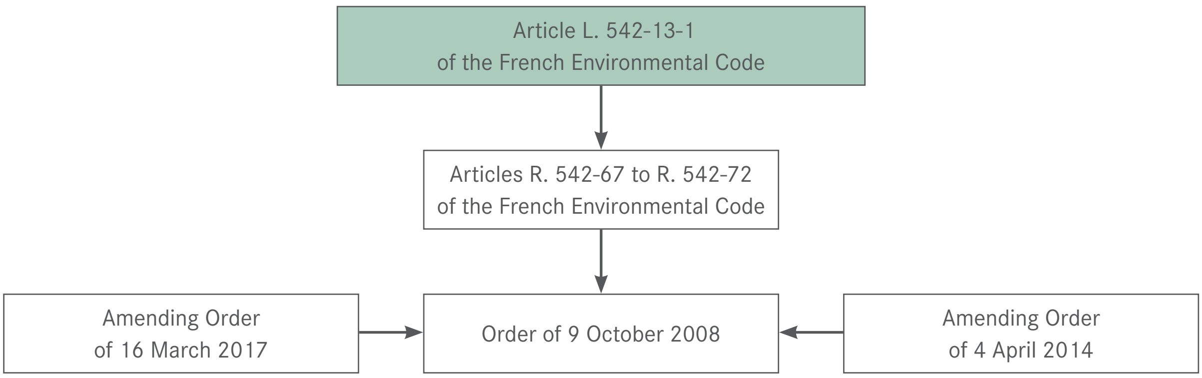
For the 2018 edition of the National Inventory, the existing waste stocks are as of the end of 2016, forecasts are as of the end of 2030, end of 2040 and at term, meaning completion of dismantling of nuclear facilities authorised as of the end of 2016.

ARTICLE 7 OF THE ORDER OF 9 OCTOBER 2008, AS AMENDED, SETS THE REFERENCE DATES FOR THIS AND FUTURE EDITIONS

Edition	Stock date	Forecast dates	
2018	31/12/2016	End of 2030	End of 2040
2021	31/12/2019	End of 2030	End of 2040
2024	31/12/2022	End of 2030	End of 2040
2027	31/12/2025	End of 2040	End of 2050
2030	31/12/2028	End of 2040	End of 2050

Only waste from the operation and dismantling of existing or authorised facilities as of the end of 2016 is covered in the National Inventory. Operation of a nuclear facility includes its service life and its dismantling phase.

REGULATIONS THAT APPLY TO THE NATIONAL INVENTORY



1 Order of 9 October 2008 on the type of information that those responsible for nuclear activities and the companies identified under Article L. 1333-10 of the French Public Health Code are required to collate, update and periodically submit to Andra.

2 Orders of 4 April 2014 and 16 March 2017 amending the Order of 9 October 2008 on the type of information that those responsible for nuclear activities and the companies identified under Article L.1333-10 of the French Public Health Code are required to collate, update and periodically submit to Andra.

PRINCIPLES

Compilation of the National Inventory of Radioactive Materials and Waste is based on strict methodology and meticulous data verification procedures.

There are several objectives:

- inventory the radioactive materials and waste held by each producer or other entities in France, including waste from other countries that will be returned to foreign customers. Andra has performed this survey since 1992. Originally based on voluntary declarations by waste producers and holders, since 2008, this work is now performed under the statutory framework described above;
- prepare an overview of current and future radioactive materials and waste in accordance with various different scenarios with some having snapshots of stock as of key dates defined by ministerial order as well as at term, meaning the end of dismantling of all nuclear facilities.

RADIOACTIVE MATERIALS AND WASTE IN FRANCE

The National Inventory accounts for all radioactive materials and waste found in France. It thus takes into account radioactive materials and waste resulting from the reprocessing of fuel from abroad, even though they will be returned to the countries of origin.

Operators of nuclear facilities that perform reprocessing operations on behalf of customers in other countries publish an annual report that lists all radioactive materials and waste that belong to customers in other countries in compliance with Article L. 542-2-1 of the Environmental Code.

Five principles have guided the preparation of the National Inventory to ensure its reliability, quality and suitability for use as a reference:

- **availability of information:** the duty to inform citizens is fulfilled by providing data that can be understood by a broad readership.
  At the same time, the aim is to help authorities prepare the National Radioactive Materials and Waste Management Plan by providing them with a realistic inventory that reflects the waste producers' best estimates at the time of the declarations;
- **exhaustiveness:** the National Inventory provides a survey not only of existing waste resulting from recent and current activities, but also of that produced since the earliest applications of the properties of radioactivity for industrial, military, medical and research purposes. The aim is to present a "snapshot" of all waste found in France at a given time regardless of its physical or chemical, conditioning, or liquid or solid state, or high or low level of activity. The scope of the survey is not restricted to waste disposal or storage facilities. It also covers all installations that contain waste - even temporarily - due to be managed by Andra, for example medical research or university laboratories. It also includes radioactive materials;
- **neutrality:** the National Inventory transcribes the collected data in a factual manner without assessing the level of risk associated with the situations and management methods described;
- **transparency:** the National Inventory provides an overview of radioactive materials and waste, regardless of source. This approach seeks to complement the efforts to increase transparency in recent years undertaken by public authorities, waste producers and the French Nuclear Safety Authority (ASN)[1].
  To comply with this principle a steering committee (see "stakeholders" overleaf), chaired by Andra's Chief Executive Officer and composed of members from outside Andra, oversees preparation of the National Inventory;
- **responsibility of those declaring and checking of management solutions by Andra:** the National Inventory reproduces the data given in the declarations submitted by waste producers. Each producer is therefore responsible for the declaration it submits. If necessary, Article R.542-71 of the Environmental Code entitles Andra to inform the appropriate authorities should a waste producer or holder fail to fulfil its obligations regarding declarations. Furthermore, Andra checks whether the waste management solution proposed by the producer is suitable. The obligations of waste producers and holders regarding declarations do not release Andra from its duty to ensure that the inventory is exhaustive by cross-checking various sources of information, including scrutiny of national and local media. When the presence of radioactive waste has been proven on sites that are not yet listed, the sites in question are incorporated into the National Inventory at the next update.

1 Act 2006-686 of 13 June 2006 on Transparency and Security in the Nuclear Field.

The management solution proposed in the National Inventory does not guarantee that the waste will be accepted at the corresponding waste disposal facility.

The National Inventory presents all waste, whether or not it has already been conditioned; assumptions about conditioning methods must also be made to quantify waste volumes. This corresponds to producers' best understanding at time of declaration, without prejudice to the conditioning that may actually be implemented.

STAKEHOLDERS

Since 2008, waste producers and holders have made the vast majority of declarations via the Internet. The procedures for verifying declared data depend on the type of producer:

- **major entities in the nuclear industry** (Andra, Orano, CEA, EDF) that manage several sites.
  Each site appoints "officers" who are well-acquainted with stocks and complete the declaration forms (declarants). The declarations are then verified and validated by a supervisor from each organisation (declaring supervisor). Forecasts are declared directly by supervisors;
- **producers from outside the nuclear power industry** produce smaller amounts of radioactive waste. Each nuclear activity manager submits a declaration directly without supervisor validation.
  Andra verifies all data in the declaration comparing it with the previous declaration, checking for consistency, cross-checking with any other available sources and examining the proposed waste management solution, etc.
  Once analysed, Andra validates the declarations after any necessary communication with the producer and corrections;
- **The Steering Committee** for the National Inventory was created with regard to transparency and effectiveness. It offers the opportunity to develop a consensus on the inventory. The Steering Committee's main mission is to validate the assumptions needed for performing the National Inventory and the main conclusions resulting from analysis of the declarations before they are made public. It must also ensure that the data is made available to the public with the greatest possible transparency.

In addition, in compliance with the requirements of the 2016-2018 National Radioactive Materials and Waste Management Plan (PNGMDR), each year Andra presents the plan's working group with an update on the quantities of materials or waste in disposal facilities or storage based on producers' annual declarations.

"Producers from outside the nuclear power industry" are radioactive waste producers or holders from the medical sector, research (excluding CEA) and industry (apart from nuclear power). These are mainly producers covered by Article R. 542-68 of the French Environmental Code.

COMPOSITION OF THE NATIONAL INVENTORY STEERING COMMITTEE

Membership of the Committee is as follows:

- representatives of relevant ministries (environment and energy);
- representatives of the Nuclear Safety Authorities (ASN and ASND);
- representatives of the French National Radioactive Waste Management Agency (Andra);
- representatives of the main waste producers (both nuclear and non-nuclear power sectors);
- a representative of the National Assessment Board (CNE) with observer status;
- representatives of civil society and environmental protection organisations as well as local information commissions (CLI).

DOCUMENTS PROVIDING DATA

In view of its knowledge of waste, production sites and management solutions, Andra is ideally suited for the inventory and survey tasks entrusted to it under the French Environmental Code. The information it gathers is correlated with the various other sources to which it has access.

This information is provided in either a physical document or in a Web version on the site inventaire.andra.fr:

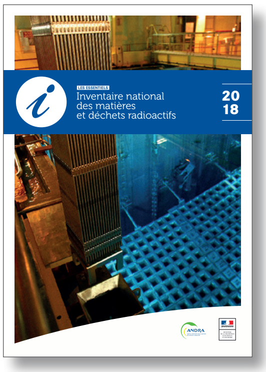
- a physical document and Web version for:
  - this *Synthesis Report*,
  - *Essentials;*
- a Web version for:
  - *the Geographical Inventory,*
  - *the Catalogue of Waste Streams,*
  - open data files.

The new digital tool developed on the National Inventory website can be used to view the *Catalogue of Waste Streams* and the *Geographical Inventory* online. Filters are available for the production of personalised documents and these or all documents offered can be printed.

SYNTHESIS REPORT

This document provides a detailed description of all current and future radioactive materials and waste found in France. Quantities are grouped by category and economic sector.

The quantitative section is supplemented by special reports which focus on themes such as waste treatment and conditioning or dismantling and cleanup of facilities.



ESSENTIALS

The *Essentials 2018* document gives a summary of the main figures from the 2018 National Inventory.

L'INVENTAIRE GÉOGRAPHIQUE [GEOGRAPHICAL INVENTORY]

The *Geographical Inventory* reproduces the declarations of producers. It presents each site by administrative region, *département* and municipality. It also inventories Andra's repositories, national defence facilities, producers from outside the nuclear power industry and legacy sites. These legacy sites include mining sites and legacy disposal facilities.

Information is given as facts in geographically-based reports. These reports provide data on the radionuclides present, waste volume (when available) and management solutions.

The waste category as defined in Chapter 1 is given, in addition to the waste stream to which it belongs (as described in the *Catalogue of Waste Streams*). Each type of waste found on the site is noted, along with its activity and the volume after conditioning.

LE CATALOGUE DESCRIPTIF DES FAMILLES [CATALOGUE OF WASTE STREAMS]

The survey conducted along the lines of the principles described earlier leads to a large quantity of waste being declared. For the sake of simplicity and presentation, the waste has been assigned to families known as “waste streams” (defined as a group of radioactive waste that has similar characteristics). A detailed description of each radioactive waste stream in the National Inventory can be found in the *Catalogue of Waste Streams*.

The *Catalogue of Waste Streams* has a report for each waste stream that presents the stocks as of the end of 2016, specifying the fraction on the producer’s or holder’s site or in Andra disposal facilities, the total activity of the waste declared by producers and holders at the date of the inventory (31 December 2016) and forecasts for production as of the end 2030 and the end of 2040.

These forecasts are based on Scenario SR1 for the renewal of the nuclear power fleet with EPR and FNR reactors with an operating period of between 50 and 60 years for current reactors.

IS THE NATIONAL INVENTORY REALLY EXHAUSTIVE?

Successive updates of surveys since 1993 have provided fuller and more detailed knowledge in each sector concerning the location of waste and some of its characteristics, as the producers themselves have improved their knowledge of their waste.

The issue of exhaustiveness arises at two levels: the location of sites where radioactive waste is present, and the quantities and category of the waste described at surveyed sites.

A producer may overlook some waste when making a declaration. However, as the major producers also declare their waste stocks to the French Nuclear Safety Authority (ASN), there is little risk that anything will be omitted. The two declarations are generally compared by the producer or drawn up together. In addition, the French Nuclear Safety Authority (ASN) carries out regular on-site checks of declarations.

In the case of Orano, waste stocks are also audited by a body commissioned by its customers.

From one edition to the next, some facilities may no longer be included in the survey because they no longer contain radioactive waste (e.g. dismantled and cleaned-up facilities). Conversely, there may be new waste-producing facilities.

The fact that declarations have been statutory since 2008 has led to improved comprehensiveness of declared data for this edition of the National Inventory. Furthermore, in response to incidents at the Tricastin site in south-east France in the summer of 2008, the Minister for the Ecological and Inclusive Transition (formerly Minister for Ecology, Energy, Sustainable Development and Town and Country Planning) asked the High Committee for Transparency and Information on Nuclear Safety (HCTISN) for recommendations. As a result, more detailed information concerning certain legacy sites has been provided in the National Inventory. However, there may be potential holders of radioactive waste that have never approached Andra.

As seen in Chapter 01, the very notion of “radioactive waste” is subject to interpretation for certain types of waste with very low levels of radioactivity.

APPENDIX

02

Activity of radioactive waste

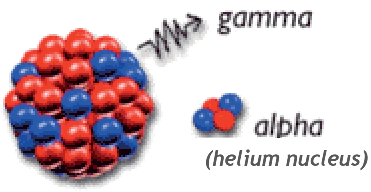
RADIOACTIVITY

In nature, most atoms (that constitute matter) have stable nuclei. Others have unstable nuclei: they have excess particles (protons, neutrons or both) that cause them to transform (by decay) into other nuclei (stable or unstable). They are said to be radioactive, since during transformation they emit radiation whose nature and properties vary.

RADIATION

There are three types of radiation, corresponding to three forms of radioactivity:

- α **radiation:** emission of a helium nucleus (composed of 2 protons and 2 neutrons) also known as an "α particle", which travels only a few centimetres in air and can be stopped by a sheet of paper;



- β **radiation:** transformation of a neutron into a proton accompanied by the emission of an electron. Aluminium foil or a pane of ordinary glass will stop electrons;

- γ **radiation:** emission of electromagnetic radiation, of the same nature as visible light and X-rays, but with much more energy. It is therefore more penetrating. Several centimetres of lead or tens of centimetres of concrete are required to stop them.

ACTIVITY LEVEL AND LIFETIME

Radionuclides are radioactive atoms that decay and emit radiation, which is the origin of the phenomenon of radioactivity. Certain radionuclides are highly radioactive (several billion billion becquerels), while others have low activity (measured in thousandths of becquerels).

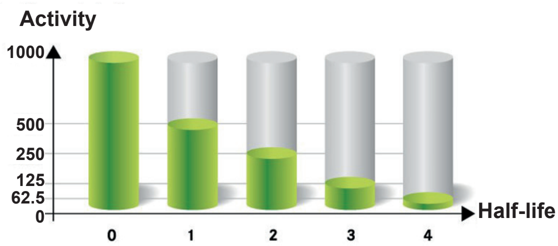
In addition, the lifetime of radionuclides (period during which they emit radiation) varies greatly from one radionuclide to another. The radioactive half-life is the time required for one-half of the atomic nuclei of a radionuclide to decay. The activity of a sample containing atoms of only this radionuclide is thus divided by two after one half-life. After 10 such half-lives, the activity would be divided by a factor of 1,000.

The half-life may range for example from a fraction of a second for polonium-214 to 4.5 billion years for uranium-238.

The radioactive half-life of a radionuclide has an inverse relationship to activity: the longer the half-life, the lower the activity. The following table gives examples of activities for 1 gram samples (iodine-131, caesium-137, plutonium-239 and uranium-238).

EXAMPLES OF THE RELATIONSHIP BETWEEN HALF-LIFE AND ACTIVITY

Radionuclide	Half-life	Specific activity
Iodine-131	8 days	4.6×10^{15} Bq/g
Caesium-137	30 years	3.2×10^{9} Bq/g
Plutonium-239	24,113 years	2.3×10^{6} Bq/g
Uranium-238	4.5 billion years	12,400 Bq/g



Radioactive decay curve: the activity is divided by four after two half-lives, by eight after three half-lives, etc.

In nuclear physics, activity is often expressed with respect to volume (activity concentration in Bq/l or Bq/m^3), mass (specific activity in Bq/g) or surface area (surface activity in Bq/cm^2). Specific activity is the number of decays of a radioactive substance per unit of time and unit of mass. In the Catalogue of Waste Streams, *it is expressed in becquerels per gram of finished package.*

MEASUREMENT OF RADIOACTIVITY

Our senses do not perceive radiation from radioactivity. It is measured by quantifying its effects.
The methods employed use the track that radiation leaves in the matter it has penetrated. Detectors currently in use are based on various designs (counters containing a gas, scintillators or semiconductors) but all rely on the same principle: they convert photons or electrons created by radiation into an electric signal to count the number of decays.

Units of measure for radioactivity

The becquerel and gray are units of measure for radioactivity and its energy. The sievert is a unit for measuring effects.

- **Becquerel (Bq)**
  Measures the level of radioactivity, or activity. It corresponds to the number of atoms that decay per unit of time (second).

  The previous unit was the curie (Ci): 1 Ci = 3.7x10^{10} Bq, named for the discoverers of radium, Pierre and Marie Curie.

- **Gray (Gy)**
  Measures the quantity of energy absorbed (absorbed dose) by matter (organism or object) exposed to ionising radiation. 1 gray corresponds to an energy absorbed of 1 joule per kilo of matter.

  The previous unit was the rad: 1 Gy = 100 rad.

- **Sievert (Sv)**
  The sievert is used to assess the biological effect of naturally occurring or artificial radiation on people by type of radiation.

  The previous unit was the rem: 1 Sv = 100 rem.

Radiological monitoring: radiation measurement on a waste package

MAIN QUANTITIES MEASURED

Quantity measured	Definition	Units
Activity	Number of decays per second	becquerel (Bq)
Absorbed dose	Quantity of energy transferred to matter	gray (Gy)
Effective dose	Effects of radiation on the organism	sievert (Sv)

Although the becquerel is an extremely small unit, current measurement devices are often sensitive enough to detect this level of activity under optimal conditions. In addition, activity is measured instantly using portable devices, provided that the device is suited to the radiation that is actually present.

HOW IS THE ACTIVITY OF WASTE PACKAGES MEASURED?

Each decay is accompanied by the emission of radiation (gamma) or particles (alpha, beta, neutron). Since their energy is characteristic of the decayed nucleus, it is necessary to measure this radiation (intensity and energy) using suitable, correctly calibrated instruments in order to assess the activity of waste and quantify the various radionuclides.

Measurements are taken using spectrometry on packages and/or samples.

Certain radionuclides are, however, difficult to measure due to their low quantity or low energy radiation. In this case, correlation factors are established between the activity of these radionuclides and that of a more easily measured radionuclide used as a tracer.

This makes it possible to assess the distribution of the activity of the various radionuclides in the waste (radiological spectrum).

Usually, the producer evaluates the activity of the waste during production or conditioning.

GLOSSARY AND ABBREVIATIONS

	Terms	Definitions
A	**Actinide**	Natural or artificial radionuclide with an atomic number between 89 (actinium) and 103 (lawrencium). For certain authorities, the actinide series begins with element 90 (thorium).
	Activation product	Nuclides formed by neutron irradiation of a material.
	Activity	Number of nuclear isomeric decays or transitions produced per time unit in a radioactive substance. The unit of activity is the becquerel.
B	**Back end of fuel cycle**	Nuclear fuel cycle operations after use in the reactor, from spent fuel reprocessing to radioactive waste disposal.
	Baddeleyite	Rare natural zirconium oxide mineral (ZrO_2).
	Becquerel (Bq)	International System of Units (SI) measurement unit for activity. Corresponds to the activity of a quantity of radioactive nuclides for which the mean number of nuclear isomeric decays or transitions per second is equal to 1 (1 Bq = 1 s^{-1}). This unit replaces the curie (1 Ci = 3.7×10^{10} Bq). Multiples are typically used: megabecquerel (MBq, one million becquerels, 10^6 Bq), the gigabecquerel (GBq, one billion, 10^9 Bq), the terabecquerel (TBq, one thousand billion, 10^{12} Bq), the petabecquerel (PBq, one million billion, 10^{15} Bq) or the exabecquerel (EBq, one billion billion, 10^{18} Bq).
	Bituminised sludge	Sludge resulting from coprecipitation operations in liquid radioactive effluent treatment plants and conditioned in bitumen.
	Burnup fraction	Total energy released per unit mass of a nuclear fuel. It is currently expressed as gigawatts-day per tonne of heavy metal (GWd/t).
C	**Cigeo**	Industrial Centre for Geological Disposal.
	Cires	Industrial facility for grouping, storage and disposal.
	CNE	National Assessment Board.
	Conditioned equivalent volume	This is the unit used to prepare the statements. It allows waste to be accounted for using a single, common unit. Forecasts also use the unit of “conditioned equivalent volume”. For waste for which the conditioning is not yet known, assumptions are performed to assess the conditioned equivalent volume. In the specific case of deep geological disposal, additional disposal packaging may be necessary for handling, safety or retrievability purposes. Only the volume of primary packages is indicated in this document.
	Conditioning matrix	Solid material used to immobilise or confine radioactive waste, or simply to improve the mechanical crushing resistance of waste packages.
	Confinement (of radioactive materials)	Retaining radioactive waste in a predetermined area using a set of devices (barriers) aimed at preventing the dispersal of unacceptable quantities of radioactive material outside this area.
	Container	In the nuclear industry, a term referring to a movable sealed vessel used for transport, storage and disposal operations.
	Contaminated site	In a radioactive contamination context, term used to describe an area or site significantly contaminated by natural or artificial radioactive substances.
	Contamination (radioactive)	Unwanted presence of significant quantities of radioactive substances on the surface or within any environment.
	CSA	Aube disposal facility for LILW-SL.

	Terms	Definitions
C	**CSD-C**	Standard container for compacted waste.
	CSD-V	Standard container for vitrified waste.
	CSM	Manche disposal facility. The Manche disposal facility has been in what is now officially called the closure phase (formerly called the monitoring phase, a preparatory phase for the start of the post-closure monitoring phase which occurs once all closure provisions have been completed) since January 2003 (Decree 2003-30 dated 10 January 2003), although this phase effectively started in 1997 after the end of closure operations.
	CWDF	Conventional waste disposal facility.
D	***Département***	In the administrative divisions of France, the *département* is one of the three levels of government below the national level, between the administrative regions and the *commune*.
	Dismantling	Technical operations performed to dismantle and possibly scrap nuclear equipment or part of a nuclear facility. In French regulations, term referring to the demolition phase of a nuclear facility, comprising all operations after the decommissioning order.
	Disposal package	Additional container into which one or more radioactive waste packages may be placed for disposal at a specific facility. This additional packaging is required for handling, safety or retrievability functions.
E	**Enriched recycled uranium (ERU)**	Enriched uranium obtained through enrichment of uranium from fuel reprocessing.
	ENU fuel	Enriched natural uranium (ENU) fuel made from uranium oxide. The uranium concentration in enriched natural uranium can range from 3.25% to 4.5%, and the mean burnup fraction can range from 33 GWd/t to 55 GWd/t
	ERU fuel	Fuel made from reprocessed uranium.
F	**Fast neutron reactor (FNR)**	Nuclear reactor in which the presence of materials potentially causing neutron slowdown is limited, thereby allowing fission reactions to be mainly produced by fast neutrons.
	Fissile	Term used to describe a nucleus that is capable of undergoing fission through interaction with neutrons in all energy ranges, including thermal neutrons. Actinide nuclei with odd neutron numbers are either fissile (^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu, etc.) or short-lived ß emitters (^{237}U, ^{243}Pu, ^{244}Am, etc.). In the case of the latter, the probability of neutron-induced fission is negligible, even at high flux. Term used to describe a substance containing one or more fissile nuclides. In such cases, the term “fissile material” is used.
	Fission product	Nuclides resulting from the fission of a fissile element (nucleus): each nucleus of fissile material subject to nuclear fission splits into two (and occasionally three) parts, which stabilise as new atoms. When leaving the nuclear reactor, most of these fission products (approx. 95% by mass) are stable (approx. 85%) or have short half-lives (approx. 10%). A few (approx. 5%), for example ^{99}Tc and ^{129}I, have long half-lives.
	FNR fuel	Plutonium and uranium mixed oxide fuel (MOX) for fast neutron reactors (Superphénix, Phénix). Fuel for the Superphénix reactor are made of approximately 80% (natural or depleted) uranium and 20% plutonium.
	Front end of fuel cycle	Nuclear fuel cycle operations from mining to fuel fabrication.
	Fuel (nuclear fuel)	Substance containing nuclides that are consumed by fission in a nuclear reactor to sustain a nuclear chain reaction.

	Terms	Definitions
	Fuel assembly	Group of fuel elements that remain attached to each other, particularly during reactor core refuelling operations.
	Fuel rod	Small diameter tube, sealed at both ends, containing fuel pellets.
G	**Gas-cooled graphite-moderated reactor (GCR)**	First generation nuclear fission reactor using natural uranium as fuel, graphite as moderator and carbon dioxide gas as coolant.
	Glove box	A glove box is a confinement structure which completely isolates a process using a transparent wall (special material that filters part of the radiation). Gloves are installed in the wall to allow safe handling of radioactive materials. The device generally includes ventilation that keeps the box at a negative pressure in relation to the exterior, thus confining the radioactive materials inside.
	Graphite waste	In France this is a category for waste containing graphite components (pile sleeves and bricks) from the operation and decommissioning of GCRs (approximately 20,000 tonnes). This graphite contains tritium and long-lived isotopes (carbon-14, chlorine-36).
H	**HCTISN**	French High Committee for Transparency and Information on Nuclear Safety.
	Heavy metal	In the field of nuclear fuel, term generally referring to all actinides. In practice, it is mainly used for uranium, plutonium and thorium.
	HLW	High-level waste mainly comes from spent fuel after reprocessing. The activity level of this waste is around several billion becquerels per gram.
	Hulls and end caps	Radioactive waste comprising fuel assembly hulls and end caps once the rods have been sheared up and the fuel has been chemically dissolved.
I	**IAEA**	International Atomic Energy Agency (iaea.org).
	ICPE	Environmentally regulated facility
	ILW-LL	Intermediate-level long-lived waste comes primarily from spent fuel reprocessing. The activity of this waste is from around one million to one billion becquerels per gram.
	Industrial volume	This volume corresponds to the volume of water displaced by submersion of a waste package.
	Isotope	Any nuclide of a given element. All the nuclides of a single element.
L	**LILW-SL**	Low- and intermediate-level short-lived waste mainly comes from the operation and dismantling of nuclear facilities, fuel cycle installations, research centres, and a very small part from biomedical research activities. The activity level of this waste is generally in the range of a few hundred to one million becquerels per gram.
	LLW-LL	Low-level long-lived waste is mainly graphite waste from GCRs and radium-bearing waste. Graphite waste has an activity level of between 10,000 and a few hundred thousand becquerels per gram. Radium-bearing waste has an activity level between a few tens of becquerels per gram and a few thousand becquerels per gram.
	Long-lived waste	Radioactive waste in which the main radioactive components are radionuclides with a radioactive half-life greater than 31 years.

	Terms	Definitions
M	**“Marked” site**	Site exhibiting traces of natural or artificial radionuclides that can be detected without necessarily requiring any specific action.
	Metastable	State in which an atomic nucleus is “stuck” in an excited state (at an energy level higher than its fundamental state) for a certain period of time, from several billionths of a second to several billion years.
	Minor actinide	Common term referring to neptunium, americium or curium formed during nuclear combustion.
	Moderator	Material made of light nuclei which slow down neutrons by elastic diffusion. Moderators are used in slow neutron nuclear reactors to increase the probability of neutron interaction with the heavy nuclei of the fuel. The moderator should not capture neutrons, causing them to be ‘wasted’, and be sufficiently dense to ensure effective slowing down.
	MOX fuel	Uranium and plutonium mixed oxide fuel. The MOX used in PWR power plants is made of depleted uranium and of plutonium with a mean concentration of 8.65% and a maximum value of 9.5%.
N	**NORM waste**	Waste containing naturally occurring radioactive material (NORM) is generated by the use or processing of raw materials that contain naturally occurring radionuclides but are not used for their radioactive properties. Such waste may require special management.
	Nuclear fission	Decay of a heavy nucleus, generally by splitting into two nuclei with atomic masses ranging from 70 to 170.
	Nuclide	Nuclear species characterised by its atomic number Z and its mass number A, equal to the number of nucleons in its nucleus. Each chemical element generally possesses several isotopic nuclides. A nuclide is designated by its chemical symbol, preceded by its mass number A as a superscript and its atomic number Z as a subscript, e.g. ${}^{238}_{92}U$.
O	**OPECST**	French Parliamentary Office for the Evaluation of Scientific and Technological Choices
	Operating waste	Operating waste is produced during operation or dismantling of a facility.
P	**Package with core source elements**	These ILW-LL category packages contain spent sealed sources collected from “small-scale nuclear activities waste producers”. The waste was conditioned in concrete packages between 1972 and 1985 for disposal. The packages were then reconditioned in non-alloy steel containers and stored at Cadarache near Marseille in 1994.
	Phosphogypsum	Phosphogypsum is precipitated solid calcium sulphate hydrate, produced for the manufacture of phosphoric acid and phosphate fertilizers when calcium fluorophosphate minerals are treated.
	Plutonium	Element with atomic number Z = 94. It was initially produced for military applications. Generated in nuclear reactors by irradiation of uranium-238 and currently used as a MOX fuel component in certain light-water reactors. It is also the fuel used in most fast reactor studies.
	PNGMDR	French National Radioactive Materials and Waste Management Plan.
	Pressurised water reactor (PWR)	Thermal neutron reactor using light water as moderator and coolant. This water is maintained in the liquid state inside the reactor core through pressure high enough to prevent bulk boiling at the operating temperature.

R

Terms	Definitions
Radiation protection	Set of measures intended to protect the health of populations and workers against the effects of ionising radiation and to ensure compliance with basic safety standards. It also includes implementing the necessary means to achieve these objectives.
Radioactive waste conditioning	Operations intended to prepare radioactive waste for subsequent transport, storage or disposal. These operations may include encapsulation, vitrification, cementation, bituminisation and containerisation.
Radioactive cleanup	Operations performed in a nuclear facility or site in order to eliminate or reduce radioactivity (particularly through decontamination or removal of radioactive materials) so as to recover radioactive substances in a controlled manner. Term equivalent to “cleanup” with regard to contamination by radioactive substances.
Radioactive half-life	Interval of time required for one-half of the atomic nuclei of a radionuclide to decay. The radioactivity of a pure sample of a single isotope would then be halved. After 10 such half-lives, the radioactivity would be divided by a factor of 1,000.
Radioactive material	A radioactive material is a radioactive substance for which subsequent use is planned or intended (after processing, if necessary).
Radioactive pollution	Direct or indirect introduction, by human activity, of radioactive substances into the environment likely to contribute to or cause a danger to human health, deterioration of biological resources, ecosystems or property, interfering with the legitimate use of the environment. Legacy pollution is pollution resulting from past human activity. Residual pollution concerns a quantity or concentration of pollutants remaining in a given environment after remediation.
Radioactive source	A device, radioactive substance or facility that emits ionising radiation or radioactive substances.
Radioactive substance	Substance containing natural or artificial radionuclides where the activity or concentration justifies radiation protection monitoring.
Radioactive waste disposal	Operation consisting of placing radioactive waste in a facility specially designed for the potentially definitive disposal of the substances concerned in compliance with human health, safety and environmental protection requirements.
Radioactive waste disposal facility	Facility intended for long-term disposal of radioactive waste. Disposal in surface, near-surface or deep geological repositories may be considered, depending on the radiological risks associated with the waste.
Radioactive waste holder	Waste producer or any other person in possession of waste (Article L. 541-1-1 of the French Environment Code).
Radioactive waste package	Conditioned and packaged radioactive waste.
Radioactive waste	Radioactive waste refers to radioactive materials for which no subsequent use is planned or envisaged. Final radioactive waste is radioactive waste that can no longer be processed by extracting recoverable materials or reducing its polluting or hazardous character under current technical and economic conditions.
Radioactivity	Property of a nuclide that allows it to undergo spontaneous transformation (into another nuclide) with emission of radiation (particles, X-rays, gamma rays, etc.), or spontaneous fission with emission of particles and gamma rays. In addition to spontaneous fission, the main forms of radioactivity are alpha radioactivity, beta radioactivity (β+, β-, internal conversion), gamma radioactivity and electron-capture radioactivity. Gamma radioactivity often accompanies the other forms.
Radioelement	Chemical element in which all the isotopes are radioactive. Term to be avoided as sometimes used for a radioisotope or radionuclide.

	Terms	Definitions
R	**Radionuclide (or radioisotope)**	Radioactive atoms that undergo radioactive decay and emit radiation, which is the origin of the phenomenon of radioactivity.
	Rare earth	Element from the group comprising the lanthanides and two chemically similar elements (yttrium and scandium).
	Recycled uranium	Uranium from spent fuel reprocessing.
	Regulated nuclear defence facility (INBS)	A regulated nuclear defence facility is a geographical zone including at least one regulated nuclear facility with defence-related activities that requires special protection against nuclear proliferation, malicious acts or disclosure of classified information. All of the facilities and equipment, both nuclear and non-nuclear, within the above-mentioned zone are part of the regulated nuclear defence facility. The nuclear facilities included in the regulated nuclear defence facility are called the “individual facilities of the regulated nuclear defence facility”. Nuclear safety and radiation protection of regulated nuclear defence facilities (INBS) are ensured by the Nuclear Safety Authority for Defence-related facilities and activities (ASND), which is under the authority of the representative in charge of nuclear safety and radiation protection for defence-related activities and facilities (DSND). The ASND defines nuclear safety regulations for regulated nuclear defence facilities consistently and in coordination with those defined by the French Nuclear Safety Authority (ASN). Both entities are independent of nuclear operators.
	Regulated nuclear facility (INB)	In France, a nuclear facility subject to specific regulations on account of its type and characteristics or the quantities or activity levels of all the radioactive substances it contains.
	Remediation	All cleanup and redevelopment operations carried out to make a site suitable for a given use.
	Reprocessing of spent fuel	Operations performed on spent fuel from nuclear reactors in order to extract recoverable materials (e.g. uranium, plutonium) and condition the remaining waste. Spent fuel reprocessing may also be used to separate other elements.
S	**Scenario**	Set of assumptions regarding events or types of behaviour used to describe the potential changes of a system in time and space.
	Short-lived waste	Radioactive waste containing significant quantities of radionuclides with a radioactive half-life less than or equal to 31 years.
	SIENID	Defence-related nuclear experimental facilities and sites.
	Spent fuel	Nuclear fuel unloaded from a reactor after irradiation.
	SPM	Suspended particulate matter, residues from the processing of rare earths containing thorium.
	Storage (of radioactive material or waste)	The temporary placement of radioactive matter or waste in a specially designed facility, pending subsequent retrieval.
	Structural waste	Radioactive waste composed of metallic structures of spent fuel assemblies from water-cooled reactors. This term may also be used to refer to spent fuel assemblies from sodium-cooled fast reactors.

	Terms	Definitions
T	tHM	Tonnes of heavy metal.
	Toxic chemical	Chemical substance or element liable to have harmful effects on human health in case of ingestion and/or inhalation. The health impact of a toxic chemical is quantified based on its toxicological reference value (TRV), a generic parameter comprising the various toxicity values used to establish a relationship between a dose and an effect (where there is a threshold for toxic effects), or between a dose and probability of effect (where there is no threshold for toxic effects, often carcinogenic). Various elements or substances used in the nuclear field or present in fission products exhibit radioactive toxicity. The following in particular are taken into consideration in studies for deep radioactive waste disposal: arsenic, cadmium, cyanide, chromium, mercury, nickel, lead, antimony, selenium, boron, uranium, beryllium and asbestos.
	Tritiated waste	Radioactive waste containing tritium, possibly requiring specific management due to the high mobility of this element.
	Tritium	Hydrogen isotope with a mass number of 3. Tritium is a low-energy beta emitter (mean of 13 KeV) with a half-life of 12.3 years. It is used in a large number of marked molecules. Current nuclear fusion projects are all based on the deuterium-tritium reaction. In current civilian industrial applications, tritium is first and foremost a radioactive waste product requiring specific management due to its high mobility.
V	Vitrified waste	In the nuclear field, term referring to radioactive waste conditioned in a glass matrix. Fission product solutions were the first waste to be vitrified. There are plans for other less radioactive waste to be vitrified in the future.
	VLLW	Very low level waste results primarily from the operation, maintenance and dismantling of nuclear power plants, fuel cycle installations and research centres. The activity level of this waste is generally less than one hundred becquerels per gram.
W	Waste producer	Any person whose activity produces waste (initial waste producer) or any person performing waste treatment operations leading to a change in the nature or composition of this waste (secondary waste producer) (Article L. 541-1-1 of the French Environment Code).
	Waste recovery and conditioning	Waste from waste recovery and conditioning consists of legacy waste that has not been conditioned during production and which is or will be conditioned and disposed of by those in possession of it.
	Waste stream	A group of radioactive waste or waste packages that possess identical characteristics in terms of origin, physical and radiological properties and eventually, conditioning.
	Waste treatment	Mechanical, physical or chemical operations intended to modify the characteristics of waste materials.
Z	Zircon	Zircon is a natural silicate mineral ($ZrSiO_4$).

Cover photo: Radiation monitoring of an LILW waste package on arrival at the Aube disposal facility (CSA).
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ANDRA
French national radioactive waste management agency

inventaire.andra.fr, the reference website for all radioactive materials and waste on French territory.

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