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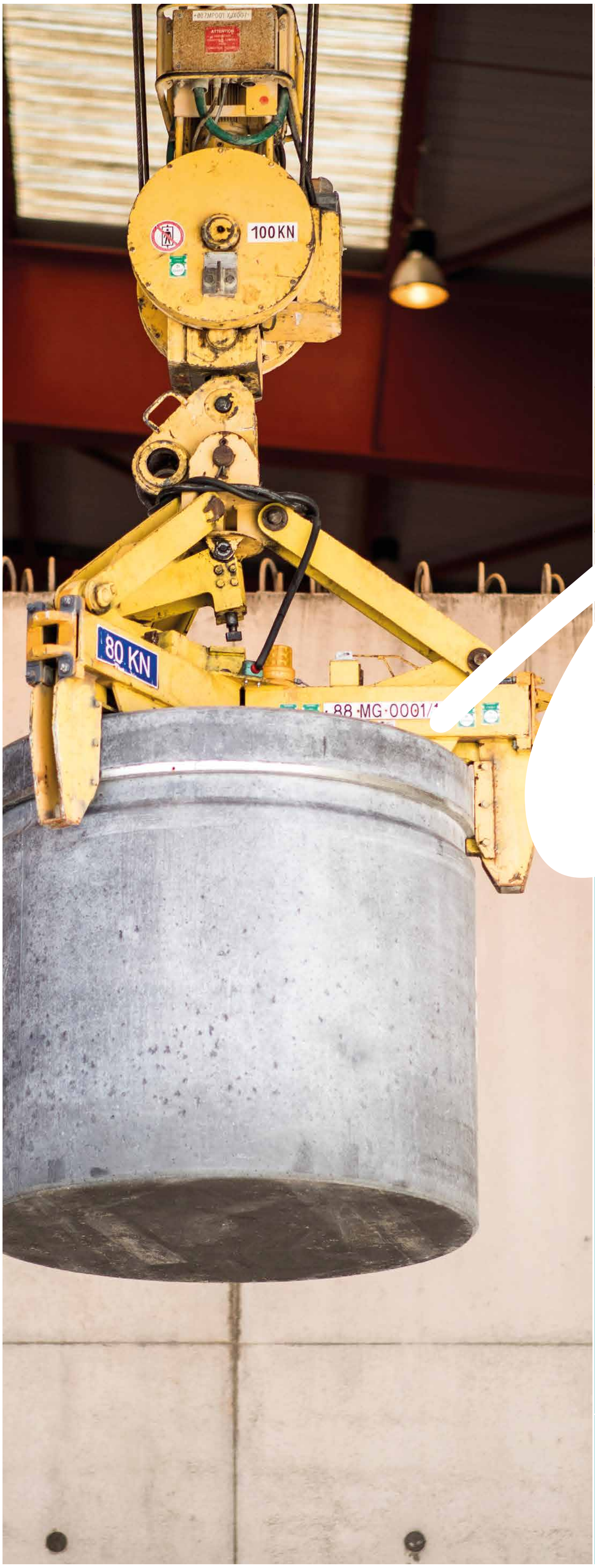
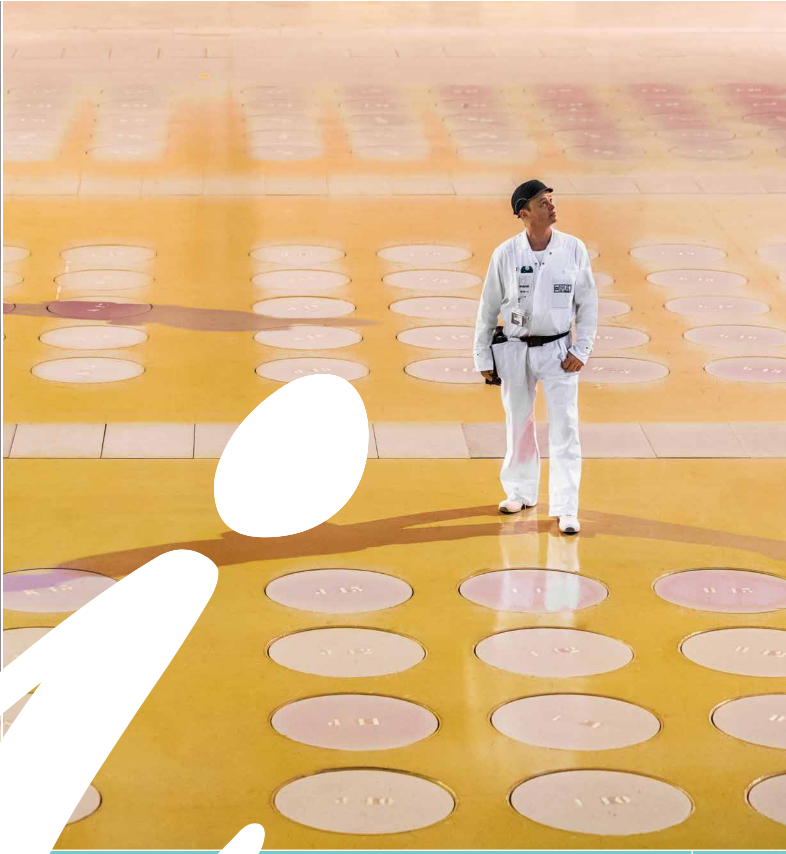
ANDRA
Agence nationale pour la gestion des déchets radioactifs





National Inventory
of Radioactive Materials and Waste

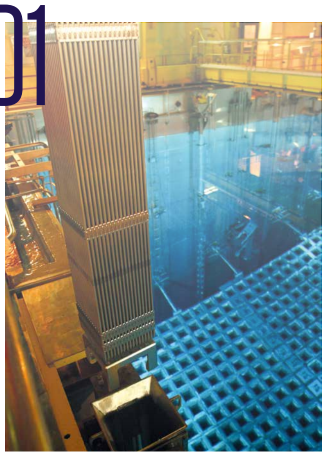
SUMMARY REPORT 2023

Every five years, Andra publishes a new edition of the *National Inventory of Radioactive Materials and Waste.*

The content of this inventory is periodically updated and expanded by including the results of the forecasting and evaluation work set out in the National Radioactive Materials and Waste Management Plan (PNGMDR).

Find out more
www.inventaire.andra.fr

01



Radioactive materials and waste and their management

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Inventory at the end of 2021

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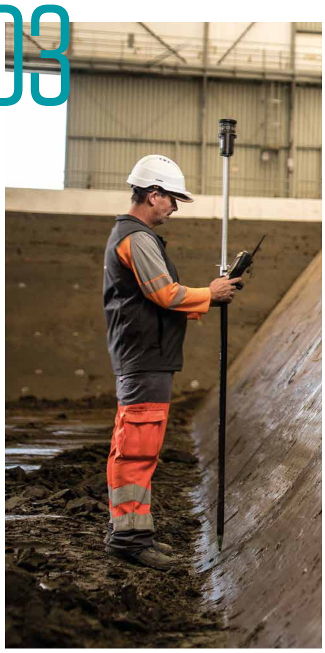

Forecast inventories

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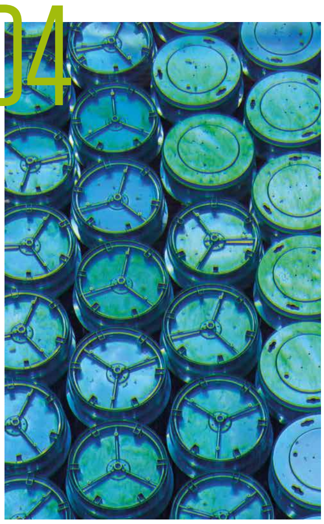

Storage

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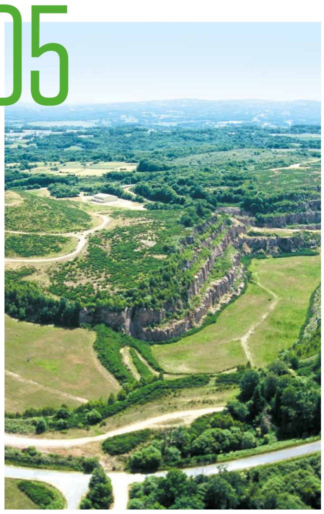

Specific management methods

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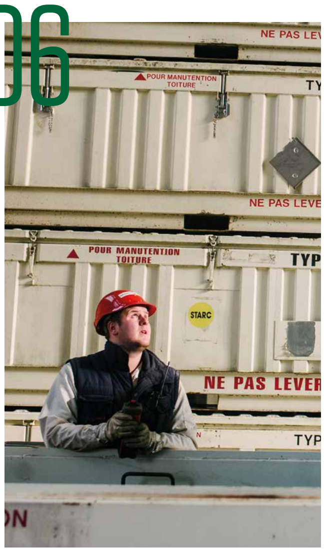

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01

Radioactive materials and waste and their management

THE SOURCE OF RADIOACTIVE MATERIALS AND WASTE

The National Inventory of Radioactive Materials and Waste lists the sources of radioactive materials and waste, divided into five economic sectors that result in radioactive materials and waste being produced, held or processed:

- **the nuclear power sector** which mainly comprises nuclear power plants for electricity production, as well as facilities dedicated to producing nuclear fuel (mining and processing of uranium ore, chemical conversion and enrichment of uranium concentrate), reprocessing spent fuel and recycling of the materials extracted from spent fuel;
- **the research sector** including research in the civil nuclear domain (including research activities undertaken by the Alternative Energies and Atomic Energy Commission), in medicine, in nuclear and particle physics, agronomy, chemistry, biology, etc.;
- **the defence sector** which mainly comprises the nuclear deterrent, 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 mainly include rare earth mining, production of sealed sources, as well as a range of applications such as weld inspections, sterilisation of medical equipment, and sterilisation and preservation of food products, etc.;
- **the medical sector** which includes diagnostic and therapeutic activities (scintigraphy, radiotherapy, etc.).

The sectors that make the greatest contribution to generation of radioactive waste in France are the nuclear power, research and defence sectors.

In accordance with Article L. 542-1 of the French Environmental Code, producers of radioactive waste are responsible for managing their waste properly before it is removed to a final disposal site, and for managing their materials properly, with respect for the protection of human health, safety and the environment.

FOCUS — ARTICLE L.542-1 OF THE FRENCH ENVIRONMENTAL CODE

Article L. 542-1 of the French Environmental Code stipulates that: *"Sustainable management of radioactive materials and waste of any kind that results, in particular, from operation or dismantling of facilities that use radioactive sources or materials, shall be conducted with respect for the protection of human health, safety and the environment.*

The necessary means to ensure the final and permanent safety of radioactive waste shall be identified and implemented, in order to prevent or limit the burden on future generations.

The entities that generate spent fuel and radioactive waste shall be responsible for these substances, without prejudice to the responsibility of waste holders as entities responsible for nuclear activities. In the event of any failure in this regard by the entities generating and holding such waste, where the waste has been generated on French territory, the State shall ultimately be held liable for these substances and may entrust the French National Agency Radioactive Waste Management Agency (Andra) to ensure that the waste is managed, in accordance with Article L. 542-12. The entity responsible for managing spent fuel or radioactive waste shall have the technical and financial capacity to enable it to comply with the obligations imposed on it by this chapter".

Natural and artificial radioactivity

The sources of the radioactive substances may either be natural or caused by human activities.
There are many natural sources of radioactivity: ores (uranium and thorium isotopes, potassium-40, or daughter elements, such as radium and radon), cosmic radiation (tritium, carbon-14), etc. These are natural radionuclides that are distributed throughout the biosphere.
The radionuclide concentration is extremely variable depending on the material concerned and its source: exposure to naturally occurring radionuclides can vary by more than an order of magnitude between different regions of the world (from an average of 2.9 mSv/year in France* to more than 50 mSv/year in some regions of India or Brazil).

The many different uses of the properties of radioactivity have been generating radioactive materials and waste since the beginning of the 20th century. Most of the waste and materials come from nuclear power plants generating electricity, from spent fuel reprocessing facilities and from other civilian and military nuclear facilities.
Research laboratories and nuclear medicine services also contribute to generation of radioactive waste, to a lesser degree, along with some industries that use radioactive substances.

*Source IRSN.

FOCUS

THE REGULATIONS

Article L. 542-1-1 of the French Environmental Code defines a number of concepts that are useful to refer to when considering the *national inventory of radioactive materials and waste.*

RADIOACTIVE SUBSTANCES, MATERIALS AND WASTE

"A radioactive substance is a substance containing natural or artificial radionuclides, where the radionuclide concentration or activity is such that radiation protection monitoring is required".
These radioactive substances may be classified as radioactive materials or radioactive waste:
"Radioactive materials are radioactive substances for which there is a future use planned or envisaged, possibly after processing".

In some cases, processing such materials for future use may generate waste.
"Radioactive waste consists of radioactive substances for which there is no future use planned or envisaged, or which have been 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, under current technical and economic conditions, in particular by extraction of the recoverable part or by reducing its polluting or hazardous nature. Radioactive waste management includes all operations relating to the handling, pre-treatment, treatment, conditioning, storage and disposal of radioactive waste, excluding off-site transportation".

In accordance with Article L. 542-13-2, radioactive material may be reclassified as radioactive waste by the administrative authority, after consultation with the ASN (Nuclear Safety Authority), if its prospects for recovery are not sufficiently established.

RADIATION PROTECTION MONITORING

Where a substance contains radionuclides, the basis for justification of radiation protection monitoring is not necessarily a threshold of activity or concentration per radionuclide. As a precautionary measure, the justification for such monitoring is presumed to be established where substances arise from nuclear activity and where they are contaminated, activated or likely to be so.
Nuclear activities, according to Article L. 1333-1 of the French Public Health Code are "activities involving a risk of human exposure to ionising radiation related to use of either an artificial source, whether a substance or a device, or a natural source, whether a naturally occurring radioactive substance or a material containing natural radionuclides".

In accordance with the Directive 2013/59/Euratom of 5December 2013 establishing basic safety standards for health protection against hazards arising from exposure to ionising radiation, the Member States of the European Union may implement release thresholds, below which the materials concerned fall outside the scope of the regulations regarding radioactivity. Where release thresholds are applied, depending on the country concerned, these thresholds, for each radioelement, may either be universal (regardless of material concerned, origin and destination) or may be determined according to material, origin and destination.

In France, there is specific legislation governing management of radioactive materials and waste. The regulations provide for management of waste resulting from a nuclear activity, depending on the location of its production and not based on measurement of its radioactivity. Any waste that arises from sites that can generate radioactive waste must be managed in specialist facilities, regardless of any radioactivity measurement, and regardless of whether it is actually radioactive or not.

Since 1st January 2022, Article D. 1333-6-4 of the French Public Health Code has introduced a possibility of targeted derogations, allowing recovery of very low-level metallic radioactive waste on an individual case basis. For activities that were not considered to be nuclear activities prior to introduction of the new definition by the Order of 10 February 2016, the criterion of limited exposure is used to assess whether radiation protection monitoring is required: the sum of the effective doses received by any person as a result these activities must not exceed 1 mSv/year (*Article R. 1333-38 of the French Public Health Code*), and depending on an acceptability study regarding the radiological impact associated with waste management, which must demonstrate that there is no requirement for radiation protection monitoring. In this case, under certain conditions, the waste may no longer be considered radioactive. The waste concerned includes waste containing naturally occurring radioactive material (NORM). As part of the transposition of Directive 2013/59/Euratom, these management procedures will be reviewed insofar as activities that involve naturally occurring radionuclides with non-negligible exposures in terms of radiation protection will now be considered to be nuclear activities.

SPENT FUEL MANAGEMENT IN FRANCE

"Spent fuel is considered to be nuclear fuel that has been permanently removed from the reactor, after having been irradiated in the core. Spent fuel management includes all operations involved in the handling, storage, reprocessing or disposal of spent fuel, excluding any off-site transportation."
As France has chosen to reprocess spent fuel to extract the recoverable materials that it contains, spent fuel is not considered to be radioactive waste.

RELEASES

Activities using radioactive substances may be a source of controlled releases into the environment, in gaseous or liquid form. These releases fall outside the scope of the *National Inventory of Radioactive Materials and Waste.* Releases from BNIs are described and quantified in the public reports due to be published each year by their operators in accordance with Articles L. 125-15 and 16 of the French Environmental Code. Data on ICPE releases are collected each year by the French Ministry for Ecological Transition and Territorial Cohesion.

DEFINITIONS USED IN THE FRENCH ENVIRONMENTAL CODE

WASTE PRODUCER

Article L. 541-1-1: *"Any entity conducting an activity that generates waste (initial producer of waste) or any entity that carries out waste treatment operations that result in alteration of the nature or composition of such waste (secondary waste producer)".*

WASTE HOLDER

Article L. 541-1-1: *"Waste producer or any other entity that is in possession of waste".* An item of radioactive waste may have several holders over the time period between its production and its disposal (initially the producer/holder, then the carrier, followed by the storage facility operator, then the disposal facility operator).

WASTE MANAGEMENT

Article L. 541-1-1: *"Waste sorting at source, waste collection, transportation, recovery, disposal and, more broadly, any operation involved in the procedures for handling of waste, from waste production to final treatment, including monitoring of waste disposal facilities after closure, in accordance with the provisions concerning ICPE facilities, as well as waste trading or brokering activities and supervision of all these operations".*

RESPONSIBILITIES

Article L. 542-12: *"Any waste producer or holder is required to manage it, or to ensure that it is managed, in accordance with the provisions of this chapter.*
Any waste producer or holder is responsible for the management of this waste up until its final disposal or recovery, even where the waste is transferred to a third party for treatment.
Any waste producer or holder shall ensure that any entity to whom the waste is entrusted is authorised to take charge of it".

Article L. 542-12: *"The entities that generate spent fuel and radioactive waste shall be responsible for these substances, without prejudice to the responsibility of waste holders as entities responsible for nuclear activities. In the event of any failure in this regard by the entities generating and holding such waste, where the waste has been generated on French territory, the State shall ultimately be held liable for these substances and may entrust the French National Agency Radioactive Waste Management Agency (Andra) to ensure that the waste is managed, in accordance with Article L. 542-12".*

These provisions mean that the waste producer shall be responsible for its waste and its obligations up until final disposal in accordance with Article L. 541-2 (ensuring that waste is managed, treating waste or ensuring that waste is treated, guaranteeing the quality and properties of waste, taking on any costs and damage that could be induced by the waste).
Non-producing holders are solely responsible for their nuclear activities (safety and security of installations, operations and the waste being transported, stored and disposed of).

REPORTING OBLIGATIONS

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

Article R. 542-67: *"For the purposes of conducting the national inventory as stipulated in 1° of Article L. 542-12, any operator of a site that hosts either one or more basic nuclear installations, or one or more defence-related nuclear installations, mentioned in Article L. 1333-15 of the Defence Code, or one or more ICPE facilities involved in nuclear activities in accordance with Appendix 1 to Article R. 511-9 of the French Environmental Code, or several installations falling into these categories, is required to send an inventory every year, reporting the radioactive materials and waste present on such sites on 31 December of the previous year, to the National Radioactive Waste Management Agency (Andra).*
This inventory, accompanied by a summary presentation of the site and an indication of the administrative system governing it, includes a description of the radioactive materials and waste in terms of both their physical characteristics and significant quantitative information. Radioactive waste is divided into categories. Where the site includes a basic nuclear installation in the form of a nuclear reactor, a reprocessing plant for spent nuclear fuel, or a facility for the storage or disposal of radioactive substances, the operator shall add an appendix to the annual inventory providing a breakdown of the radioactive waste present on this site, by producer and category.
For a defence-related nuclear installation as mentioned in the first paragraph of this article, the inventory shall only include the description of the radioactive waste related specifically to that installation".

Article R. 542-68: *"Any entity responsible for nuclear activities falling outside the scope of Article R. 542-67 of this Code is required to send Andra an annual inventory of the radioactive waste held, as of 31 December of the previous year, indicating the waste management solution applied".*

Article R. 542-69: *"Every operator of a site mentioned in Article R. 542-67 is required to submit a report for this site to the French National Radioactive Waste Management Agency (Andra) every five years, containing information about the estimated quantities of radioactive material and radioactive waste in each category. Where there is no final management solution suitable for this waste, the report shall specify the types of storage facilities envisaged, their available capacities and their estimated service life.*
For a defence-related nuclear installation as mentioned in the first paragraph of Article R. 542-67, the five-yearly report shall only include the description of the radioactive waste related specifically to that installation".

Article R. 542-72: *"A joint order by the ministers responsible for energy and for nuclear safety shall determine the procedures for application of this section. It shall specify the nature of information to be included in the inventories and reports required, in particular the concept of waste categories and the reference dates to be taken into account. It shall specify the deadlines and procedures for provision of documents to the National Radioactive Waste Management Agency".*

1 These articles codified the provisions of Decree No. 2008-875 of 29 August 2008 adopted for application of Article 22 of Law No. 2006-739 of 28 June 2006 governing the sustainable management of radioactive materials and waste.

CLASSIFICATION OF RADIOACTIVE WASTE AND WASTE MANAGEMENT SOLUTIONS

In France, radioactive waste is classified mainly on the basis of two major parameters used to define the appropriate waste management solution: the level of radioactivity and the radioactive half-life of the radionuclides present in the waste.

In terms of the level of radioactivity of waste, the following categories are used:

- **very low-level waste (VLLW)** with average activity level below 100 becquerels per gramme;
- **low-level waste (LLW)** with activity level between a few hundred and one million becquerels per gramme;
- **intermediate-level waste (ILW)** with activity of about one million to one billion becquerels per gramme;
- **high-level waste (HLW)** with activity of about several billion becquerels per gramme.

In terms of the radioactive half-life, the following categories are used:

- **very short-lived waste (VSLW)** which contains radionuclides with a half-life shorter than 100 days;
- **short-lived waste (SL)** with radioactivity mainly from radionuclides with a half-life shorter than or equal to 31 years;
- **long-lived waste (LL)** which contains a significant quantity of radionuclides with a half-life longer than 31 years.

Management of each type of waste requires specific means to be used or developed to be suitable for the level of hazard involved and how it changes over time. There are several categories of waste that are or will be subject to special waste management solutions.

i **The physical and chemical nature, and the level and type of radioactivity, are all characteristics that vary from one item of waste to another. Radioactive waste may contain a mix of radionuclides: depending on the composition of the waste, there will be differences in the radioactivity levels and periods of time involved. Waste that contains mostly short-lived elements is called short-lived waste, and conversely, waste that contains mostly long-lived elements is called long-lived waste.**

i **The radioactive half-life of a radionuclide is the time taken for a quantity of that radionuclide to be reduced by half by radioactive decay. At the end of 10 half-life periods, the radioactivity level is divided by 1000.**

HLW HIGH-LEVEL WASTE

This waste contains the largest proportion of the radioactivity of the waste, within a relatively small volume. High-level waste (HLW) has activity levels at several billion becquerels per gramme. It comes mainly from the nuclear power industry and related research activities, and to a lesser extent from national Defence-related activities. It consists mainly of non-recoverable substances generated by the recycling of spent fuel. Most of this waste is encapsulated in glass, then conditioned in stainless steel drums. Because of its high level of radioactivity, this waste gives off heat.

This includes:

- short-lived fission products, for example caesium-134 and caesium-137;
- long-lived fission products such as technetium-99;
- activation products and minor actinides, some of which have multi-millennial half-lives, such as neptunium-237.


CSD-V package

ILW-LL

LONG-LIVED INTERMEDIATE LEVEL WASTE

This waste mainly comes from the recycling of spent fuel and from maintenance and operation of reprocessing plants. It includes structural waste from fuel assemblies (end caps and hulls), technological waste (used tools, equipment, etc.) and waste from treatment of effluents such as certain types of sludge. It is characterised by a significant presence of long-lived radionuclides such as nickel-63 (100-year half-life).
Other types of ILW-LL come from components that have been activated during their exposure to neutron flux in reactors.
The activity of this waste ranges from around one million to one billion becquerels per gramme.


Hulls from the zirconium alloy cladding that covers fuel pellets

In France and internationally, deep geological disposal is recognised as the reference solution for managing the most highly radioactive waste. Andra has therefore designed the Cigéo project (Industrial Centre for Geological Disposal), which aims to dispose of HLW and ILW-LL waste at a depth of 500 metres, on the border between the Meuse and Haute-Marne rivers. The project is the result of 30 years of studies and research, subject to regular evaluation, including more than 20 performed in the Meuse/Haute-Marne underground laboratory. In early 2023, l'Andra submitted the construction licence application for Cigéo to the Ministry for Ecological Transition and Territorial Cohesion.

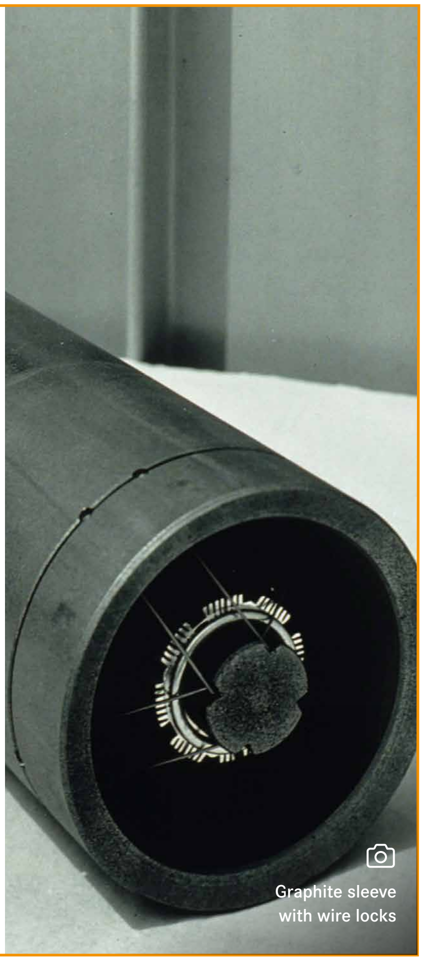
LLW-LL

LONG-LIVED LOW-LEVEL WASTE

This includes:

- radium-bearing waste, mainly from non-nuclear industrial activities, such as certain research and processing of minerals that contain rare earths. Other radium-bearing waste may also come from clean-up of sites with a history of radium contamination, where safety is ensured and maintained by Andra as part of its activities in the public interest. The level of radioactivity of this waste is generally between a few tens and a few thousand becquerels per gramme.
  The radionuclides contained in such waste are essentially long-lived alpha emitters, such as radium, uranium or thorium;
- graphite waste from the operation and dismantling of the early nuclear reactors (GCRs: gas-cooled graphite-moderated reactors) and from certain experimental reactors no longer in operation.
  This type of waste has a radioactivity level between 10,000 and 100,000 becquerels per gramme and mainly contains long-lived beta-emitting radionuclides.
  In the short term, the radioactivity of graphite waste is largely due to nickel-63, tritium and cobalt-60. In the longer term, carbon 14 becomes the majority contributor to the radioactivity;
- other types of waste, such as certain packages of legacy waste conditioned in bitumen, and uranium conversion treatment residue from the Orano Malvési plant, and operating waste from the La Hague reprocessing plant.

As part of the 2022-2026 PNGMDR, Andra is finalising the characterisation of safety issues related to the disposal facility project in the Vendeuvre-Soulaines community of municipalities. It must also propose waste management scenarios for LLW-LL, which will make it possible to develop a global management plan for this waste by 2025.


Graphite sleeve with wire locks

LILW-SL

SHORT-LIVED LOW-LEVEL AND INTERMEDIATE-LEVEL WASTE

Waste generated by use of radioactive products in a laboratory

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

LILW-SL waste mainly contains short-lived radionuclides with a radioactive half-life shorter than or equal to 31 years, such as cobalt-60 or caesium-137. It may also contain smaller quantities of long-lived radionuclides.

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

LILW-SL waste is disposed of at the surface and is monitored for the time it takes for its radioactivity to decay to negligible impact levels. At Andra disposal facilities, the time taken to reach this level is generally considered to be 300 years, a period that corresponds to about 10 half-life periods and means that the radioactivity level is divided by 1000. These facilities will therefore be monitored for at least 300 years.

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

The CSM has not accepted any waste since 1994 and is in the closure phase, while the CSA has been active since 1992, in the municipalities of Soulaines-Dhuys, Épothémont and Ville-aux-Bois.

VLLW

VERY LOW-LEVEL WASTE

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

There will be significant changes in the production of this type of waste with the dismantling of nuclear power plants currently in operation or fuel cycle facilities and research centres. The average radioactivity level of this waste is less than 100 becquerels per gramme.

Since 2003, this waste has been disposed of at Cires (Industrial facility for grouping, storage and disposal) located in the municipalities of Morvilliers and La Chaise.

The PNGMDR provides for continuing studies with the aim of reducing the volumes of VLLW waste mainly produced during dismantling operations. The options studied by Andra and the waste producers (recovery of metal parts and rubble, disposal on or near dismantling sites, etc.) must be incorporated in the update to the overall industrial plan for the management of VLLW waste by 2024. This work will be used to determine the capacity requirements for new disposal facilities to be provided to take over from Cires.


VLLW

Acaci project

VLLW waste is disposed of at the Cires facility. By the end of 2021, this facility had filled approximately 66% of its total licensed disposal capacity of 650,000 m³. In its current configuration, Cires will not be sufficient to dispose of the VLLW waste volumes produced by dismantling in the coming years. Additional management solutions are therefore currently being studied. The medium-term solution is to increase the licensed disposal capacity of Cires to more than 900,000 m³, without changing the current footprint of the disposal facility and maintaining the same safety level: this is the purpose of the Acaci project. If approved, this increase in capacity will extend the operating life of Cires by about a decade, looking ahead to 2040.

Some waste comes mainly from the medical or research sector and contains very short-lived radionuclides (with a radioactive half-life shorter than 100 days) used for diagnostic or therapeutic purposes.
These are managed by decay: this waste is stored on site, for a period of a few days to a few months, until the radioactivity decreases sufficiently to be disposed of by conventional methods.

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

Decay tanks

The classification makes it possible to schematically link one or more management methods with each category of waste *(see Chapter 6 - Special Report 1).*
However, it does not take account of certain levels of complexity that can lead to selection of a management solution that differs from that used for the category to which the waste is assimilated.
Other criteria, such as stability or the presence of toxic chemicals, must also be taken into account.

Definition of a management method must also take account of the principles and guidelines defined in the French Environmental Code, including the need to reduce the volume and harmfulness of final radioactive waste.

Two important aspects concerning the classification of radioactive waste should therefore be emphasised here:

- there is no single classification criterion that can be used to determine the category of an item of waste. It is indeed necessary to study the radioactivity of the different radionuclides present in the waste in order to position it in the classification. However, despite there being no single definitive criterion, the waste in each category is generally within a range of mass radioactivity indicated in the preceding paragraphs;
- an item of waste may fall into a particular category, but still may not be accepted in the corresponding final outlet due to other characteristics, such as its chemical composition.

In addition, during recovery of waste or dismantling of facilities, knowledge of such waste may be improved, and progress may be made in studies to optimise treatment and conditioning methods and in ongoing or planned design studies for disposal facilities, all of which may bring about changes in waste management options, and in category assignment. This is referred to as "recategorisation".


Packages waiting in the Cires collection building

CLASSIFICATION OF RADIOACTIVE WASTE AND RELATED MANAGEMENT SOLUTIONS

Radioactive half-life* / Activity**	Very short-lived (VSL) (half-life < 100 days)	Mainly short-lived (SL) (half-life ≤ 31 years)	Mainly long-lived (LL) (half-life > 31 years)
Very low-level waste (VLLW) < 100 Bq/g	Management through radioactive decay	VLLW – Surface disposal facility (Cires - Industrial facility for grouping, storage, and disposal)	
Low-level waste (LLW) between a few hundred Bq/g and one million Bq/g		LILW-SL – Surface disposal facility (Aube and Manche disposal facilities)	LLW-LL – Planned near-surface disposal facility
Intermediate-level waste (ILW) in the range of one million to one billion Bq/g			ILW-LL – Deep geological disposal facility under development (Cigéo project)
High-level waste (HLW) on the order of several billion Bq/g	Not applicable	HLW – Deep geological disposal facility under development (Cigéo project)	

* Half-life of the radioactive elements (radionuclides) contained in the waste.

** Radioactive waste activity level.

SPECIAL CASES

WASTE CONTAINING NATURALLY OCCURRING RADIOACTIVE MATERIAL (NORM)

Waste containing naturally occurring radioactive material is generated by the use or processing of raw materials that are rich in natural radionuclides (NORM) but are not used for their radioactive properties. This includes waste from the chemical or metallurgical industries (phosphate fertilisers, rare earths, zircon sands, etc.). It may be similar to long-lived very low-level waste or even very low-level waste.

The natural radionuclides considered for waste containing naturally occurring radioactive material are those of uranium-238 and thorium-232 chains, as well as potassium-40, contained in materials used in industrial processes. Industrial processes can concentrate or enhance the natural radioactivity present in certain products used and in particular in the residues that they generate.

For this particular type of waste, and with strict regulation, the circular of 25 July 2006[2] offers the option of specific management by acceptance in a conventional waste disposal facility. This may involve, for example, disposal of products from the demolition of old factories, equipment or process residues.

Tailings from treatment of very slightly radioactive materials were used as backfill at the La Palice port in La Rochelle

Waste management for waste containing naturally occurring radioactive material was modified by Decree No. 2018 434 of 4 June 2018[3] which transposes provisions from Directive 2013/59/Euratom of 5 December 2013 establishing the basic safety standards for health protection against hazards arising from exposure to ionising radiation. It is now codified in the French Public Health Code.

WASTE WITHOUT A SPECIFIC DISPOSAL SOLUTION

It is sometimes impossible to assign a category to certain items of waste, either due to certain characteristics (particularly chemical aspects) that prevent them being accepted into existing waste management systems, or because the treatment or conditioning processes are not available or are particularly complex to develop for volumes that are sometimes relatively small.

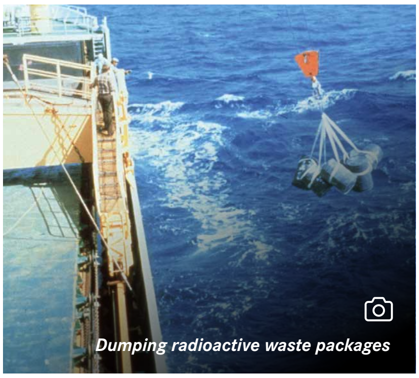
Examples include tritium-bearing waste or waste containing mercury.

The development and implementation of treatment processes for such waste is monitored as part of the National Radioactive Materials and Waste Management Plan (PNGMDR). Most waste that does not have a specific disposal solution is stored at the site where it is generated. This waste is listed in the *National Inventory*.

WASTE IN LEGACY DISPOSAL FACILITIES

Some radioactive waste in the past was managed using methods that have since evolved.

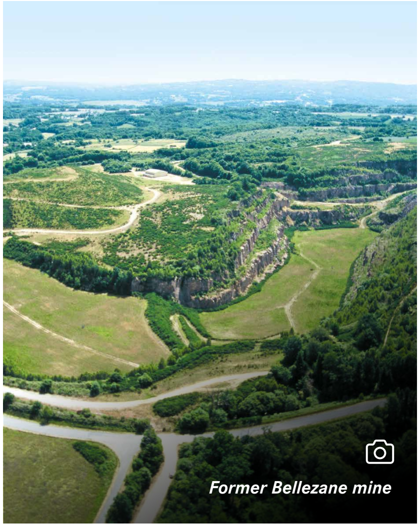
This waste was able to be disposed of within or near nuclear facilities, in conventional waste disposal facilities, on or close to former or currently operational industrial sites, or dumped at sea.



Dumping radioactive waste packages

URANIUM MINE TAILINGS

The mine tailings listed in the *National Inventory* are most often stored on or near former mining sites and have characteristics similar to VLLW or LLW-LL waste *(see Chapter 5)*.



Former Bellezane mine

2 Circular of 25 July 2006 on Classified Facilities – Acceptance of waste with enhanced or concentrated natural radioactivity in waste disposal facilities.

3 Decree No. 2018-434 of 4 June 2018 establishing various provisions concerning nuclear matters.

RADIOACTIVE MATERIALS

NATURAL URANIUM EXTRACTED FROM THE MINE (Unat)

Uranium occurs in its natural state as a very dense grey metal. It consists of three radioactive isotopes: uranium-238 (99.3%), uranium-235 (0.7%, the only natural fissile isotope) and uranium-234 (traces).
Uranium is mined. In France, uranium mines were operated until 2001. Today, the supply of natural uranium only comes from mines located abroad.

After mining, it is processed and formed into a solid uranium concentrate, then conditioned. Depending on the treatment process used, the concentrates may be in the form of uranates, called *yellowcake*, or uranium oxides (U_3O_8). The uranium concentrates are converted into uranium tetrafluoride (UF_4), then into uranium hexafluoride (UF_6), which is gaseous at low temperature: this is the uranium conversion stage.

It is in this form that natural uranium is used in the enrichment step for the purpose of producing nuclear fuel.

ENRICHED NATURAL URANIUM (ENU)

Enrichment consists of increasing the concentration of uranium-235 (energy isotope too low – content of 0.7% – in the mined natural uranium) to obtain a material that can be used as a fuel in pressurised water reactors (PWR).

At the Orano Georges-Besse II plant at the Tricastin site, centrifugation has been used to enrich uranium since 2011. The UF_6 gas is introduced into the cylinder rotating at very high speed, under vacuum, in a sealed casing. The effect of the centrifugal force sends the heaviest molecules to the side of the tube, while the lightest, which contain an atom of uranium-235, migrate to the centre. The gas enriched in the light uranium-235 isotope, in the centre of the tube, rises up. The gas enriched in uranium-238, in other words depleted and heavier, moves downwards. Enriched and depleted products are recovered at both the top and bottom ends of the tube. This elementary step of separating the molecules is repeated within a set of centrifuges placed in series, called cascades.

Enriched uranium used for power generation includes a uranium-235 content of about 4%. This value is called the enrichment rate.

After enrichment, uranium in the gaseous form UF_6 is converted to oxide (UO_2) and then compacted into pellets used to produce fuel.

DEPLETED URANIUM (DU)

During the enrichment process, the uranium-235 content of the residual material is reduced in favour of the enriched uranium content. This is called depleted uranium. Uranium depleted in uranium-235 (an isotope present with a content of around 0.3%) is transformed into a solid, stable, non-combustible, insoluble and non-corrosive material: uranium oxide (U_3O_8) appears in the form of a black powder.

Depleted uranium has been used regularly for several years as a support matrix for MOX fuel, developed in France at the Melox plant located in Marcoule. This flow represents about a hundred tonnes per year. It constitutes a uranium reserve that could be converted and further enriched (depending on the economic conditions of the uranium market).

FOCUS — RECOVERY OF DEPLETED URANIUM

The stock of depleted uranium currently present on French territory, once re-enriched, represents a deposit of about 65,000 tons of natural uranium, or about eight years' worth of the requirements for the current French nuclear power fleet.

Re-enrichment can be implemented for use as an enriched natural uranium(ENU) fuel. Depleted uranium, in particular when obtained from a second enrichment cycle, could make it possible to meet the requirements of the world's fleet of fast neutron reactors in the longer term.

As well as its energy potential, the depleted uranium has properties, some of which have already been exploited in industries outside the nuclear power sector (batteries, thermoelectric catalysts, reversible thermochemical heat disposal). Uranium recovery by exploitation of these properties is the subject of an R&D program led by Orano.

However, there are uncertainties concerning these prospects for recovery, according to ASN. A feasibility study for a repository concept for depleted uranium has been conducted by Andra to deal with situations where all or part of the depleted uranium stock could not be recovered under acceptable technical and economic conditions. Depleted uranium is used in industries outside the nuclear power sector as radiation shielding or a counterweight.

URANIUM OBTAINED FROM REPROCESSING SPENT FUEL (REPU)

The uranium obtained from spent fuel at the Orano reprocessing plants, located at La Hague, constitutes about 95% of spent fuel by mass and still contains a significant proportion of the U-235 isotope. The residual enrichment in uranium-235 is about 0.7% to 0.8% for PWR fuels with burnups of 45 to 55 GWd/t. RepU is stored as U_3O_8.

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

ENRICHED URANIUM OBTAINED FROM REPROCESSING SPENT FUEL

Uranium obtained from reprocessing spent fuel (RepU) still contains a proportion of the U-235 isotope despite a more complex isotopic composition than natural uranium, in particular due to the presence of uranium-234 and 236. It is therefore able to be enriched subsequently. The presence of uranium-236, a neutron absorber acting as a poison in nuclear fission, requires enrichment to higher levels than those necessary for natural uranium, in order to compensate for the loss of reactivity. Enriched uranium obtained from spent fuel reprocessing can be used to make enriched reprocessed uranium (ERU) fuel.

As with natural uranium, centrifugation can be used to enrich uranium obtained from spent fuel reprocessing. However, there is only one facility in the world currently carrying out this operation, which belongs to the Russian group Rosatom and is based in Seversk, in the Tomsk region of Siberia.

The supply of enriched reprocessed uranium fuel assemblies for EDF reactors has been interrupted for about ten years for technical and economic reasons. EDF plans to resume use of enriched reprocessed uranium (ERU) fuel from 2023.
At the end of 2021, there was no stock of enriched uranium obtained from spent fuel reprocessing available in France, and the first delivery took place at the end of November 2022 with the aim of ensuring this recovery.

FOCUS — EXAMPLE OF USE OF MATERIALS CONTAINING THORIUM BY ORANO MED

Orano Med is the medical subsidiary of Orano. Created in 2009, its activities are focused on developing new targeted therapies to combat cancer, *with* the use of lead-212.

Lead-212 is a rare isotope obtained from the thorium-232 decay chain. This alpha-emitting element is now at the heart of research projects in nuclear medicine for the development of new cancer treatments.

Orano Med has developed a process used to extract lead-212, which is now being implemented in the Maurice-Tubiana laboratory. Orano Med works in the therapeutic field of alphatherapy, or alpha radioimmunotherapy, where lead-212 is combined with use of an antibody to recognise and destroy cancer cells, reducing the impact on surrounding healthy cells. Clinical and preclinical trials have been launched in the United States and France respectively.

The principle of alphatherapy has been understood for several years, but the development of treatments has been held back by the scarcity of alpha-emitting isotopes, and by the technical difficulties of producing and purifying these isotopes for medical uses. As Orano has a source of thorium nitrate consisting mainly of thorium-232, Orano Med is carrying out recovery operations to ensure that lead-212 production is compatible with requirements for long-term work to develop these new treatments.

ASN considers that this use of lead-212, however, does not alter the quantities of thorium-bearing substances held or their radiotoxicity.

THORIUM

Thorium occurs mainly in the form of thorium hydroxide or thorium nitrate. As part of its rare earth ore processing activities, Solvay has produced the following:

- between 1970 and 1987, a compound obtained from treating monazite with chloride: crude thorium hydroxide (HBTh), potentially recoverable (*see box opposite*);
- until 1994, thorium nitrate, from the treating monazite with nitrate.

SUSPENDED PARTICULATE MATTER (SPM)

The suspended particulate matter from the neutralisation treatment of chemical effluents produced at the Solvay plant contains an average of 25% rare-earth oxides, which are recoverable by-products.

NUCLEAR FUELS

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

Enriched natural uranium (ENU) fuels are composed of fuel rods containing UO_2 pellets which are themselves grouped together into fuel assemblies. These are the fuels mainly used in EDF's pressurised water reactors (PWR).

Enriched reprocessed uranium (ERU) fuel consists of enriched uranium obtained from spent fuel reprocessing. Use in four authorised PWR reactors, which has been interrupted for about ten years, is scheduled to resume in 2023.

Mixed uranium-plutonium (MOX) fuels are composed of depleted uranium and plutonium obtained from spent fuel reprocessing in the form of (U, Pu)O_2 oxide powder pellets. MOX fuels are manufactured at the Melox plant in Marcoule and are currently used in 22 PWR reactors authorised for this purpose.

Fuel for the Phénix and Superphénix fast neutron reactors (FNR), made from mixed uranium and plutonium oxide, now permanently decommissioned and no longer used.

Civilian CEA fuels are used in special reactors for research purposes. They can also be used in production of radioelements for nuclear medicine and industries outside the nuclear power sector. These are more varied than EDF fuels in terms of shape and of physical and chemical composition, and also far fewer in number. These may be fuels of the oxide, metal, hydride type, etc.

FOCUS — RECOVERY OF SUSPENDED PARTICULATE MATTER AND CRUDE THORIUM HYDROXIDE

The recovery of these materials relates to their rare earth, thorium and uranium content.

Rare earths are used in many everyday consumer products such as flat screens, certain batteries, fibres or optical glass, etc. Approximately 10,000 tonnes of rare earth oxides may be recovered from treatment of suspended particulate matter (SPM) and raw thorium hydroxide (HBTh). Thorium could be useful in nuclear applications in a "thorium cycle". Similarly, some methods are being considered for recovery of thorium in industries outside the nuclear power sector.

However, there are some uncertainties involved in these prospects for recovery, which led ASN, in its opinion of 9 February 2016[4], to consider that it is essential to secure funding for the long-term management of thorium-bearing substances.

4 ASN opinion No.2016-AV-0256 of 9 February 2016 on studies concerning the assessment of the recoverability of radioactive materials submitted in accordance with the French National Radioactive Materials and Waste Management Plan 2013-2015, with the aim of preparing the French National Radioactive Materials and Waste Management Plan 2016-2018.

National Defence fuels used either in reactors to produce material used for the nuclear deterrent, or in the on-board reactors of submarines, ships and their prototypes on land.

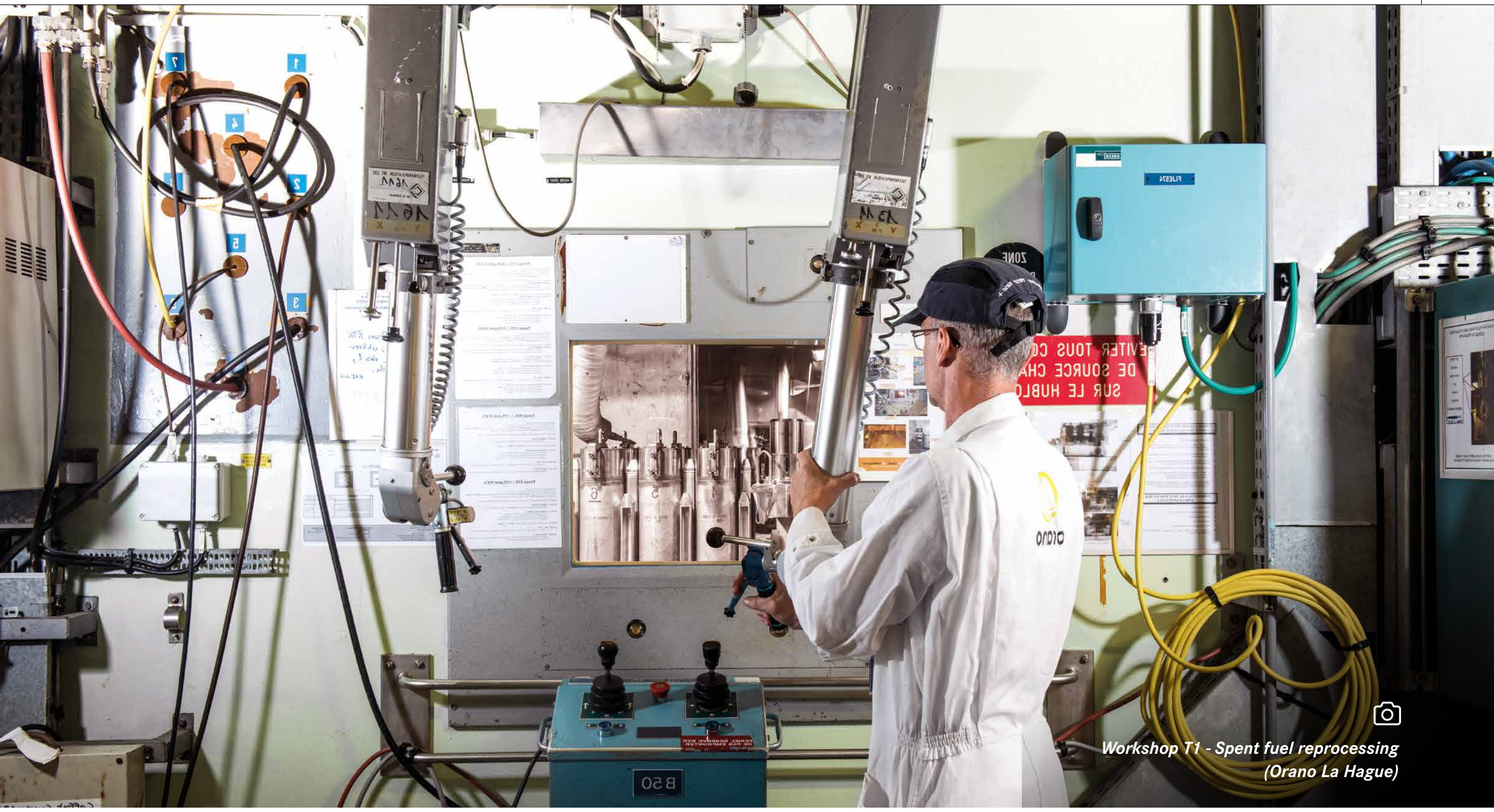
For all these fuels, stocks of fuels are maintained at all times - before use, in use or spent.

New fuels are transported in suitable packaging, by road or rail, from the fuel production plant to the nuclear power plants. As soon as the fuel arrives on site, it is stored in the fuel building ready to be used in the reactor.

Fuel that is currently in use in nuclear power reactors stays there for three to four years. After that, due to its reduced performance, it will be removed and stored in a cooling pool near the reactor before being sent to the Orano La Hague reprocessing plant, where enriched natural uranium fuels are reprocessed in order to extract residual fissile material or produced in the reactor. These materials will be recycled to create new fuel.

It should be noted that classification of a substance as radioactive may be the consequence of a decision made by the State (this is generally the case, for example, with spent fuel) or a decision made by its owner. In the latter case, the supervisory authority may object to this classification and request that it should be classified as radioactive waste.

i A fuel assembly consists of a group of rods held in place by structural grids. These rods are long zirconium alloy tubes that contain stacked pellets of nuclear materials forming the fuel.
A nuclear power plant reactor contains several dozen fuel assemblies.
The wall or cladding of these rods and their end caps ensure containment of radioactive products with respect to water under high pressure and at high temperature.



Workshop T1 - Spent fuel reprocessing (Orano La Hague)

PLUTONIUM OBTAINED FROM SPENT FUEL AFTER REPROCESSING

During the reprocessing of irradiated ENU fuel, the plutonium formed by neutron capture within the reactor is extracted from it.
A spent uranium fuel assembly from a PWR reactor contains about 1% plutonium (by mass). This plutonium has an energy potential about 100 times greater than that of uranium.

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

Plutonium is used today to produce MOX fuel.

The plutonium extracted from spent fuel belongs to Orano customers, French or foreign energy companies. Plutonium is generally shipped to foreign customers in the form of MOX fuel, for use in their reactors.

FUEL SCRAP

Scrap from non-irradiated fuel awaiting reprocessing will eventually be reprocessed and recycled in nuclear power reactors.

OTHER MATERIALS

The new Superphénix core is the fuel that should eventually replace the fuel used during the operation of the plant. Due to the permanent shutdown of Superphénix, this fuel refill was never used and therefore not irradiated.

GENERAL PRINCIPLES FOR MANAGEMENT OF RADIOACTIVE MATERIALS AND WASTE

WASTE MANAGEMENT POLICY

Radioactive waste management principles are governed by a strict regulatory framework, defined at national and international level. France is also a signatory to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, established under the supervision of the International Atomic Energy Agency (IAEA)[5], which defines the management principles.

AT EUROPEAN LEVEL

The Council of the European Union adopted a Directive on 19 July 2011[6] establishing a European Community framework for safe and responsible management of spent fuel and radioactive waste from production to disposal (Euratom Directive).

This directive covers all stages of management of the spent fuel and radioactive waste resulting from civilian activities. Each Member State is ultimately responsible for management of spent fuel and radioactive waste generated on its territory.

The Directive requires each Member State to establish and maintain a framework to develop national programmes for spent fuel and waste management, issue of authorisations, recording of inventories, monitoring and inspection provisions, implementation measures such as suspension of operation, allocation of responsibilities, provision of information and public participation, and financing of waste management. The Directive also stipulates that each Member State shall establish and maintain a competent regulatory authority for management of spent fuel and radioactive waste, subject to certain conditions put in place to ensure its independence.

AT NATIONAL LEVEL

France has defined and implemented a public policy on radioactive waste, within a legislative framework established in 1991 (law of 30 December 1991[7]) and consolidated in 2006 (law of 28 June 2006). These texts are codified in the French Environmental Code.

Led by the Directorate General for Energy and Climate (DGEC) within the Ministry for Ecological Transition and Territorial Cohesion, this policy has three pillars:

- a National Radioactive Materials and Waste Management Plan (PNGMDR)[8], updated every five years by the State and establishing a research and implementation programme, with a timetable;
- provisions for independent evaluation of research, public information and dialogue with all stakeholders;
- guaranteed availability of the necessary financing: under the polluter pays principle stipulated in Article L. 110-1 of the French Environmental Code, according to which *"the costs resulting from measures to prevent, reduce and combat pollution must be borne by the polluter"*, the waste producer is responsible for financing management of the waste, including in the long term.

FRENCH LAW

Article L. 541-1 of the French Environmental Code establishes the principles of preventing or reducing waste production, the responsibility of producers continuing until the time of disposal of their waste, traceability and the need to inform the public.

The French Environmental Code states that *"sustainable management of radioactive materials and waste of any kind that results, in particular, from operation or dismantling of facilities that use radioactive sources or materials, shall be conducted with respect for the protection of human health, safety and the environment" (Article L. 542-1)*.

Many provisions are implemented to comply with this legislative framework:

- requirements concerning treatment and conditioning, transportation and facilities, as defined by the competent authorities, who then monitor compliance;
- procedures to reduce the volume and toxicity of waste:
  - for the waste generated, the processes of sorting, treatment, conditioning and characterisation of the radiological content. These are defined and implemented by waste producers. Research and development studies are often required and are carried out by different bodies, in particular by the CEA;
- the design and construction of disposal facilities with the necessary level of safety. This involves either storage (as a temporary solution) which is generally the responsibility of the waste producers, or disposal (final permanent solution) for which Andra is responsible *(see Chapter 6 - Special Report 1)*;
- transport and storage or disposal operations, including monitoring and surveillance aspects, including long-term disposal;
- provisions intended to inform the public.

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5 *Joint Convention on the safety of spent fuel management and the safety of radioactive waste management, available at:* http://www-ns.iaea.org/conventions/waste-jointconvention.asp

6 Council Directive 2011/70/Euratom of 19 July 2011 establishing a European Community framework for responsible and safe management of spent fuel and radioactive waste.

7 Law no. 91-1381 of 30 December 1991 governing research on radioactive waste management.

8 PNGMDR (National Radioactive Materials and Waste Management Plan), available on the ecologie.gouv.fr website

CONTROL OF NUCLEAR MATERIALS

Because France has a nuclear energy industry and is aware of its non-proliferation responsibilities, it has adopted regulations and an organisational system to ensure control of nuclear materials. These regulations cover both materials in civilian use and national defence-related materials.

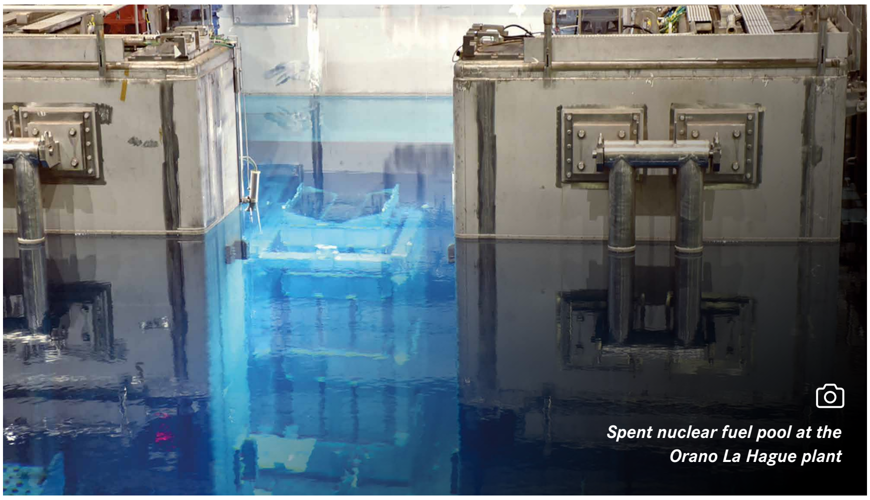
At the national level, the protection and control of nuclear materials are subject to specific regulations under the Defence Code and related regulatory texts.

There are six nuclear materials covered by the French legislation: plutonium, uranium, thorium, tritium, deuterium and lithium 6 *(Article R. 1333-1 of the French Defence Code - it should be noted that deuterium and lithium 6 are not radioactive)*. The relevant definition is reviewed at regular intervals in the context of changes in knowledge and techniques. Only plutonium, uranium and thorium are considered in the *National Inventory*.

The aim of these regulations is to prevent the risk of loss, theft or misuse of nuclear materials, and to protect such materials and the related facilities or transport from malicious acts.

In this context, the regulations impose a number of provisions, applicable in combination with each other, on the operators and manufacturers who hold such materials, such as the following:

- provisions for physical protection of materials from malicious acts and sabotage by placing barriers and other devices between the public domain and the premises where the materials are held;
- provisions for monitoring of materials, which make it possible for the location and use of the materials to be known at any time;
- provisions for accounting, in order to ensure that the exact quantities of materials held are known at any time. Each operator must maintain its own nuclear materials accounting records, which shall be compared regularly with centralised accounts kept by the French Institute for Radiation Protection and Nuclear Safety (IRSN). For example, for plutonium and uranium, accounting is recorded to the nearest gramme;
- containment measures to prevent unauthorised movements of materials;
- surveillance measures with the aim of guaranteeing containment integrity and checking that no materials have been removed by illicit methods.



Spent nuclear fuel pool at the Orano La Hague plant

In order to hold these materials, an operator shall require prior authorisation from the competent authority, which in France is the senior defence and security official of the Ministry in charge of energy. This authorisation is only issued after analysis of a file provided by the operator covering physical protection, monitoring, accounting, etc. This analysis is carried out by the IRSN, which acts in support of the ministerial authority.

Granting of authorisation requires the operator to carry out a safety study to assess the effectiveness and appropriateness of the protection system with regard to reference risks defined by the public authorities. Threats are periodically reassessed by State specialist departments to take account of any developments in the national and international context.

At international level, compliance with the non-proliferation treaty and the Euratom agreement is monitored respectively by the IAEA and by departments of the European Commission. These controls relate, on one hand, to the reporting and monitoring of movements of nuclear materials (plutonium, uranium and thorium) between countries, and, on the other hand, to the reporting of flows and stocks of materials held at national level for nuclear materials that fall outside the scope of the materials assigned to National Defence requirements. When applied to French facilities, these international controls take the form of inspections carried out by Euratom inspectors and, to a lesser extent, by IAEA (trilateral agreement between IAEA, Euratom and France).

ENTITIES INVOLVED IN MANAGEMENT OF RADIOACTIVE MATERIALS AND WASTE

INSTITUTIONAL FRAMEWORK

The National Radioactive Materials and Waste Management Plan (PNGMDR) draws on data from the *National Inventory* to take stock of existing management methods, identify the foreseeable needs for storage or disposal facilities and determine the objectives to be achieved for the radioactive waste for which no permanent management solution has been found, as well as using the work of a multi-disciplinary working group, co-chaired by ASN and the DGEC, composed of representatives of the administration, the safety authorities, radioactive waste managers, waste producers, and representatives of environmental protection organisations.

Within the Ministries for Ecology and Energy:
- the Directorate General for Energy and Climate (DGEC) is responsible for developing policy and implementing government decisions concerning the civilian nuclear sector;
- the General Risk Prevention Directorate (DGPR), and in particular the Nuclear Safety and Radiation Protection (MSNR) mission, works to develop, coordinate and implement the government's missions concerning nuclear safety and civilian radiation protection, excluding the missions entrusted to ASN. This mission also works with ASN to ensure monitoring of issues concerning the management of former uranium mines *(see Chapter 5)* and sites and soils polluted by radioactive substances *(see Chapter 6 - Special Report* 4). The DGPR also works on developing policy for management of conventional waste, including waste containing naturally occurring radioactive material *(see Chapter 5 - NORM).*

On scientific issues in general, and in particular those related to nuclear programmes, Parliament has set up its own evaluation body: the Parliamentary Office for the Evaluation of Scientific and Technological Choices (OPECST). This is an organisation that consults those involved in the management of radioactive materials and waste and publishes assessment reports and recommendations, which can be referred to at senat.fr/opecst

Parliament relies on the National Assessment Board (CNE), which is responsible for making an annual assessment of the progress and quality of research into the management of radioactive materials and waste. This body was created by the law of 30 December 1991, now codified in Article L. 542-3 of the French Environmental Code. The Board publishes an annual report which is sent to Parliament and made public, available on cne2.fr

The National Financing Assessment Board (CNEF) assessing the costs of dismantling of basic nuclear installations and management of spent fuel and radioactive waste is a body created by the law of 28 June 2006, in order to control the financing of long-term nuclear costs.

The High Committee for Transparency and Information on Nuclear Safety (HCTISN) is a body providing information and ensuring consultation and debate on the risks related to nuclear activities and the impact of these activities on human health, the environment and nuclear safety, established by the law of 13 June 2006 on transparency and safety in the nuclear sector (TSN law)[9].
The duties of this body are now specified in Article L. 125-34 of the French Environmental Code.
HCTISN's reports and recommendations are available at hctisn.fr

The Nuclear Safety Authority (ASN), created by the law of 13 June 2006 on transparency and safety in nuclear matters (TSN law), is an independent administrative authority, with duties now as specified in Article L. 592-1 of the French Environmental Code:
- it works on behalf of the State to ensure control of nuclear safety and radiation protection. It monitors waste producers and Andra in their nuclear activities or operations requiring radiation protection measures;
- it also handles the licensing procedures for basic nuclear installations (BNI);
- it provides individual authorisation for possession of certain radioactive sources or certain equipment using ionising radiation;
- it relies on the expertise of the French Institute for Radiation Protection and Nuclear Safety (IRSN).

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

9 French Law No 2006-86 dated 13 June 2006, relating to transparency and safety in the nuclear sector.

RADIOACTIVE WASTE PRODUCERS

In accordance with Article L. 542-1 of the French Environmental Code, producers of radioactive waste are responsible for managing their waste properly before it is removed to a final disposal site. In particular, they must sort and define waste treatment and conditioning methods, in accordance with available technologies, with the aim of reducing the quantity and toxicity of radioactive waste.

They carry out conditioning of waste, under strict quality assurance procedures required by regulations[10]. They ensure storage of waste for which there is not yet any final disposal site.

They are also responsible for transporting conditioned waste to Andra's disposal facilities.

For some waste producers who do not have adequate resources due to the low volume of waste they produce, such as non-CEA research laboratories or hospitals, Andra may also provide waste collection, treatment, conditioning and storage.

HOLDERS OF RADIOACTIVE MATERIALS

The main holders of radioactive materials are as follows:

- Orano operates in every stage of the fuel cycle, apart from use of nuclear fuels. This cycle includes uranium extraction, concentration, conversion, enrichment, fuel production and then spent fuel reprocessing;
- the civilian CEA conducts research in the nuclear field. It uses the fuel in its reactors for research purposes;
- Framatome operates solely upstream of the cycle in production and sale of new fuel assemblies;
- EDF produces electricity by using fuel in its nuclear power plant reactors;
- Solvay extracts rare-earth metals from thorium-containing ores;
- national Defence works for the nuclear deterrent and uses fuel for its naval propulsion activities.

THE ROLE OF ANDRA

The National Radioactive Waste Management Agency (Andra) is in charge of the long-term management of French radioactive waste.

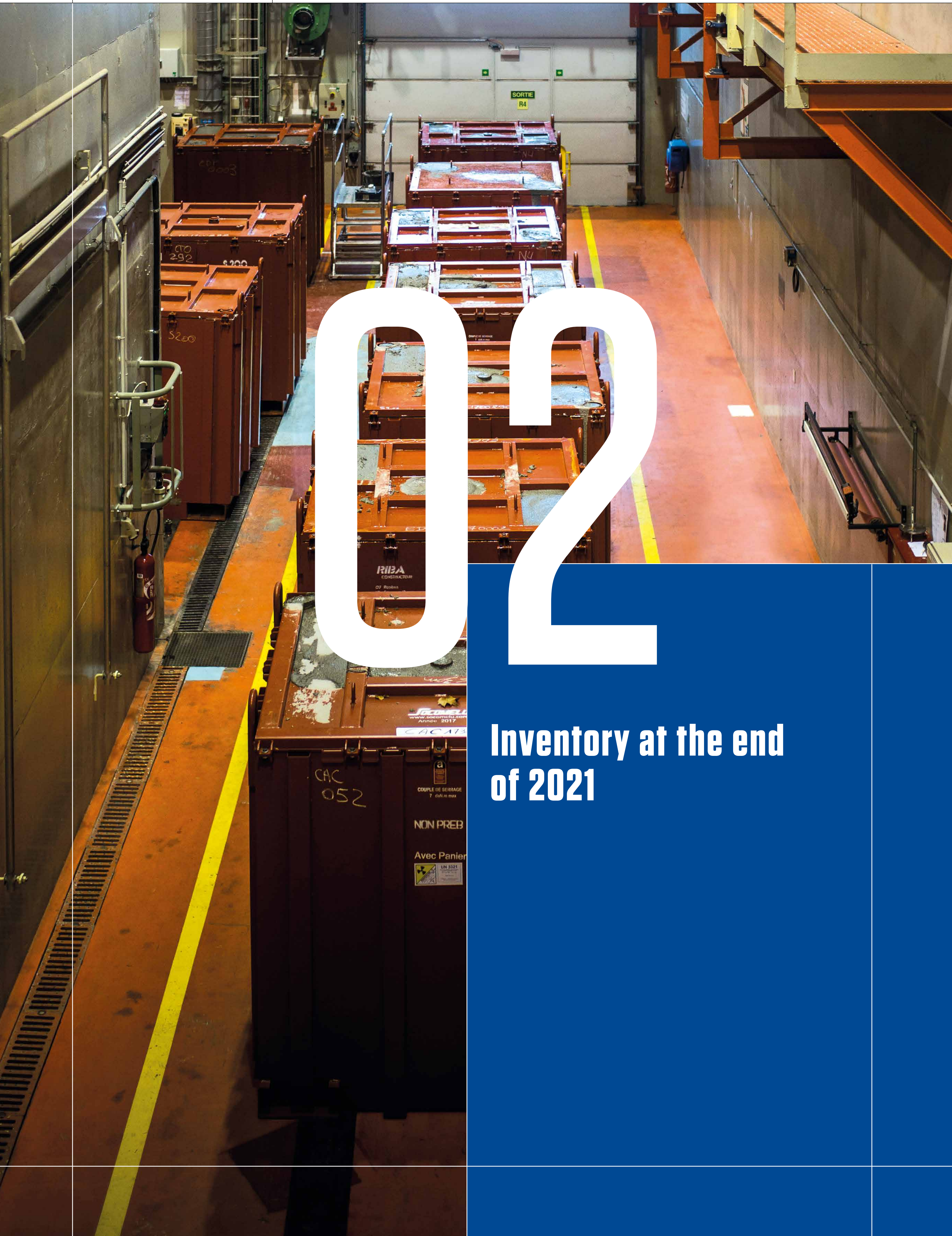
It is a public body operating in industrial and commercial fields (EPIC) with a role that has been successively defined by two laws:

- law of 30 December 1991 concerning research into management of long-lived, high-level radioactive waste. This law created the Agency as a public body, in particular entrusting it with research into deep geological disposal of long-lived high- and intermediate-level radioactive waste;
- framework act of 28 June 2006 on the sustainable management of radioactive materials and waste. This law broadens and strengthens the role of the Agency and its fields of activity;
- Andra's duties are now codified in Article L. 542-12 of the French Environmental Code.

Andra is supervised by the French Ministries for energy, the environment and research and is the public undertaking for the deployment of public radioactive waste management policy. The agency operates independently to producers of radioactive waste.

The State sets Andra's objectives by means of a contract covering objectives and performance. The most recent version of this contract covers the 2022-2026 period. It is available on Andra's website.
andra.fr

10 Order of 7 February 2012 stipulating the general rules concerning basic nuclear installations.



02

Inventory at the end of 2021

The first section of this chapter provides a quantitative overview of the inventory materials and waste at the end of 2021, and the second section indicates, for each of the economic sectors, the radioactive materials and waste listed on 31 December 2021.

Scope of waste included in the inventories

Although the majority of radioactive waste comes from the nuclear power industry and related research activities, there are many other sectors that also generate radioactive waste, such as industries outside the nuclear power sector, defence, research outside the nuclear power industry or medicine.

This chapter presents the balance sheets of the inventory statements made by producers or holders of radioactive materials and waste in 2022. In accordance with Decree No. 2008-875 of 29 August 2008 and the Order of 9 October 2008, as amended by the Orders of 4 April 2014 and 16 March 2017, these statements concern the inventory of radioactive materials and waste present on these sites as of 31 December 2021.

In total, the 2023 edition lists nearly 1,000 geographical sites under the terms of *the National Inventory (see Appendix 1)* at which radioactive materials and waste were located at the end of 2021. Details of the sites covered can be found at inventaire.andra.fr.

Waste package collection building at Cires

Waste not included

The waste considered for the balance sheets does not take account of waste subject to "specific" management methods. This covers:

- tailings from processing of uranium ore present on former mining sites. The *National* Inventory identifies 16 sites where these tailings are stored permanently on site;
- legacy waste that may have been disposed of in or near nuclear facilities, conventional waste disposal facilities, placed in legacy repositories or disposed of at sea.

The following are also not quantified in the inventories:

- radioactive substances located on contaminated sites that have hosted activities handling radioactivity (*see Chapter 6 - Special Report 4*);
- very short-lived waste (VSLW), which is managed by on-site decay before disposal by means of conventional solutions. It is therefore not sent to a dedicated radioactive waste disposal facility;
- uranium conversion treatment tailings (RTCU) generated by the Orano Malvési plant are shown separately. In 2014 and 2015, under the National Radioactive Materials and Waste Management Plan (PNGMDR), Orano submitted studies on the long-term management of this waste, which is stored in settling and evaporation ponds, and is not conditioned. Studies for on-site disposal are still ongoing. Pending a decision, this waste is presented separately in the quantified records of existing waste as at 31 December 2021.

INVENTORY BY CATEGORY

RADIOACTIVE WASTE

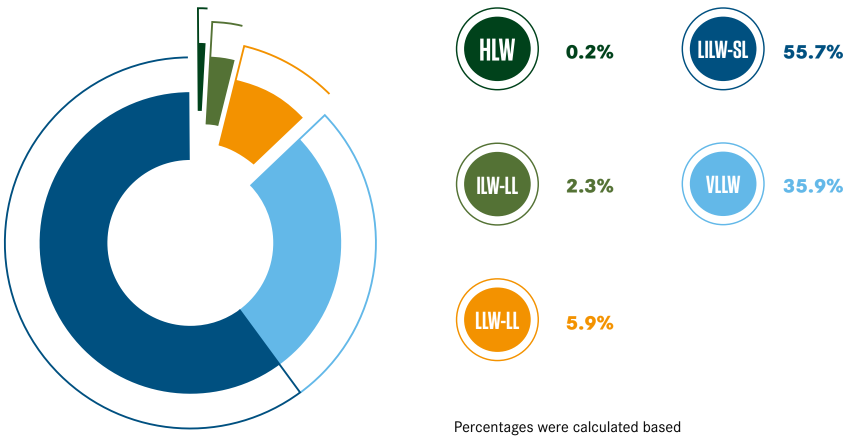
Article L. 542-1-1 of the French Environmental Code defines radioactive waste as *"radioactive substances for which there is no future use planned or envisaged, or which have been reclassified as such by the administrative authority in accordance with article L. 542-13-2. Final radioactive waste is radioactive waste that can no longer be processed, under current technical and economic conditions, in particular by extraction of the recoverable part or by reducing its polluting or hazardous nature".*

VOLUMES OF RADIOACTIVE WASTE AT END OF 2021

The volume of radioactive waste identified from the start of waste production to 31 December 2021 is approximately 1,760,000 m^3 (conditioned equivalent volume), i.e. approximately 220,000 m^3 more than on 31 December 2016 (2018 edition of *the National Inventory*).

The volumes of radioactive waste present on French territory on 31 December 2021, including foreign waste intended for return to its country of origin (*see box on page 32 - Foreign Waste and Materials*), are shown in the table and graph opposite. In the table, these volumes are compared to those present at the end of 2016.

Waste volume distribution by waste category



Percentages were calculated based on the exact figures, then rounded.

Inventory and changes in waste by category

Category	Volume at end of 2021 (m^3)	Change 2021/ 2016 (m^3)
HLW	4320	+ 670
ILW-LL	39500	- 5,470
LLW-LL	103000	+ 12,600
LILW-SL	981000	+ 64,100
VLLW	633000	+ 150,000
DSF*	304	- 1,500
Total	~ 1,760,000	+ 220,000

* Waste without a specific disposal solution represents just under 0.1% of the total volume of waste and is not shown in the diagram below.

FOCUS – UNIT OF VOLUME USED

The unit adopted for the inventory records is the "conditioned equivalent volume". It allows waste to be accounted for using a single, common unit.

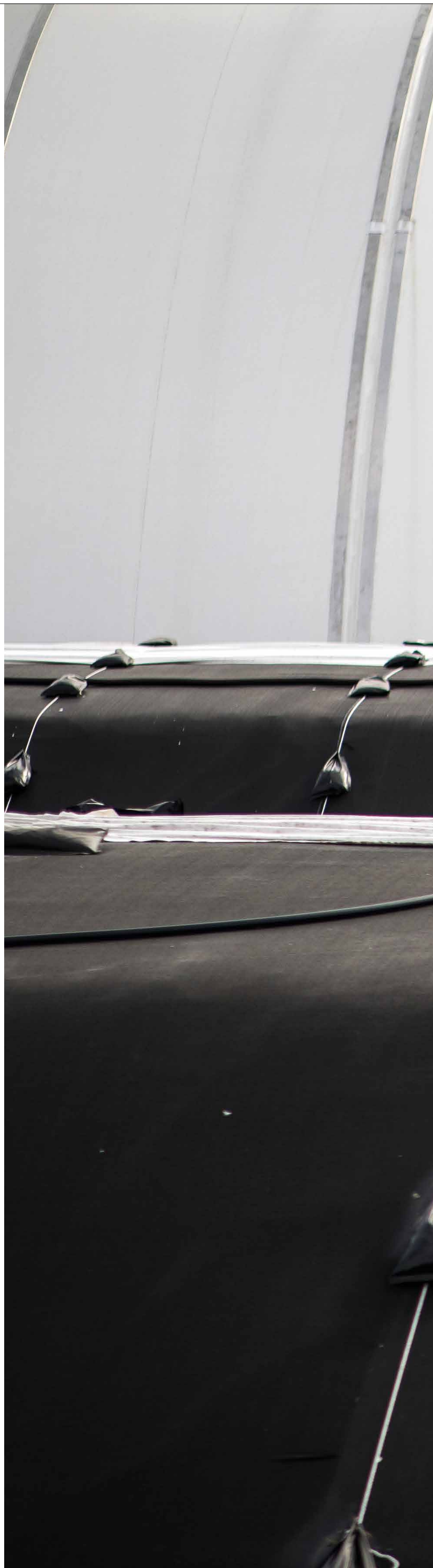
Stated waste volumes are those of conditioned waste, i.e. waste that the producers do not intend to process further before disposal.
This conditioned waste constitutes primary packages.

For waste that has not yet been conditioned, the conditioned equivalent volume is estimated, corresponding to the primary package envisaged, based on the assumptions to date.

A primary package may potentially be placed in a disposal container to provide handling, containment and possible retrievability functions. This volume is not included in the "conditioned equivalent volume".

The volumes shown in the table on page 29 are based on a certain number of assumptions, detailed in the waste stream data sheets available on the Internet (inventory.andra.fr). The main assumptions are:

- assumptions about conditioning for non-conditioned waste. In accordance with the amended decree of 9 October 2008, producers must declare *"the conditioned equivalent volume of waste, including for non-conditioned or preconditioned waste, according to the related conditioning assumptions"*. The assumptions applied by the waste producers correspond to the best assessment available at the time of providing the statement. They may be under study or under discussion with the French Nuclear Safety Authority (ASN) or Andra with the aim of disposal;
- waste from dismantling operations is accounted for if the dismantling operation actually took place on 31 December 2021. For this reason, the LLW-LL graphite waste that is still in the GCR reactor boxes (stacks, reflectors in place, support areas) are not counted in the inventory at the end of 2021, but are taken into account in the waste volume forecasts, according to their forecast dismantling date *(see Chapter 3)*;
- if the study of the management solution for a particular waste category is still in progress, this category is classified according to the assumption adopted by the waste producer. Andra checks the proposed classification. The choice of category does not presume that waste is accepted at the disposal facility;
- foreign waste mentioned in Article L. 542-2-1 of the French Environmental Code, intended for return to foreign customers, is accounted for with the waste present at the Orano La Hague plant;
- spent sources other than lightning conductors (sealed sources, smoke detectors, source rods, source rod assemblies, etc.) are covered by a specific category not linked to the waste classification management solutions, except for old packages stored at Cadarache (ILW-LL package of "source blocks"). In this edition, no conditioned equivalent volume is assigned to these sources, due to the variability of possible management and conditioning assumptions at this stage. Lightning conductors are assigned to two waste categories, of type LLW-LL.



VLLW waste disposal cells

FOCUS — WASTE FROM THE ORANO MALVÉSI SITE

The Orano Malvési industrial site (Narbonne) has been carrying out the first stage of the necessary conversion for the nuclear fuel cycle since 1960. It is the sole point of entry into France for natural uranium from mines, and it purifies this uranium and transforms it into uranium tetrafluoride (UF_4). The liquid effluents from the process are neutralised with lime and then channelled into the settling ponds where the solids separate from the liquids. The settling ponds are therefore filled as the solid fraction of the effluents (fluorine and metal hydroxide sludge) constituting the solid waste of the conversion process increases. The liquid fraction of the effluents (nitrated liquids), clarified by settling, reaches the evaporation ponds where it is concentrated by the natural evaporation process.

Waste from the Orano Malvési pond is shown separately in the quantified balance sheets for the existing inventory of waste as of 31 December 2021 and in the forecasts pending a decision concerning long-term management of this waste.
The legacy waste from the Orano Malvési plant (ÉCRIN facility, e.g. legacy uranium conversion treatment tailings (RTCU), and evaporation ponds, e.g. nitrated effluent) is stored on site. Research is ongoing to find a safe, long-term management solution in a disposal facility at the Malvési site, given the specific nature of the waste generated (large volumes).

The reduction in the volume of waste from the Orano Malvési plant (- 57,000 m^3) is due to reassessment of the volumes of sludge present in the settling ponds and reduction in volume during the transfer of sludge to the ÉCRIN facility.

For the waste generated since 1st January 2019, Orano has worked on two projects intended, on one hand, to reduce the volume of solid waste generated and favour use of existing waste management solutions, and, on the other hand, to treat the process liquid effluents (with a thermal process), together with those already stored in the evaporation ponds. These changes in the process lead to differentiation of two categories of waste to be generated:

- solid waste, composed of fluorines and gypsum, produced by the plant in the form of densified sludge and stored in cells on the site;
- solid waste resulting from the heat treatment of nitrate-containing liquid effluent, produced by operation of the conversion facilities, but also by the recovery of waste already stored in the evaporation ponds.

RTCU waste generated after 2019 is no longer considered to be comparable to legacy RTCU and, after treatment and packaging, is included in the VLLW and LLW-LL management solutions in accordance with Article 63 of the Order of 23 February 2017 (Decree No. 2017-231).

Orano Malvési waste	Volume on-site at end of 2021 (m^3)
Settling ponds	39,000
ÉCRIN Facility	258,000
Evaporation ponds	372,000
Total	669,000

Orano Malvési waste	Volume at end of 2016 (m^3)	Change 2021/ 2016 (m^3)
Total	612,000	- 57,000

* Quantities given are expressed as gross volume.

FOCUS — FOREIGN MATERIALS AND WASTE

France has adopted the principle of prohibiting disposal in France of radioactive waste from abroad. This principle was introduced into the law in 1991, taking account of the industrial activities of reprocessing spent nuclear fuel or radioactive waste, and was reaffirmed and clarified by the law of 28 June 2006 codified in the French Environmental Code.

The French nuclear industry has developed a technology for reprocessing spent fuel, with a view to removing recoverable materials (uranium and plutonium) for other uses in the nuclear power sector and separating out the final waste for disposal. This technology, applied to the French nuclear cycle, was shared with foreign energy companies by the CEA in the 1970s (by contract). From 1977, the CEA, then Cogema, which subsequently became Areva and is now Orano, included a clause in all their contracts allowing the final waste from the reprocessing of their fuels to be returned to these foreign customers.

In order to monitor compliance with these provisions, the operators concerned must, in accordance with Article L. 542-2-1 of the French Environmental Code, prepare a yearly report on the condition of waste and flows of foreign radioactive substances, including a forecasting component.

These reports are public:

- CEA report – Information concerning operations related to spent fuel or radioactive waste from abroad – 2022 report, available on the CEA website: cea.fr;
- Orano Report – Treatment of foreign spent fuels at the Orano La Hague facilities – 2022 Report, available on the Orano website: orano.group

Spent fuel transport packaging

DEVELOPMENTS SINCE THE 2018 EDITION

The changes observed between volumes of waste at the end of 2016 and those at the end of 2021 are not only due to current waste production, but also to other changes, the main examples of which are described in detail below.

HLW

The changes in the HLW waste inventory at the end of 2021 largely corresponds to current waste production resulting from the vitrification of fission product solutions generated by spent fuel reprocessing at the Orano La Hague plant.

ILW-LL

The inventory volume at the end of 2021 decreased by about 5,470 m^3 compared to the volume at the end of 2016, presented in the 2018 Edition.

the current production of ILW-LL waste, acts counter TO the recategorisation of part of the solid waste and cemented sludge from CEA Cadarache (initially ILW-LL in LILW-SL) and a significant proportion of the asphalt packages from CEA Marcoule (initially ILW-LL in LLW-LL) because of their radioactive content.

These recategorisations are accompanied by a modification of the reconditioning scenario: the increase in the conditioned equivalent volume in the LILW-SL and LLW-LL categories is greater than the decrease in conditioned equivalent volume in the ILW-LL category. This increase does not correspond to an increase in the quantity of radioactive waste.

LILW-SL

The increase in the volume of LILW-SL waste at the end of 2021 is largely explained by five additional years of operation of the

nuclear power reactor fleet and the dismantling operations carried out during this period.
the recategorisations of ILW-LL and LLW-LL have also applied.

LLW-LL

The volume of LLW-LL waste has increased by about 12,600 m^3 since the last edition of the *National Inventory.* Current annual waste production in this category is composed of radium-bearing waste from the Framatome Jarrie site and process sludge produced by the Orano Malvési natural uranium conversion plant.

The change in volumes is due to a balance between:

- the recategorisation of all structural waste from GCR fuels stored in silos 115 and 130 of the Orano La Hague site (initially LLW-LL in LILW-SL) due to changes in assumptions in recovery operations, in particular for conditioning and the rate of incorporation of magnesium waste;
- the recategorisation of a proportion of the CEA Marcoule asphalt packages (initially ILW-LL) following the improvement in knowledge and incorporation of its radiological decay, in accordance with the forecast disposal handover date.

VLLW

In comparison with the figures at the end of 2016, an increase was recorded in the volume of VLLW waste of approximately 150,000 m^3 at the end of 2021, mainly due to dismantling operations.

The reduction in the volume of waste without a specific disposal solution is due to identification of a waste management stream for part of this waste, in particular the oils and organic waste, being directed into the VLLW or LILW-SL categories.

RADIOLOGICAL CONTENT OF RADIOACTIVE WASTE AT END OF 2021

Radiological activities as of 31 December 2021 are declared by waste producers.

For the VLLW and LILW-SL waste, the producers report the activity of the waste present on their sites. Andra reports the activity of the waste present in its disposal facilities. This activity is estimated according to a method based on measurements or evaluations by calculation.

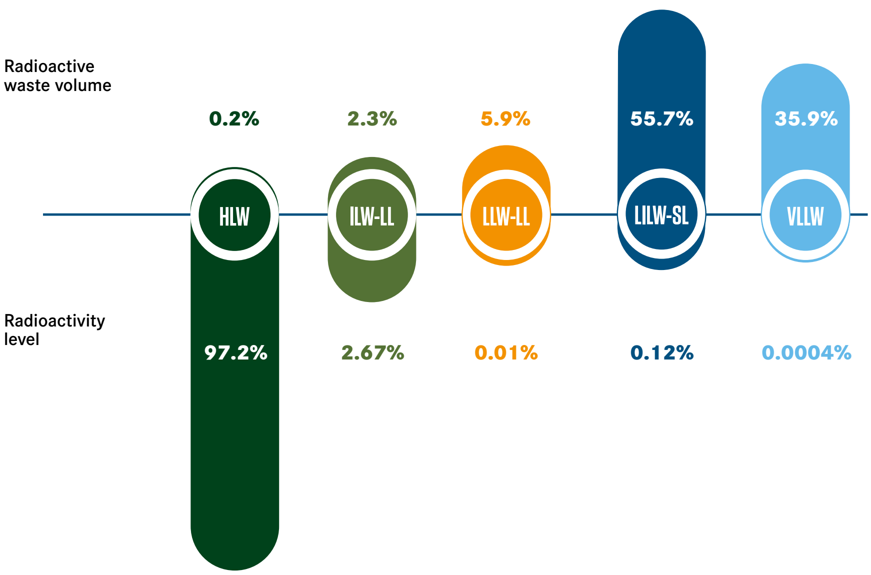
In the case of HLW, ILW-LL and LLW-LL waste, the activity is measured during the production of the waste packages. The activity of waste awaiting conditioning is estimated by calculation or on the basis of analyses performed on samples. This information will be refined during their conditioning. The total activity reported by the waste producers is in the region of 226,000,000 TBq.

The table and graph below summarise the total reported activity.

ACTIVITIES REPORTED AS OF 31 DECEMBER 2021

Category	Activity at end of 2021 (TBq or 10^{12} Bq)
HLW	220,000,000
ILW-LL	6,060,000
LLW-LL	20,200
LILW-SL	281,000
VLLW	968
Total	~ 226,000,000

BREAKDOWN OF VOLUMES AND RADIOACTIVITY LEVELS FOR WASTE INVENTORY AT END OF 2021



Percentages were calculated based on the exact figures, then rounded.

The activity reports as of 31 December 2021 show that:

- **HLW waste contains 97.2% of the total activity** of the radioactive waste present at 31 December 2021. This is the waste extracted from spent fuels (fission products and minor actinides produced in reactors). The main radionuclides contributing to this activity are caesium-134, caesium-137 and its metastable daughter product barium-137, strontium-90 and its daughter product yttrium-90;
- **ILW-LL waste accounts for 2.67%** of total radioactivity. Activated waste from reactors and structural waste from nuclear fuels (compacted hull and end caps packages (CSD-C) and cemented hull and end caps packages) contribute to nearly 75% of the total ILW-LL waste activity. The main radionuclides contained in the activated waste are iron-55, cobalt-60, cadmium-109 and tritium for short-lived emitters, nickel-63 and metastable silver-108 for long-lived emitters. In the case of fuel structure waste, the radionuclides contributing most to the activity are iron-55, strontium-90 and its daughter product yttrium-90, caesium-137 and its metastable daughter product barium-137, tritium and cobalt-60 for short-lived emitters and nickel-63 for long-lived emitters;
- **LLW-LL waste represents 0.01%** of total radioactivity. The graphite waste mainly contains 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 mainly contains naturally occurring alpha-emitting radionuclides (radium, uranium, thorium, etc.);
- **the LILW-SL waste accounts for 0.12%** of total radioactivity. The solid waste packages produced by the CEA and Orano La Hague and EDF's ion exchange resin packages are the waste categories that contribute the most to the LILW-SL inventory activity;
- **VLLW waste represents 0.0004%** of total radioactivity.

RADIOACTIVE MATERIALS

A radioactive material is defined in Article L. 542-1-1 of the French Environmental Code as *"a radioactive substance for which there is a future use planned or envisaged, after processing if necessary" (see Chapter 1).*

The following radioactive materials are presented in this chapter:

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

QUANTITIES OF RADIOACTIVE MATERIALS

The quantities of radioactive materials present on French territory as of 31 December 2021, including foreign materials referred to in Article L. 542-2-1 of the French Environmental Code are shown in the table below.

The unit used to present the quantities of radioactive materials is the tonne of heavy metal (tHM), a unit 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).

INVENTORY AND CHANGES IN RADIOACTIVE MATERIALS

Radioactive materials	Mass at end of 2021 (tHM excluding spent fuels from national defence in tonnes)	2021/2016 trend (tHM excluding spent fuels from national defence in tonnes)
ENU fuels before use	733	+ 285
ENU fuels in use in nuclear power plants	3,970	- 476
Spent ENU fuels pending reprocessing	11,200	- 198
ERU fuels before use	-	-
ERU fuels in use in nuclear power plants	-	- 53
Spent ERU fuels pending reprocessing	630	+ 52
Mixed uranium-plutonium fuels before use or under manufacture	11	- 27
Mixed uranium-plutonium fuels in use in nuclear power plants	215	- 215
Spent mixed uranium-plutonium fuels pending reprocessing	2,390	+ 558
Non-irradiated mixed uranium-plutonium fuel scrap pending reprocessing	337	+ 70
Non-irradiated uranium fuel scraps pending reprocessing	-	-
Spent FNR fuels pending reprocessing	125	+ 5
Research reactor fuels before use	0.04	+ 0.04
Fuel in use in research reactors	0.7	- 0.1
Other civil spent fuel	61	+ 1
National Defence spent fuel	202	+25
Non-irradiated separated plutonium, in all its physical-chemical forms	65	+ 11
Mined natural uranium, in all its physical-chemical forms	37,800	+ 7,910
Enriched natural uranium, in all its physical-chemical forms	3,290	- 562
Enriched uranium from spent fuel reprocessing, in all its physical-chemical forms	-	-
Uranium from spent fuel reprocessing, in all its physical-chemical forms	34,200	+ 4,580
Depleted uranium, in all its physical-chemical forms	324,000	+ 14,300
Thorium, in the form of nitrates and hydroxides	8,510	- 54
Suspended particulate matter (by-products from processing of rare earth ore)	5	- 0.1
Other materials	70	-

Yellowcake

DEVELOPMENTS SINCE THE 2018 EDITION

The changes recorded between quantities of radioactive materials in the 2018 Edition and the 2023 Edition of *the National Inventory* are due to:

- the routine operation of the French nuclear power plant fleet;
- the reprocessing of spent ENU fuel, which allows extraction of the plutonium and the uranium it contains, resulting in a continuous increase in the volume of uranium obtained from spent fuel reprocessing;
- storage of spent fuel of mixed uranium-plutonium (MOX), ERU, scrap, depleted uranium and RepU pending recovery;
- operational difficulties encountered by the Mélox plant, in particular resulting in an increase in the stock of non-irradiated separated plutonium and scrap, a decrease in production of MOX assemblies, offset by additional ENU fuels;
- occasional recovery of thorium and suspended particulate matter in industries outside the nuclear power sector and medicine.

Some countries have chosen not to reprocess their spent fuel.
In the United States, spent fuel is stored in pools near to the reactors that generated it. After the temperature of the fuels has decreased sufficiently, the fuel assemblies are taken out of the pools to be stored dry, under circulating air, inside a storage system with thick walls providing protection from radiation.
In Sweden, spent fuels are collected and stored underwater in a subsurface facility (25 metres) pending commissioning of geological disposal.

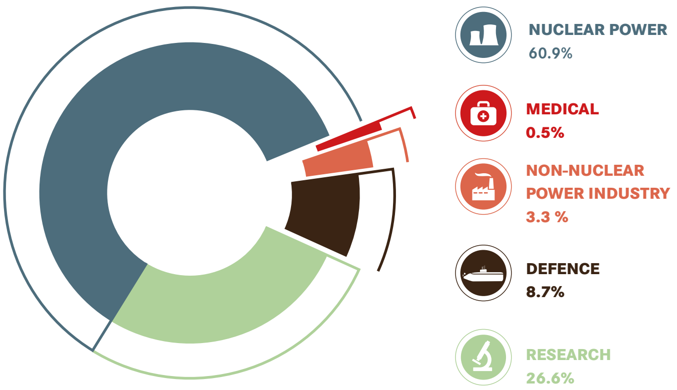
INVENTORY OF WASTE BY ECONOMIC SECTOR

In this section, the radioactive waste and radioactive materials listed on 31 December 2021 are presented according to their economic sector.

The five economic sectors are defined as follows:

- **the nuclear power sector** which mainly comprises nuclear power plants for electricity production well as facilities dedicated to producing nuclear fuel (mining and processing of uranium ore, chemical conversion and enrichment of uranium concentrate), reprocessing spent fuel and reprocessing of spent nuclear fuel;
- **the research sector** including civil nuclear, medical, nuclear and particle physics, agronomic, chemical and biological research, etc.
- **the defence sector** which mainly concerns the nuclear deterrent, 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 mainly include rare earth mining, production of sealed sources, as well as a range of applications such as weld inspections, sterilisation of medical equipment, and sterilisation and preservation of food products, etc.;
- **the medical sector** which includes diagnostic and therapeutic activities (scintigraphy, radiotherapy, etc.).

BREAKDOWN OF RADIOACTIVE WASTE AT END OF 2021 BY ECONOMIC SECTOR



Percentages were calculated based on the exact figures, then rounded.

BREAKDOWN OF TOTAL MASS OF RADIOACTIVE MATERIALS BY ECONOMIC SECTOR

Economic sector	Quantity at end of 2021 (in tHM)
Nuclear power generation	421,000
Research	218
Defence	202 tonnes
Industries outside the nuclear power sector	6,340
Medical	-

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

Volume at end of 2021 (m³)	Nuclear power generation	Research	Defence	Industries outside the nuclear power sector	Medical
HLW	3,930	159	232	-	-
ILW-LL	26,200	8,090	5,060	172	3
LLW-LL	50,100	13,100	19,100	20,700	98
LILW-SL	637,000	248,000	65,700	22,300	8,400
VLLW	355,000	200,000	62,800	14,900	103
Total	~ 1,070,000	~ 470,000	~ 153,000	~ 58,100	~ 8,610

NUCLEAR POWER SECTOR

This economic sector includes nuclear power plants, fuel cycle facilities, waste treatment facilities and maintenance centres for facilities in this sector.

This sector generates all types of radioactive waste. It includes all radioactive materials concerning ENU, MOX and ERU fuels, as well as plutonium, thorium and uranium in all its physical-chemical forms. New and irradiated Superphénix fuels are included in this sector.

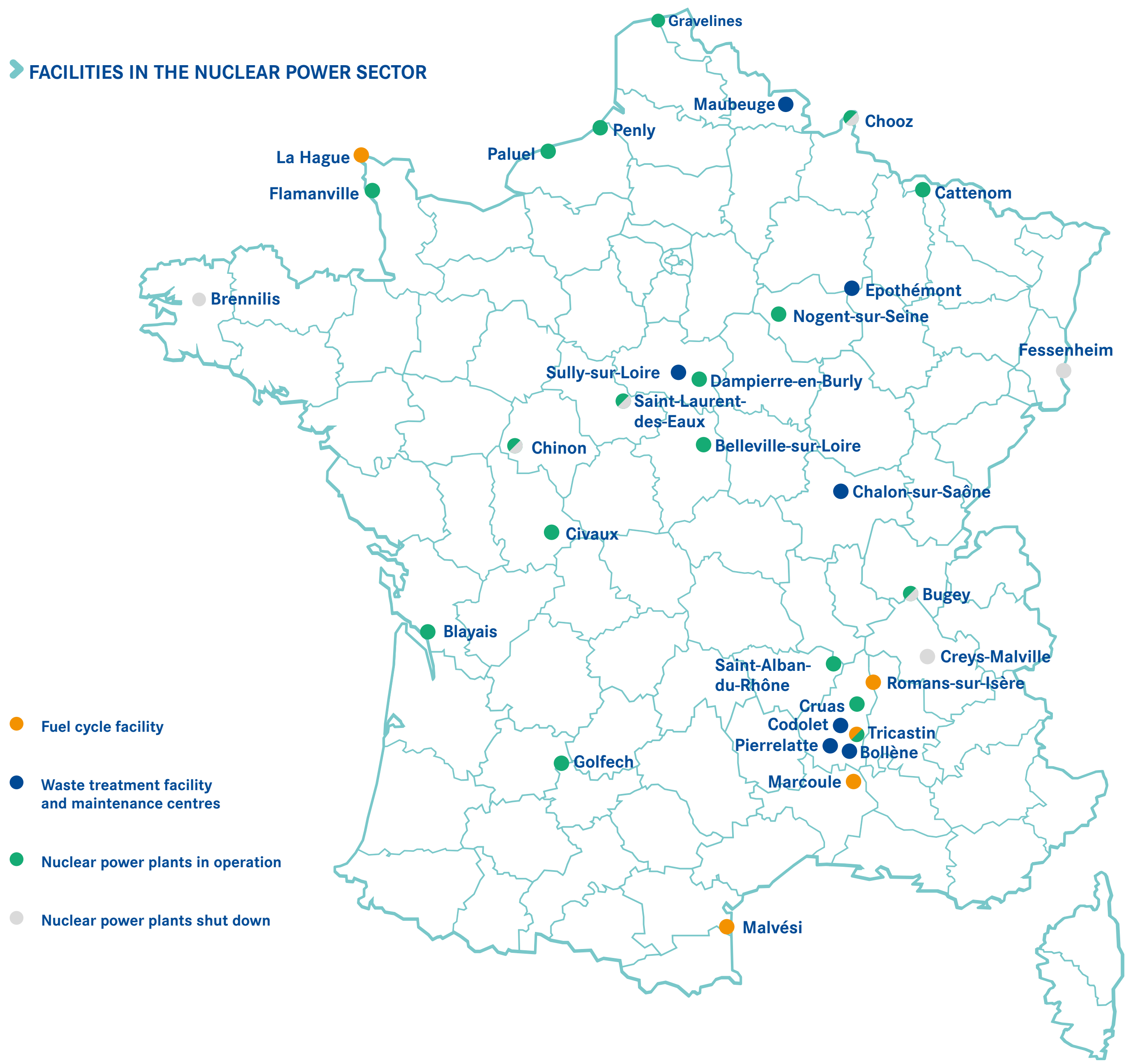
NUCLEAR POWER PLANTS

Reactors in operation

Since the shutdown of the two reactors at the Fessenheim power plant in 2020, the French nuclear power plant fleet currently consists of 56 operational nuclear reactors located at 18 geographical sites.

These reactors were commissioned in the period from 1977 to 1999 and are primarily operating with enriched uranium (ENU) fuel.

FACILITIES IN THE NUCLEAR POWER SECTOR



An EPR pressurised water reactor (Flamanville site) is under construction and will be added to the operational fleet when it is commissioned in 2024[1].

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

In addition to HLW and ILW-LL resulting from spent fuel reprocessing from nuclear power plants, the operation of the reprocessing plant also generates ILW-LL, LILW-SL and VLLW waste.

The ILW-LL waste produced by reactors in the operational phase is mainly poison clusters (fixed clusters used to reduce core reactivity during the first operating cycle) and control clusters (mobile clusters with absorber rods that slide into the fuel assembly in order to regulate the reactor power).

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

LILW-SL and VLLW waste consists of equipment, filtration/purification residues (resins, filters, sludge, etc.), consumables (vinyl, cotton uniforms, etc.) or scrap parts (taps, tubes, etc.).

This waste has been contaminated by contact with fluids (reactor coolant system water, ventilation air, etc.) that carry fission products or corrosion products activated during their movement in the reactor core.

Except for incinerable waste and scrap metal intended for melting down, which is sent to Cyclife France's Centraco units, the EDF LILW-SL waste is conditioned on the sites of nuclear power plants in concrete packages, or metal drums or boxes.

EDF's VLLW waste is varied in nature. This is waste from the "potential nuclear waste generation areas" of nuclear power plants with a very low level of radioactivity, which is difficult to measure in some cases. Some of this waste is generated by dismantling of older reactors and by the operation of nuclear power plants.

Maintenance operations in the nuclear power plants of the fleet, such as replacement of vessel heads and steam generators, generate large volumes of steel in particular. A Technocentre project for recovery of this VLLW metal waste is under consideration, in accordance with the PNGMDR 2022-2026.

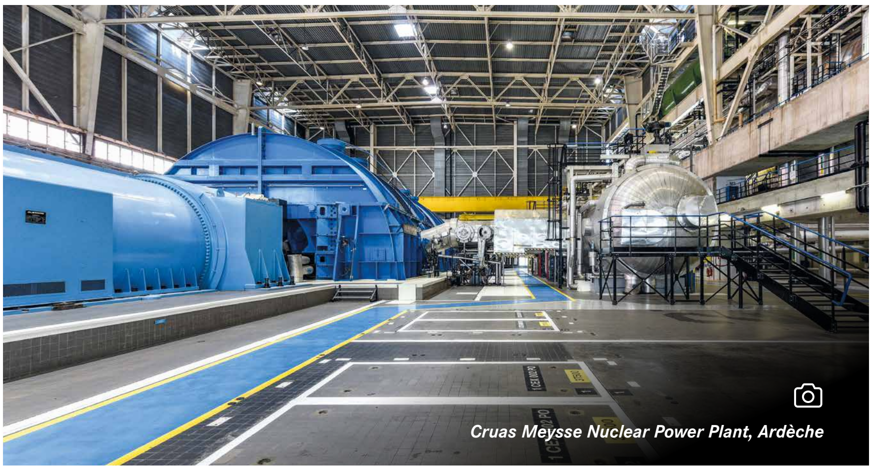
Spent fuel reprocessing: annual generation by a waste reactor of the HLW and ILW-LL categories is about 3 m³. Dismantling: deconstruction of a PWR reactor is envisaged to produce an average of 13,000 m³ of radioactive waste, mainly LILW-SL and VLLW. This quantity incorporates feedback from **EDF and varies according to the power of the reactor.**

FOCUS — FUELS IN NUCLEAR POWER REACTORS

PWR fuel assemblies stay in the core of nuclear power reactors for a few years. Once unloaded, they are then stored in a cooling pool near the reactor before being removed to the Orano La Hague reprocessing plant.

A 900 megawatt reactor uses 157 fuel assemblies continuously, each of which contains approximately 500 kg of uranium. The radioactive material present in nuclear power reactors is predominantly ENU uranium oxide fuel and, to a lesser extent, MOX mixed uranium and plutonium fuel used in 22 licensed reactors.

The use of ERU enriched reprocessed uranium fuel is currently suspended. At the end of 2023, the four reactors of the Cruas nuclear power plant are authorised to use ERU-type fuel made from enriched reprocessed uranium (RepU).



Cruas Meysse Nuclear Power Plant, Ardèche

1 The planned electrical power for the Flamanville EPR is 1650 MWe.

OPERATIONAL REACTORS

Site and Start-up dates (first reactor/last reactor)	Number of reactors in operation in PWR sector	Net power per reactor in MWe*	Number of reactors allowed to load MOX fuel
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	1330	-
Saint-Alban (08/1985 – 07/1986)	2	1335	-
Flamanville (12/1985 – 07/1986)	2	1330	-
Cattenom (11/1986 – 05/1991)	4	1300	-
Belleville (10/1987 – 07/1988)	2	1310	-
Nogent-sur-Seine (10/1987 – 12/1988)	2	1310	-
Penly (05/1990 – 02/1992)	2	1330	-
Golfech (06/1990 – 06/1993)	2	1310	-
Chooz B (08/1996 – 04/1997)	2	1455	-
Civaux (12/1997 – 12/1999)	2	1450	-
18 sites	56 reactors	61.3 GWe	24 reactors

* MWe: electric megawatt.

Reactors in the phase of preparation for dismantling

Since permanent shutdown of its electricity generation on 30 June 2020, the Fessenheim nuclear power plant has entered the phase of preparation for dismantling. Its dismantling is estimated to take 15 years from the entry into force of the dismantling decree. This will be published after an examination period. Dismantling activities may begin upon the entry into force of the decree, which will take place no later than one year after this publication. Dismantling should therefore start in 2026.

Until the decree is obtained and implemented, the preparatory operations for dismantling will be carried out. These operations aim to "reduce the risks and disadvantages present at the installation", including the removal of fuel assemblies to the Orano La Hague reprocessing plant. This also involves removal of waste and effluents and emptying of circuits. At this stage 99.9% of the radioactivity will be removed. During these operations, EDF will also refine its knowledge of the installation: inventories of hazardous materials, asbestos identification, radiological studies, etc.

Reactors undergoing dismantling

EDF operated six reactors of the old GCR system (gas-cooled graphite-moderated reactors) developed by the CEA, spread over three sites: the three Chinon A reactors, the two Saint-Laurent-des-Eaux A reactors and the Bugey 1 reactor. Dismantling of these reactors is underway and the resulting waste is accounted for in this economic sector.

The start of dismantling of the first CGR container, EDF's GCR lead unit, is planned for around 2035. The removal of EDF's LLW-LL graphite waste will begin by 2045, then continue until 2070, with the dismantling of the other GCR reactors. The reconditioning of waste (sleeves) contained in the silos of Saint-Laurent A is scheduled for the beginning of the 2030s. Graphite sleeves stored in silos at the Saint-Laurent-des-Eaux site and at the Marcoule and La Hague sites are accounted for as waste already generated.

Three reactors from three different sectors are also being dismantled. This is the first PWR in Chooz, the Brennilis EL4 heavy water reactor and the Creys-Malville fast neutron reactor.

At the Creys-Malville site, irradiated FNR fuels and the new core of the Superphénix reactor are currently being stored.

REACTORS BEING DISMANTLED

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

FUEL CYCLE FACILITIES

Mined uranium ore is crushed, ground and then impregnated with an oxidising acid solution to dissolve the uranium in order to selectively extract it from the solution. This is followed by several purification steps before obtaining a uranium mine concentrate called *yellowcake*. This is the form in which the ore arrives at the Orano Malvési conversion plant in France.

Yellowcake

Conversion

After the uranium contained in the mining concentrates is purified, it is transformed into uranium hexafluoride (UF_6), and in this form it is in a gaseous state at a temperature of 60°C: this is the conversion stage. This gaseous state is essential for the process used in enrichment plants.

This transformation is carried out in two stages:

- in the Orano Malvési plant, where *yellowcake* becomes uranium tetrafluoride (UF_4);
- then in the Orano Tricastin plant, where a fluorination process is used to transform uranium tetrafluoride to uranium hexafluoride.

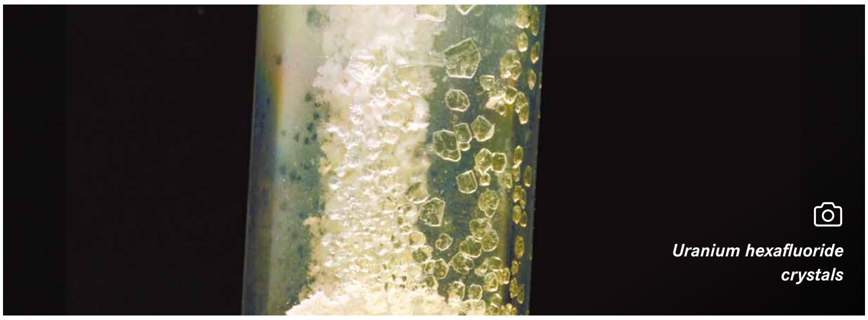
The chemical treatment carried out at the Orano Malvési plant results in solid residues and liquid effluents.

The radioactive material used in the conversion step is mined natural uranium in different physical-chemical forms.

FOCUS — WASTE FROM URANIUM ORE EXTRACTION PROCESS

Uranium mining in France ended in 2001. The ore processing tailings as well as some other resulting waste are permanently disposed of on former mining sites *(see Chapter 5)*.

Open-cast uranium mine



Uranium hexafluoride crystals

Enrichment

Natural uranium mainly consists of two isotopes: uranium-238 and uranium-235. Fissile uranium-235 is much less abundant in its natural state than uranium-238, accounting for only 0.7% of natural uranium.

Enrichment consists in increasing the proportion of uranium-235. The uranium currently used as fuel in most reactors is enriched to about 4% uranium-235.
At the Orano Georges-Besse II plant at the Tricastin site, centrifugation has been used to enrich uranium since 2011.

The fuel conversion and enrichment sites generate radioactive operating waste, with low or very low uranium contamination, which is disposed of at CSA and Cires. It is generally conditioned in drums or boxes.

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

Fuel manufacturing

at THE end of 2023, there are essentially two types of fuels produced for power generation: ENU (made from enriched natural uranium oxide) and MOX (made from mixed uranium and plutonium oxide). The use of ERU fuels (made from enriched reprocessed uranium), which stopped in 2013 for technical and economic reasons, is in the process of being resumed by EDF.

Enriched natural uranium oxide fuel (ENU)

Enriched uranium hexafluoride (UF_6) is transformed into uranium oxide powder, then compacted in the form of pellets to allow manufacturing of ENU fuel. The pellets are introduced into metal sheaths, which hold them in place, to form the fuel assemblies.

The Framatome plant in Romans-sur-Isère carries out these two operations. The waste generated by the plant is essentially VLLW waste from operation and maintenance of installations.

Uranium and plutonium mixed oxide fuel (MOX)

The Orano Melox plant, located at the Marcoule site, has been manufacturing MOX fuel since 1995 using a process similar to the ENU fuel manufacturing process, but using a mixture 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 step is also used.

MOX fuel production at Cadarache is now stopped. Dismantling began in 2007.
Industrial production at the Melox plant started in 1995. Its production licence is for 195 tHM (tonnes of heavy metal) of MOX fuel per year, for use in French and foreign reactors in the light water process.

The waste produced by Melox is LILW-SL and ILW-LL technological waste, some of which is non-irradiating, but it is contaminated with alpha-emitting radionuclides.

Melox also produces non-irradiated mixed uranium-plutonium fuel scrap (pellets, powders, etc.) considered as radioactive material and unable to be recycled directly in the generation circuit. The waste is sent to the Orano La Hague reprocessing plant for storage to be used later.

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

Fuel reprocessing

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

The process for reprocessing spent fuel consists of, on one hand, extracting the recoverable materials uranium and plutonium and, on the other hand, of conditioning the final waste.

The operations carried out in the reprocessing plants can be broken down into three stages:

- **acceptance and storage** in spent fuel pools for cooling the fuel assemblies prior to reprocessing (for a period of a few years);
- **spent fuel assembly reprocessing** by:
  - mechanical shearing of fuel assemblies in sections of approximately 35 mm;
  - chemical dissolving of the spent fuel contained in these sections by use of nitric acid;
  - separation of dissolved plutonium and uranium by use of chemical extraction and purification. Recycled uranium from spent fuel reprocessing (RepU) is transferred to the Tricastin workshop to be transformed into U_3O_8.
    The separated plutonium is sent to the MOX fuel manufacturing plant (Melox);

- **treatment and conditioning** of the final waste in stable forms, suitable for their activity and for the radioactive half-life periods of the elements contained:
  - fission products and minor actinides are incorporated into a glass matrix, poured into a stainless steel container (CSD-V); this waste constitutes the majority of HLW waste;
  - the metal components of PWR fuel assemblies (cladding tubes, grids, end caps) are now decontaminated, compacted and conditioned in standard compacted waste containers (CSD-C). This structural waste used to be mixed in a cement matrix. Compaction has helped to optimise the volume of waste to be disposed of. These two waste categories form a large proportion of the ILW-LL waste;
  - structural waste from GCR system fuel assemblies is currently stored in silos at La Hague, Marcoule or at the Saint-Laurent-des-Eaux site. The conditioning process is currently being studied.

Fuel reprocessing also generates maintenance and operating waste conditioned in different types of containers depending on their type, level of activity and management solution. The ILW-LL solid waste (tools, gloves, filters, etc.) is generally compacted and placed in a drum; the conditioning methods for the sludges resulting from effluent treatment have changed.

Fuel pellets

FOCUS OPERATIONS PERFORMED IN REPROCESSING PLANTS

The spent fuel reprocessing at the first reprocessing plant (on Marcoule) stopped at the end of 1997 and was quickly followed by the start of the dismantling programme, which represents the largest dismantling worksite in France.
These dismantling operations (now under CEA responsibility), excluding support facilities, should produce several thousands of tonnes of waste, most of which can be disposed of in a surface site.
In 1966, a second spent fuel reprocessing plant was commissioned at the La Hague site: UP2-400. It was operated by the CEA until 1976, then by Cogema, which first became Areva and then Orano. It is now stopped. With a capacity of 400 tonnes of fuel per year, the UP2-400 plant first reprocessed spent fuel from the GCR system, and was then adapted to reprocess fuel from the PWR sector.

From 1976 to 1987, the UP2-400 plant alternately reprocessed spent fuel from both the GCR and the PWR sectors.

From 1987, UP2-400 was assigned in particular to the PWR sector, while the Marcoule plant provided reprocessing of fuels from other sectors.

To meet French and foreign requirements, in the early 1980s Orano undertook construction of two new plants, with the same capacity (around 800 tonnes/year each), which are now reprocessing spent fuel at this capacity:

- UP3 (started in 1990) was originally a dedicated plant for spent fuel supplied by foreign customers;
- UP2-800 was commissioned in August 1994, and took over from the UP2-400 plant (shut down since 1st January 2004).

The preferred first step was asphalting, which consisted of coating the sludge in bitumen. Reduction in the volumes of effluents to be treated has substantially reduced the quantities generated and optimisation of the conditioning processes and changes in safety-related constraints have led to the use of other processes such as vitrification or cementing. LILW-SL waste is disposed of at the CSA facility. It can be pre-treated at the Cyclife France Centraco plant by incineration or melting depending on the physical-chemical nature of the waste concerned.

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

WASTE TREATMENT FACILITIES AND MAINTENANCE CENTRES

Operation of the various installations that handle radioactivity is accompanied by ancillary but mandatory industrial operations: the treatment of waste related to operation and maintenance centres. The operator generally carries out this treatment and manages the resulting waste.

In some cases, the operator may use specialist establishments located at other sites that carry out these operations.

Waste treatment centres

Cyclife France's Centraco facility at Codolet runs two processes:

- melting of metal waste;
- incineration of some types of waste.

It handles solid waste that can be incinerated and low-level liquid waste generated by nuclear facilities, research laboratories and hospitals. The resulting ash and clinker are inert and conditioned in packages intended for Andra's industrial centres in Aube. The ingots resulting from melting of metal waste are either recovered to produce radiation protection integrated into the waste packages, or intended to be sent to Andra's industrial centres in Aube. The Orano facility in Bollène specialises in transformation, conditioning and storage of radioactive materials with the aim of decontaminating them. They therefore generate radioactive waste.

Daher in Épothémont is a specialist in sorting and conditioning VLLW waste according to the specifications of Andra or Centraco of Cyclife France. The Onet Technologies Sogeval facility in Pierrelatte offers radioactive waste treatment and storage services.

Maintenance centres

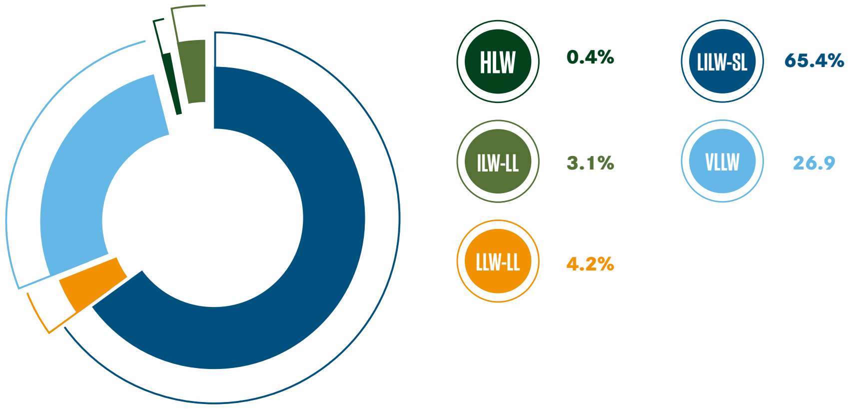
Specialist companies provide maintenance of major installations or decontamination of certain equipment.

These maintenance centres generally hold more limited quantities of waste than waste treatment centres, with most of the waste intended for the Andra LILW-SL disposal facility in Aube.

The company Somanu (nuclear maintenance company), in Maubeuge, specialises in repair, maintenance and expertise for equipment mainly coming from the reactor coolant system and its auxiliaries.

Operated by Framatome, the Tooling Maintenance Centre in Chalon-sur-Saône and the Tooling Maintenance and Decontamination Centre in Sully-sur-Loire carry out maintenance operations on the tooling used during operations on nuclear sites.

RADIOACTIVE WASTE INVENTORY FOR THE NUCLEAR POWER SECTOR



Category	Volume at end of 2021 (m³)
HLW	3,930
ILW-LL	26,200
LLW-LL	50,100
LILW-SL	637,000
VLLW	355,000
Total	~ 1,070,000

Percentages were calculated based on the exact figures, then rounded.

VOLUME OF WASTE FROM THE ORANO MALVÉSI PLANT

Orano Malvési waste	Volume at end of 2021 (m³)*
Settling ponds	39,000
ÉCRIN Facility	258,000
Evaporation ponds	372,000
Total	669,000

* Quantities given are expressed as gross volume.

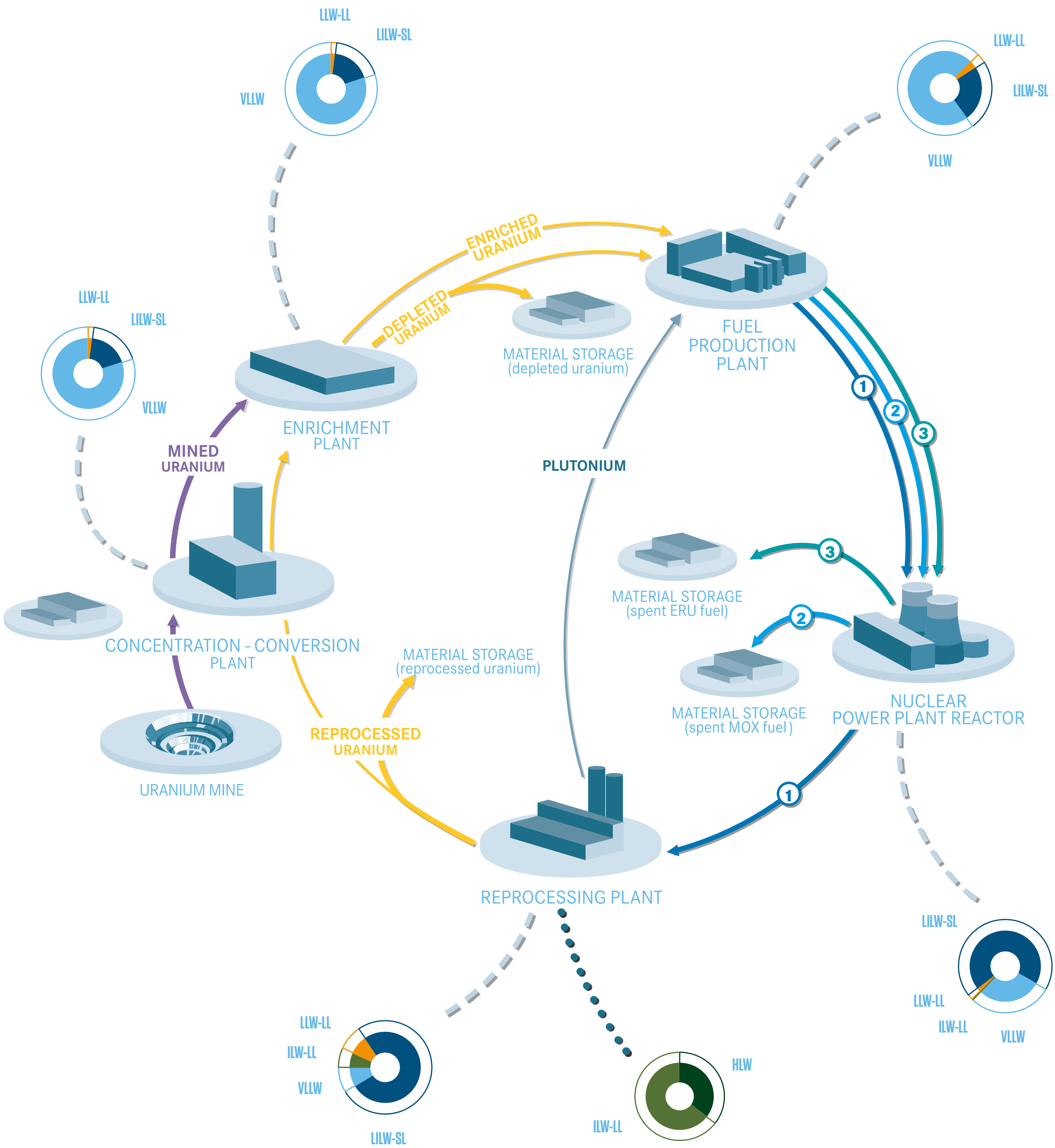
RADIOACTIVE MATERIALS INVENTORY FOR THE NUCLEAR POWER SECTOR

Radioactive materials	Mass at end of 2021 (tHM)
ENU fuels before use	733
ENU fuels in use in nuclear power plants	3,970
Spent ENU fuels pending reprocessing	11,200
ERU fuels before use	-
ERU fuels in use in nuclear power plants	-
Spent ERU fuels pending reprocessing	630
Mixed uranium-plutonium fuels before use or under manufacture	11
Mixed uranium-plutonium fuels in use in nuclear power plants	215
Spent mixed uranium-plutonium fuels pending reprocessing	2,390
Non-irradiated mixed uranium-plutonium fuel scrap pending reprocessing	337
Non-irradiated uranium fuel scrap pending reprocessing	-
Spent FNR fuels pending reprocessing	106
Non-irradiated separated plutonium, in all its physical-chemical forms	63
Mined natural uranium, in all its physical-chemical forms	37,700
Enriched natural uranium, in all its physical-chemical forms	3,290
Enriched uranium from spent fuel reprocessing, in all its physical-chemical forms	-
Uranium from spent fuel reprocessing, in all its physical-chemical forms	34,200
Depleted uranium, in all its physical-chemical forms	324,000
Thorium, in the form of nitrates and hydroxides	11
Other materials (new Superphénix core)	70

FOCUS

PRODUCTION OF RADIOACTIVE MATERIALS AND WASTE BY THE NUCLEAR POWER SECTOR IN FRANCE

① Enriched natural uranium oxide fuel (ENU)
② Uranium and plutonium mixed oxide fuel (MOX)
③ Enriched recycled uranium oxide fuel (ERU)
Operating and dismantling waste - Inventory at the end of 2021
Residual waste after reprocessing spent fuel - Inventory at the end of 2021



RESEARCH SECTOR

The research sector includes all research activities for the nuclear power sector and the medical sector. It does not take account of research conducted for the defence sector, which is included in defence.

This sector includes:
- the facilities and establishments of the four civil studies centres of the French Alternative Energies and Atomic Energy Commission (CEA): Cadarache, Marcoule, Paris-Saclay, Grenoble;
- all public or private research institutions, for example: the European Centre for Nuclear Research in Prévessin-Moëns (CERN), the Laue-Langevin Institute in Grenoble (ILL), the Large Heavy Ion Accelerator in Caen (Ganil) or the Institute of Nuclear Physics in Orsay (IPN d 'Orsay). Most of these establishments use radioactivity in particular as a tool for characterisation.

The radium-bearing waste generated by clean-up of the former Bouchet uranium ore processing plant operated by the CEA between 1946 and 1970 is attributed to this economic sector.

The radioactive materials in the research sector correspond to fuels from research reactors before use, in use or spent. This sector also includes a proportion of plutonium and uranium in all its physical-chemical forms. Phénix fuel awaiting reprocessing also contributes to this economic sector.

CEA CIVIL STUDY FACILITIES

Due to the number and variety of the civil CEA nuclear activities, there is a very varied range of waste generated and needing to be managed, most of which comes from activities related to nuclear energy within the Directorate of Energy (DES).

The DES provides public authorities and manufacturers with expertise and innovation for implementation of a low-carbon energy system. It has an integrated approach covering:
- decarbonised energy production. In particular, it provides support to nuclear industry companies for current and future technologies (2nd and 3rd generation reactors, fuel cycle, 4th generation reactors, SMR, defence);
- the technical operation of the energy system through implementation of energy storage and flexibility tools, intelligent management of demand on the grids and conversion between energies;
- resource management. It helps with better management of materials and substances by working on manufacturing processes, recycling and life cycle analysis of materials.

At the same time, as a civil nuclear operator, DES manages and develops its fleet of nuclear research facilities (research reactors or critical models, hot laboratories to allow conducting of studies on irradiated objects, experimental platforms) and support facilities (workshop, analysis and characterisation laboratory, waste treatment facility, storage, etc.). It conducts construction and renovation programmes for its facilities, as well as clean-up and dismantling programmes for those that have reached the end of service life, and manages the waste generated. In some cases, it develops the methods and tools suitable for these operations.

CEA CIVIL STUDY CENTRE FACILITIES

DES deploys most of its activities in three centres:

Marcoule (Gard)

The nuclear activities of the Marcoule centre are more specifically related to research into the nuclear fuel cycle and completion of major clean-up and dismantling (AD) and waste recovery and conditioning (RCD) sites of the facilities that have been shut down (pilot workshop and plant related to reprocessing, GCR and Phénix reactors, etc.). The facilities of the Marcoule centre in operation (in particular Atalante) are dedicated to the research and development of techniques for preparing uranium, reprocessing spent nuclear fuels, techniques for dismantling nuclear facilities at the end of their service life and for managing the most highly radioactive waste. The Phénix reactor (shut down at the end of 2009) was built and operated by the CEA and EDF, as a research tool in particular for programmes looking at consumption of plutonium and incineration of actinides.

Cadarache (Bouches-du-Rhône)

The nuclear activities of the Cadarache centre are mainly focused on research into optimisation of nuclear reactors and studies of the behaviour of uranium or plutonium-based fuels in various configurations and on fourth-generation reactors.

The site has facilities for R&D on nuclear fuels (experimental reactor of the FNR sector currently shut down: Rapsodie, or the PWR system: Scarabee, Cabri) and irradiated materials, waste treatment facilities, and waste and material storage facilities. The Jules-Horowitz reactor (RJH), currently under construction, will be used for development and qualification of nuclear materials and fuels, but also for nuclear medicine.

FOCUS THE CEA CENTRE IN GRENOBLE (ISÈRE)

The denuclearisation programme for the CEA centre in Grenoble covers six nuclear facilities, the oldest of which dates from 1958: three research reactors (Mélusine, Siloette, Siloé), the active materials analysis laboratory (Lama) and two effluent and nuclear waste treatment facilities (STED). The project consisted of dismantling and clean-up of all six facilities.

The three reactors were decommissioned and demolished. The laboratory (Lama) was decommissioned during 2017. The STED was decommissioned in 2023, as the final step towards denuclearisation of the site.

The Grenoble centre now devotes most of its research to the development of new technologies in the fields of energy, health, information and communication.

Paris-Saclay

The Paris-Saclay centre (bringing together establishments of Saclay and Fontenay-aux-Roses since 2017) is a multi-disciplinary facility performing activities in all civil CEA fields, such as nuclear energy, life sciences, material sciences, climate and environment, technological research and education.

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

The Fontenay-aux-Roses facility is currently undergoing a transformation, moving into medical applications (radiobiology, emerging diseases, innovative treatments and gene therapy, etc.). Its nuclear research facilities, which have been shut down, are covered by a dismantling programme. Most of the waste generated is contaminated with alpha emitters as well as fission products.

At this site, nuclear research concerned the fields of chemical engineering, fuel reprocessing and the chemistry of transuranic elements.

Saclay facility (Essonne)

The main activities of the Saclay facility concern energy, global warming, health (cancer, Alzheimer's disease, prions, etc.), nanosciences, robotics, basic sciences, etc. It also plays a leading role in the design and construction of Very Large Research Infrastructure (TGIR).

Nuclear activities are focused more specifically on upstream research, simulation, materials and chemistry, as well as AD (clean-up and dismantling) and RCD (waste recovery and conditioning) operations. The Saclay facility has heavy nuclear resources (examination laboratories, Orphée and Osiris reactors shut down since 2015) for basic research, research applied to the needs of nuclear power generation, production of medical radioisotopes, research for medical applications. Some of the waste generated is treated and conditioned in the centre's support facilities: BNI 72 for solids and BNI 35 for liquids. Others are transferred to Marcoule or Cadarache for treatment and possible storage, before being removed to an existing or planned Andra site.

RESEARCH FACILITIES (APART FROM CEA CENTRES)

This is a sector of activity that includes all public or private research institutions, as well as largely or wholly dedicated research units of larger institutions or large industrial groups.

Many public or private facilities use radionuclides. Overall, at the end of 2016, Andra had around 500 producers in the field of research (excluding the CEA).

These include:

- medical research laboratories or Inserm, depending on medical or pharmaceutical faculties, located within hospitals or teaching hospitals;
- CNRS laboratories or joint research units related to CNRS, most often located inside faculties, institutes or educational establishments;
- units of the National Institute of Nuclear Physics and Particle Physics (IN2P3), including the Orsay and Caen particle accelerators (Ganil);
- the Laue-Langevin Institute (ILL) reactor in Grenoble and the European Centre for Nuclear Research (CERN) on the French-Swiss border;
- private sector facilities such as Sanofi or L'Oréal;
- reactors and various installations that have been shut down.

In the field of cellular and molecular biology, very short-lived radionuclides are used to mark the 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 non-sealed sources (i.e. small liquid samples). After use, they become liquid waste generally collected by Andra and then sent to Centraco of Cyclife France for treatment.

FOCUS — WASTE THAT WILL BE GENERATED BY THE ITER FACILITY

ITER is a civil international research facility under construction in Cadarache, based on nuclear fusion. It uses a magnetic confinement concept, consisting of using magnetic fields to enclose a plasma in a ring-shaped vacuum chamber called a "tokamak".

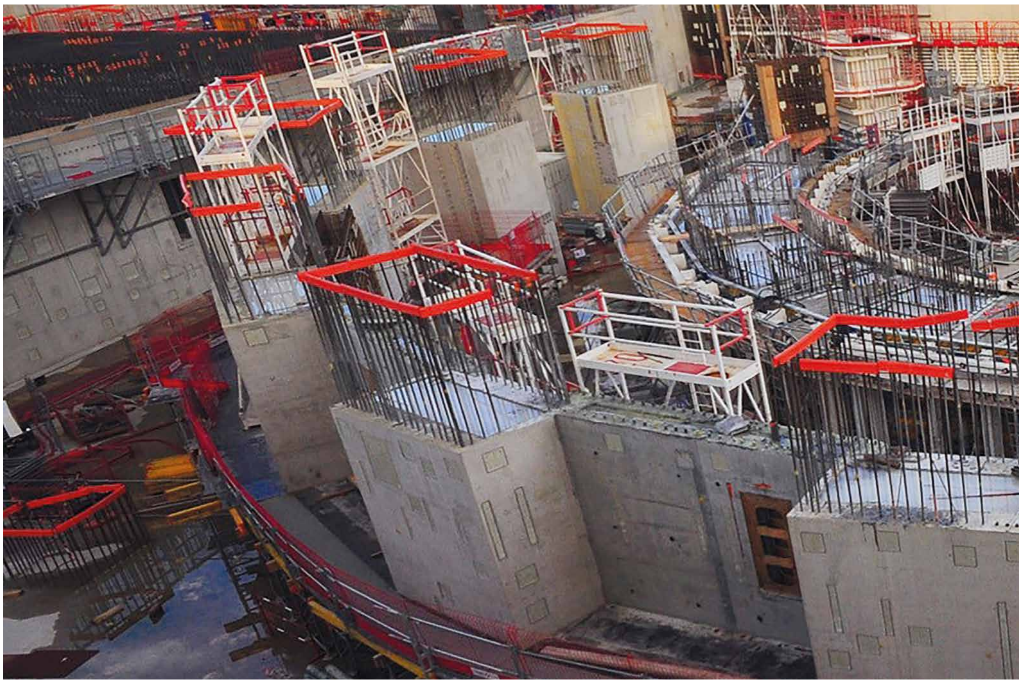
The waste generated by ITER will consist of technological waste such as parts resulting from the replacement of certain components of the machine during its operation, or dismantling waste. This waste will be characterised by the presence of tritium, used as fuel, and radionuclides resulting from activation of the vacuum chamber walls by high-energy neutrons.

According to the ITER reference schedule, the facility will start generating radioactive waste after 2030. The quantities to be generated during its operation are estimated at approximately 15,600 m^3 over the lifetime of thefacility.

The waste generated by dismantling of the facility at the end of its operation is estimated at approximately 143,000 m^3 in total. More than 90% of this waste will be VLLW or LILW-SL waste managed under existing solutions.

ILW-LL waste will be treated, conditioned and stored as part of the processes to be implemented for this type of waste, in accordance with the regulations. ITER will not produce any HLW waste.

Research is currently planned to define materials with low activation under irradiation (such as eurofer), in order to significantly reduce the quantity of waste generated. This is the objective of the IFMIF (*International Fusion Materials Irradiation Facility)* programme. This is a research and development project involving a facility to be built for irradiating materials.



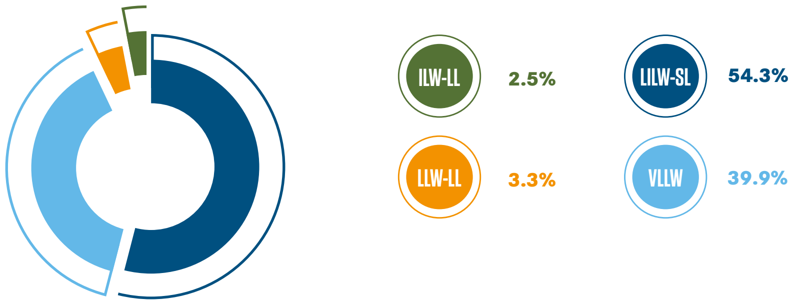
RADIOACTIVE MATERIALS INVENTORY FOR THE RESEARCH SECTOR

Radioactive materials	Mass at end of 2021 (tHM)
Fuel currently in use in research reactors	0.7
Other civil spent fuel	61
Spent FNR fuels pending reprocessing	19
Non-irradiated separated plutonium, in all its physical-chemical forms	2
Mined natural uranium, in all its physical-chemical forms	17
Enriched natural uranium, in all its physical-chemical forms	9
Depleted uranium, in all its physical-chemical forms	109
Thorium, in the form of nitrates and hydroxides	2,260

Waste with a half-life shorter than 100 days is managed on site by decreasing its radioactivity.

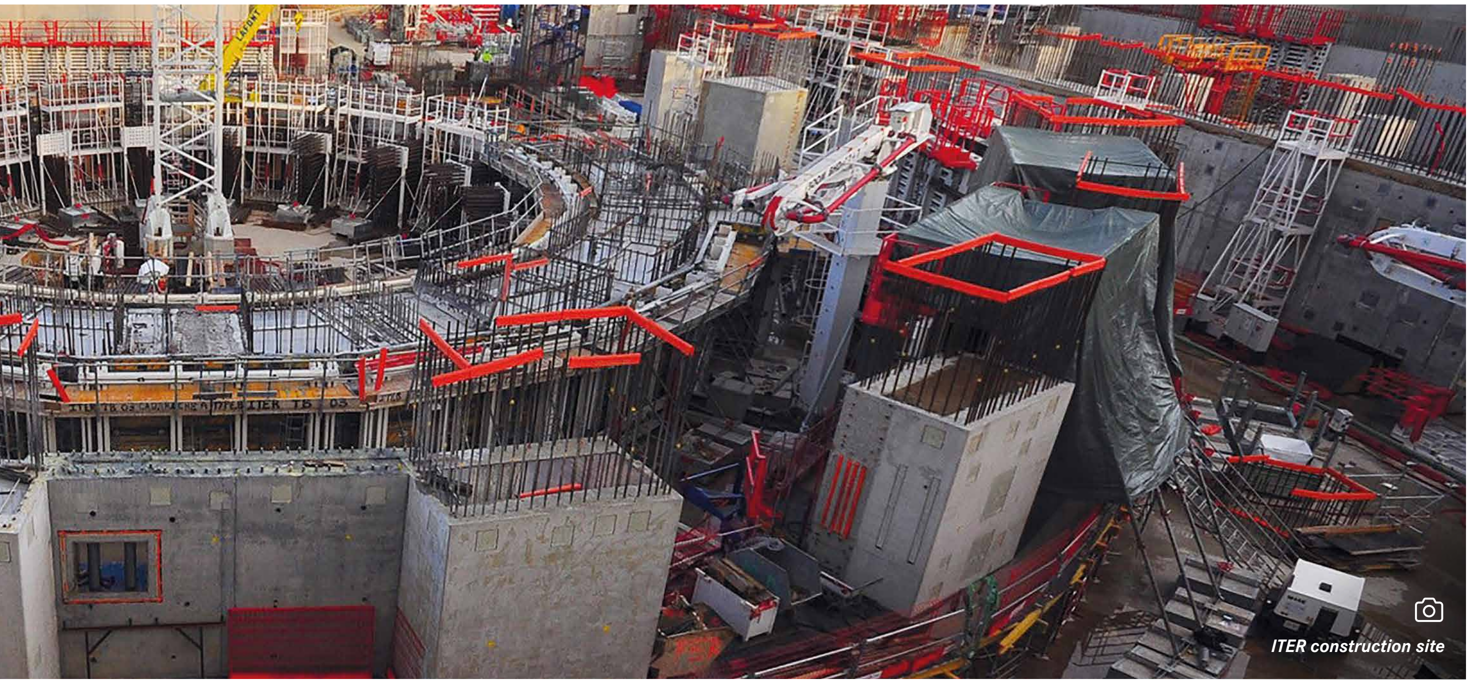
CEA centres produced nearly 94% of research sector waste at the end of 2021.

RADIOACTIVE WASTE INVENTORY FOR THE RESEARCH SECTOR



Category	Volume at end of 2021 (m³)
HLW	159
ILW-LL	8,090
LLW-LL	13,100
LILW-SL	248,000
VLLW	200,000
Total	470,000

Percentages were calculated based on the exact figures, then rounded.



ITER construction site

DEFENCE SECTOR

This economic sector includes the activities of facilities for studies, research, production and experimentation, working for the nuclear deterrent and those of various armies (French navy, air force, army, etc.), the Army Health Service (SSA), the General Directorate of Armaments (DGA) and the police.

HLW and ILW-LL waste from this sector is generated exclusively by the nuclear deterrent.

STUDY, PRODUCTION OR EXPERIMENTATION FACILITIES WORKING FOR THE NUCLEAR DETERRENT

This includes all activities related to the nuclear deterrent by the CEA Directorate of Military Applications (DAM) facilities and the nuclear propulsion installations of the DAM in Cadarache.

The DAM is responsible for the project management for the design and development of nuclear steam supply systems in French Navy buildings and for construction of the cores equipping the on-board boilers.

CEA/DAM INSTALLATIONS

The CEA DAM designs, manufactures and maintains the operational condition of nuclear charges or warheads of the French defence system. It also provides dismantling of nuclear weapons withdrawn from service.

The sites concerned by nuclear weapons and nuclear steam supply systems are Secret Basic Nuclear Installations (SBNIs):

Bruyères-le-Châtel centre

Since the construction of the Bruyères-le-Châtel site, it has manufactured the nuclear devices tested successively in the Sahara and the Pacific between 1960 and 1996, and has monitored the experiments and research on constituent materials. The facilities of this centre are currently being dismantled and mainly generate VLLW and LILW-SL waste.

There are some limited specific activities relating to physics and analyses continuing on this site.

Valduc centre

The Valduc centre produces some of the component parts of nuclear weapons. It processes their radioactive materials (plutonium, uranium) and also conducts research into the materials.

Its activities generate waste contaminated with alpha emitters on one hand and with tritium on the other. Valduc's ILW-LL waste is miscellaneous technological waste conditioned in metal drums and sent to Cadarache for storage.

Most of the packages of sludge and concentrates stuck in metal drums, generated previously by the centre's effluent treatment plant, were transferred to be stored at Cadarache.

LILW-SL waste consists, on one hand, of various items of technological and metallic waste conditioned in 200-litre drums or 5 m^3 metal boxes and, on the other hand, effluents from the installation.

The VLLW waste generated is essentially operating waste.

The Valduc centre also produces tritium-bearing waste, the most active and degassing of which is conditioned in 200-litre drums and stored at the Valduc site.

The centre has also launched a clean-up phase for some of its facilities.

Other facilities

Detonic tests were carried out up to the end of 2013 in Moronvilliers. They used uranium in the form depleted in isotope 235. The facility is now in a clean-up phase.

Similarly, detonic experiments have been conducted in the past in the Cesta facility, some of which also used uranium in a form depleted in isotope 235. For several years, Cesta's primary mission has been to provide the industrial architecture for the weapons of the nuclear deterrent.

These sites mainly contain VLLW waste (metallic waste, miscellaneous technological waste and waste generated by dismantling or clean-up) contaminated with uranium.

The Gramat centre is a defence centre with expertise concerning the vulnerability and effectiveness of weapons in the event of aggression using nuclear and conventional weapons. This test centre also used depleted uranium. The waste present on this site is VLLW waste: lightly contaminated metal waste (steels) and operating waste. The centre is now in a clean-up phase.

Finally, the DAM facilities at Cadarache working on nuclear propulsion, including onshore reactors, make it possible to develop, qualify and maintain certain systems and equipment for nuclear steam supply systems on naval vessels.

Installations shut down

Some facilities operated by Orano on behalf of DAM have been shut down since 2009. Part of the waste generated by clean-up and dismantling of these facilities is tritium-bearing waste accounted for as LILW-SL waste.

Waste from fuel reprocessing operations for the nuclear deterrent is included in the records of this section.

Since the cessation of production of fissile materials for defence purposes, which led to the closure of the Pierrelatte enrichment and recycling plants, the CEA/DAM has been responsible for the dismantling of these plants.

The CEA/DAM is also responsible for dismantling of prototype onshore reactors (PAT) and the new generation reactor (RNG) at Cadarache.

The Pacific Experimentation Centre

Waste generated by past nuclear experiments is stored at the Mururoa, Fangataufa and Hao sites in French Polynesia.

NATIONAL DEFENCE FACILITIES

This field includes professional activities related to National Defence (excluding the study, production or experimentation facilities working for the nuclear deterrent dealt with previously) that hold radioactive waste, whether they report directly to the Ministry of Defence, or whether they work on its behalf: the Air Force, Army, Navy, Directorate General of Armaments (DGA), Army Health Service (SSA) and the police.

It should be noted that, since 1st January 2009, the police are no longer dependent on the Ministry of Defence, but on the Ministry of the Interior. However, their waste typologies are the same as those of the other establishments. For the remainder of this chapter, the police are therefore included in the National Defence establishments.

Overhauled army equipment

All armies have equipment that uses the properties of radioactivity, particularly for night vision.

Such equipment, once it is used or obsolete, constitutes waste identified in each National Defence establishment (about one hundred sites identified).

Some parts of overhauled aircraft engines, containing thorium, are also listed (magnesium/thorium alloy casing for example).

Several establishments collect this waste to centralise and simplify waste management. This applies, for example, to the Châteaudun site for the French Air Force. A single joint radioactive waste collection centre is planned at the same site in Châteaudun.

National Defence ports

The military ports of Brest/Île Longue, Cherbourg and Toulon generate waste, mostly of the VLLW type, due to the construction, operation, maintenance and dismantling of submarine and aircraft carrier steam supply systems.

The reactor units of the dismantled submarines are stored in Cherbourg.

DGA facilities

At its Bourges site, the DGA holds radioactive waste generated by experiments and tests performed on weapons containing uranium in a form depleted in isotope 235.

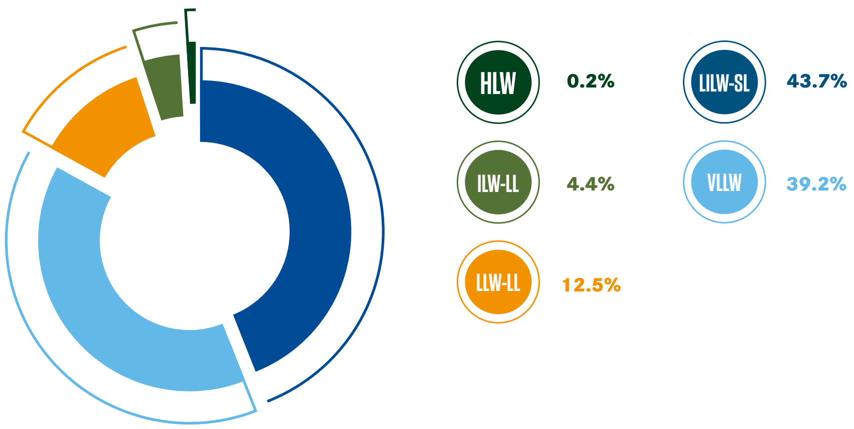
Waste generated by National Defence facilities

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

These are essentially small overhauled items of equipment incorporating radium or tritium-based luminescent paints (compasses, plates, sight lines, dials, etc.).

Most of these objects are considered to be radioluminescent objects.

RADIOACTIVE WASTE INVENTORY FOR NATIONAL DEFENCE



Percentages were calculated based on the exact figures, then rounded.

Category	Volume at end of 2021 (m³)
HLW	232
ILW-LL	5,060
LLW-LL	19,100
LILW-SL	65,700
VLLW	62,800
Total	~153,100

The defence sector is currently responsible for generating almost all of the tritium-bearing waste.

Radioactive materials	Mass at end of 2021 (tonnes)
National Defence spent fuel	202

INDUSTRIES OUTSIDE THE NUCLEAR POWER SECTOR

INDUSTRIES USING NATURALLY OCCURRING RADIOACTIVE MATERIALS FOR THEIR RADIOACTIVITY

This activity includes manufacture and use of radioactive sources (sealed or non-sealed) outside the medical field. It also concerns the manufacture and use of various objects using radioactive products (radioactive lightning rods manufactured between 1932 and 1986 gradually dismantled and collected by Andra, smoke detectors, etc.) or the properties of radioactivity (source conformity control, maintenance, etc.).

A sealed source has a limited lifetime and is renders unusable after a few months or a few years, depending on the half-life of the radionuclide concerned. Sources are not systematically considered as ultimate waste *(see Chapter 6 - Special Report 6)*.

In addition, Article R. 4452-12 of the Labour Code requires regular technical inspections of the radiation protection of the sealed sources used. Many sealed sources are returned abroad, to their suppliers.

It should be noted that the ILW-LL waste allocated to the economic sector outside the nuclear power industry corresponds to "source blocks" containing used sealed sources.

In accordance with Article R. 1333-161 of the French Public Health Code, *"a sealed radioactive source is considered to be expired, 10 years at the latest after the date of the initial registration on the supply form or, failing that, after the date of its initial entry into the market, unless extended by the competent authority. If no response is received from the French Nuclear Safety Authority for more than six months after making a request for an extension, this constitutes a decision to reject the request".*

Sources must be stored in suitable places. Some could be stored at the CSA as long as they are compatible with the safety of the facility.

RADIOACTIVE WASTE INVENTORY FOR INDUSTRIES OUTSIDE THE NUCLEAR POWER SECTOR

Percentages were calculated based on the exact figures, then rounded.

Category	Volume at end of 2021 (m^3)
HLW	-
ILW-LL	172
LLW-LL	20,700
LILW-SL	22,300
VLLW	14,900
Total	~58,100

INDUSTRIES USING NATURALLY OCCURRING RADIOACTIVE MATERIALS FOR PROPERTIES OTHER THAN RADIOACTIVITY

This sector also covers ore processing tailings and by-products that contain a significant proportion of thorium and uranium. Suspended particulate matter in its current state still contains radioactive materials.

Activities related to chemistry, metallurgy or energy production, handle radionuclides contained in certain natural mineral raw materials.

They can therefore be the source of radioactive waste, mainly of low or very low level activity.

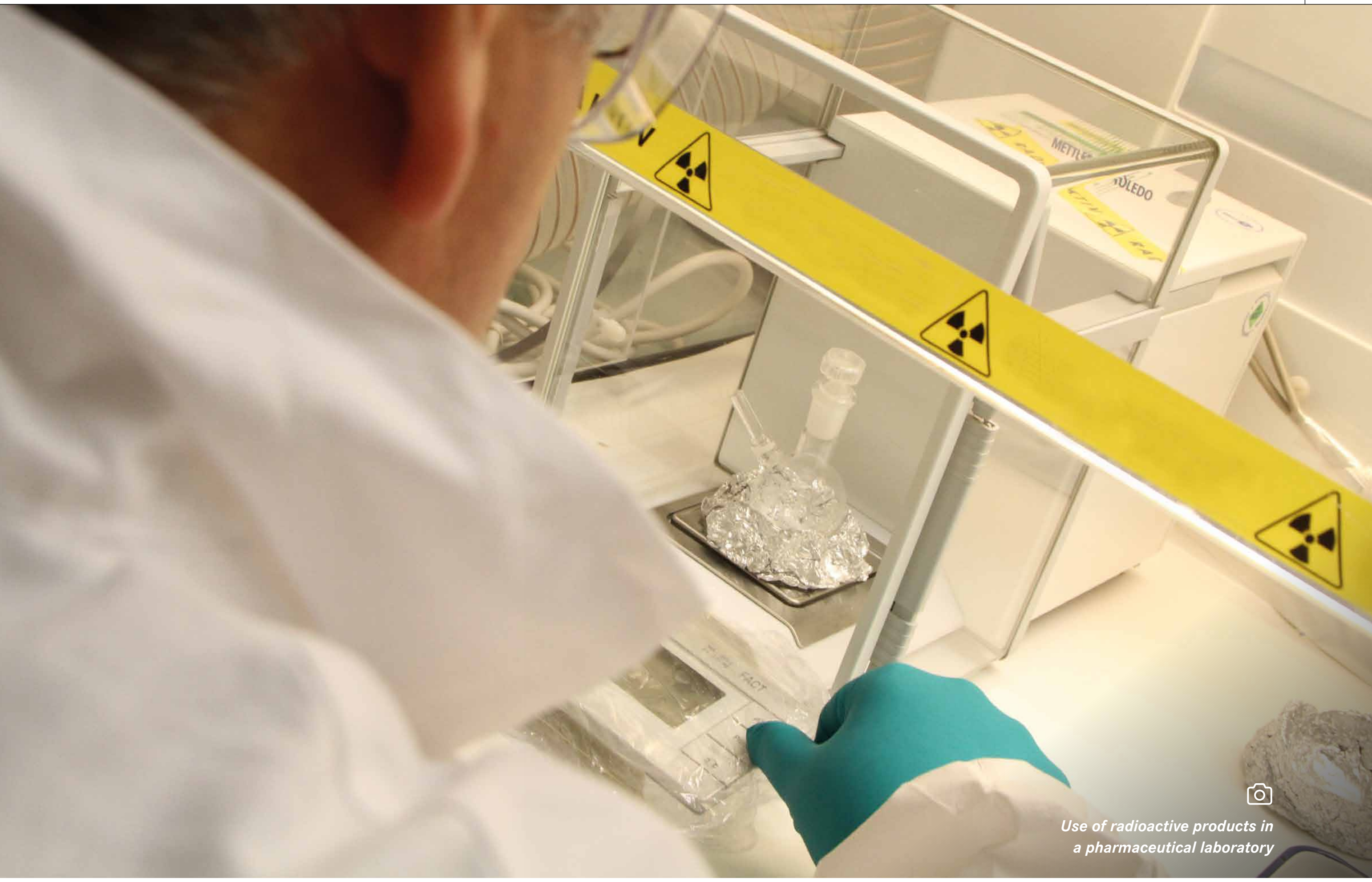
Some industries only handle naturally occurring radioactivity, with the nature of the materials used or the process used sometimes leading to concentration of radioactivity. This applies, for example, with Solvay in the field of rare-earth extraction.

The waste generated may then have sufficiently high levels of radioactivity to require a specific management solution. For these cases, the regulations provide for a potential impact study to define the appropriate, conventional or specific waste management solution.

The management solutions identified to date for this type of waste are Cires, the future LLW-LL disposal facility, conventional disposal facilities where an impact assessment has shown no impact on humans and the environment. In the past, some waste was disposed of near to the facilities.

RADIOACTIVE MATERIALS INVENTORY FOR INDUSTRIES OUTSIDE THE NUCLEAR POWER SECTOR

Radioactive materials	Mass at end of 2021 (tonnes)
Mined natural uranium, in all its physical-chemical forms	98
Thorium, in the form of nitrates and hydroxides	6,240
Suspended particulate matter (by-products from processing of rare earth ores)	5



Use of radioactive products in a pharmaceutical laboratory

MEDICAL SECTOR

This is an economic sector that includes all public or private establishments that use radionuclides for the purpose of analysis or care in the field of medicine.

Medical research centres are not included, as they belong to the research economic sector.

This sector mainly covers three areas:

- biological analyses, carried out *in vitro* on biological samples for diagnostic purposes;
- medical imaging techniques used in diagnosis;
- therapeutic applications, carried out *in vitro* or *in vivo*.

Establishments in this sector mainly use non-sealed sources, i.e. radionuclides contained in liquid solutions.

Nuclear medicine departments and laboratories associated with nuclear medicine are the largest users of radionuclides.

These same establishments also use sealed sources for radiotherapy, brachytherapy and for calibrating devices to measure the radioactivity of products injected into patients *(see Chapter 6 - Special Report 6)*.

The liquid waste produced is managed in two different ways, depending on the half-life of the radionuclides contained *(see Chapter 6 - Special Report 5)*:

- on-site decrease for very short periods;
- treatment at Centraco of Cyclife France and then disposal at Andra facilities for others.

Apart from the sources, solid waste is also managed either by decay on site followed by disposal in conventional disposal facilities, or in an Andra facility, after treatment and conditioning.

RADIOACTIVE WASTE INVENTORY FOR THE MEDICAL SECTOR AT END OF 2021

At the end of 2021, the volume of waste generated by these medical activities, apart from used sealed sources, was around 8,600 m³.

Category	Volume at end of 2021 (m³)
HLW	-
ILW-LL	3
LLW-LL	98
LILW-SL	8,400
VLLW	103
Total	~ 8,610

No radioactive material from the medical sector was reported at the end of 2021.

03

Forecast inventories

INTRODUCTION

In order to ensure the safe long-term management of radioactive materials and waste, the various players involved (decision-makers, Andra, operators of Basic Nuclear Installations, assessors, civil society, etc.) need to have a medium- and long-term vision of the volumes of radioactive materials and waste to be produced in the future, based on different strategies or possible changes in French energy policy. The aim of this forecast is to provide a basis for anticipating and taking appropriate measures to ensure continuity in terms of storage and disposal availability, without pre-empting the industrial choices that may be made.

To do this, Andra prepares assessments and forecast inventories, based on reports from the nuclear power industry, whether they are waste producers and/or holders or waste materials. The outlook presented in this chapter is based on data from a number of different exercises.

Firstly, it incorporates an assessment of the volumes of radioactive materials and waste from currently licensed facilities over different timeframes, based on contrasting energy policy scenarios derived from the current multiyear energy programme 2019-2028 (PPE2). This assessment corresponds to that carried out regularly as part of the preparation of *the National Inventory of Radioactive Materials and Waste.*

In order to cover the impact of energy policy guidelines on the management of radioactive materials and waste, it is supplemented by:

- elements from the analysis of the impact of radioactive waste generated by the potential deployment of six additional EPR2-type nuclear power reactors, studied by Andra at the request of the Directorate General for Energy and Climate (DGEC) as part of the New French Nuclear Power project (NNF);
- a qualitative analysis of the issues related to continued operation of reactors for up to 60 years, carried out by Andra specifically for this edition of the *National Inventory.*

FORECAST ASSESSMENTS OF *THE NATIONAL INVENTORY OF RADIOACTIVE MATERIALS AND WASTE*

Produced every five years, *the National Inventory* presents detailed forecast inventories of materials and waste according to different envisaged scenarios. This exercise is governed by a number of regulations and takes account of the National Radioactive Materials and Waste Management Plan (PNGMDR). It is carried out for installations with their construction licence and it considers scenarios that define the PPE2. The scenarios are prepared in a coordinated manner, within the framework of the PNGMDR which, working as a tool to coordinate management of radioactive materials and waste, takes account of the main guidelines of the current multiyear energy programme in order to ensure that the guidelines it defines for management of radioactive materials and waste are compatible with the national energy strategy.

As with the previous edition of the *National Inventory*[1], these scenarios cover a range of different developments in energy policy: continuation of nuclear power generation using different fuel reprocessing strategies, or shutdown of nuclear power generation.

In accordance with Decree No. 2008-875 of 29 August 2008 and the amended decree of 9 October 2008, prospective inventories of radioactive materials and waste are reported every five years by producers or holders of radioactive materials and waste.

In accordance with the decree of 9 October 2008, the forecast quantities in the 2023 Edition are evaluated for existing installations or those that have obtained their construction licence decree as of 31 December 2021.

Unlike volumes of waste that must be reported every year, these forecasts are only required every five years[2], solely for operators of BNIs, defence-related facilities (INBS, SIENID) or nuclear ICPEs.

More specifically, these scenarios are built around the following main principles, which reflect PPE2:

- **continuation of the reprocessing strategy** until 2040;
- **consideration of different spent fuel treatment and recycling strategies:** stopping reprocessing, mono-recycling and multi-recycling in pressurised water reactors (PWR) and then in fast neutron reactors (FNR);
- **renewal of the fleet:** the scenarios incorporating a renewal of the fleetare assuming that there will be no new EPR2 type reactor before 2035;
- **closure of existing reactors:** closure of the 12 x 900 MWe reactors of the current fleet between 2027 and 2035 (excluding the two Fessenheim reactors closed in 2020) at their fifth ten-yearly inspection with a view to achieving a 50% nuclear share by 2035.

1 2018 edition: https://inventaire.andra.fr/sites/default/files/documents/pdf/fr/andra-synthese-2018-web.pdf

2 Under the terms of Article L542-12 of the French Environmental Code, as amended by law no. 2020-1225 of 7 December 2020.

The scenarios thus defined, by integrating PPE2 on one hand and on the other hand incorporating the different energy policy guidelines required to be considered by the PNGMDR, vary in relation to the scenarios defined in the 2018 Edition.

Scenario S1 of the 2023 edition is a scenario of renewal of the nuclear power plant fleet, using EPRs and then FNRs, and assumes multi-recycling into PWR and then FNR. It provides an update to the SR1 and SR2 scenarios of the 2018 Edition (which differed only in the operating lifetime of the reactors)[3].

Scenario S2 in the 2023 edition is a scenario of renewal of the nuclear power plant fleet, using EPRs only, and assumes mono-recycling. It constitutes an update to the SR3 scenario of the 2018 edition[4].

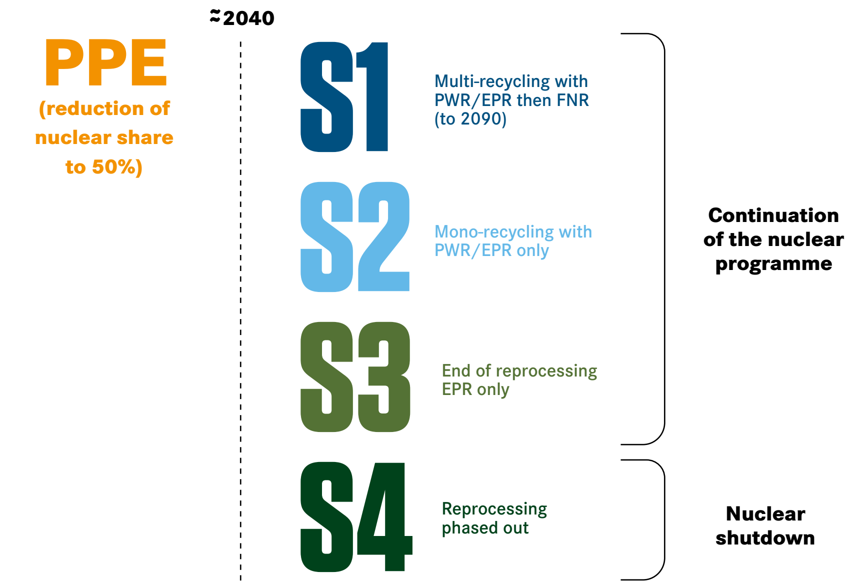
Scenario S3 in the 2023 edition is a scenario of renewal of the nuclear power plant fleet, using EPRs only, and assumes that there will be no more recycling. It is a variant of the SR3 scenario of the 2018 edition as it provides for mono-recycling for a limited time before stopping reprocessing[5].

Scenario S4 in the 2023 edition is a scenario in which the nuclear power plant fleet is not renewed. It constitutes an update to the SNR scenario of the 2018 edition[6].

OTHER PROSPECTIVE DEVELOPMENTS

In 2021, the French government carried out an analysis of the technical and economic conditions for a decision to build new high-power nuclear reactors using EPR2 technology. This analysis, which was also part of the PPE2, was carried out through the New French Nuclear Power (NNF) project and led the Directorate General for Energy and Climate (DGEC) to ask Andra to analyse the impact of the radioactive waste generated by the potential deployment of these reactors on the long-term waste management solutions, whether operational or planned.

SUMMARY OF THE DIFFERENT SCENARIOS IN THE NATIONAL INVENTORY



The aim of this study was to examine the feasibility in principle of disposing of the radioactive waste generated by the NNF project in the light of short- and very long-term safety issues, on the basis of data provided by EDF, including waste production forecasts, and considering all categories of waste associated with the operation and dismantling of these facilities: VLLW, LILW-SL, ILW-LL and HLW.

The 2023 edition of *the National Inventory* also provides additional information concerning the extension of the service life of reactors in the current fleet to 60 years. Nevertheless, it does not pre-empt ASN's position regarding the continued operation of these facilities.

With regard to small modular reactors (SMR), PPE2 also requested that preliminary design studies should be undertaken to gain a better assessment of the potential of these technologies. These technologies are currently the subject of a great deal of work, supported in particular by the France 2030 call for projects to support innovative nuclear reactors.

However, the 2023 edition of the *'National Inventory* does not include any information concerning waste that would be generated by SMR type reactors. To date, the prospects for the deployment of such reactors have not been defined with sufficient precision to enable a forecasting exercise to be carried out. This subject continues to be closely monitored by Andra, in contact with SMR and AMR (*advanced modular reactor*) project developers to encourage them to identify the nature, category and volume of the radioactive waste that will be generated, right from the initial phases of the projects. These discussions help to raise awareness among project developers of the requirement to consider the management of radioactive materials and waste, and of the data that they must provide to Andra when the time comes to identify management solutions for their radioactive waste. As in the case of the NNF project, dedicated studies may be carried out for certain reactors as part of the preparatory work for the decision to create them. These elements will be included in subsequent editions of the *National Inventory* as the development of these reactors is updated.

3 S1 is designated as scenario "SR1" in the PNGMDR.

4 S2 is designated as scenario "SR3" in the PNGMDR.

5 S3 is designated as "SR3 end of reprocessing" scenario in the PNGMDR.

6 S4 is designated as an "SNR" scenario in the PNGMDR.

PLANNING SCENARIOS: SCOPE OF THE *NATIONAL INVENTORY*

Forecast assessments are developed in a coordinated manner as part of the PNGMDR 2022-2026 *(Art. D. 542-79 of Decree No. 2022-1547 of 9 December 2022)*. They establish the guidelines of the 2019-2028 Multi-annual Energy Programming (PPE2) applicable at the time of preparation of the *National Inventory.*

The quantities of radioactive materials and waste assessed in the 2023 edition are estimated according to four different scenarios: three scenarios incorporating renewal of the current nuclear power plant fleet and one scenario without renewal, with the continuation of spent fuel reprocessing or not, depending on the individual case.

The four scenarios are based on the following shared assumptions:

- there are 57 nuclear reactors in the current power plant fleet: the 56 PWR type reactors in operation and the EPR reactor under construction at the Flamanville site, with commissioning scheduled for mid-2024;
- a reactor operating life equal to 60 years, except for 12 of them which are considered for shutdown between 2027 and 2035, in accordance with PPE2. These assumptions do not pre-empt any decisions that may be taken by ASN following the ten-yearly safety reviews performed for each of the reactors;
- a resumption of the recovery of reprocessed uranium (RepU) by EDF (see Chapter 3 – Focus on Spent Fuel Reprocessing), i.e. the manufacture and use of enriched uranium fuels (ERU) obtained from spent fuel reprocessing. This resumption of the RepU solution is active from 2023 for the four 900 MWe reactors of the Cruas NPP, then from 2027 on some of the 1300 MWe reactors;
- recycling of the plutonium extracted during the reprocessing of spent fuel in the form of mixed uranium-plutonium fuel (MOX), which would be used in 24 x 900 MWe reactors (those already licensed, plus two additional potential reactors), then in some 1300 MWe reactors.

All four scenarios provide for a common pathway up to 2040. PPE2 sets a reference date of 2040 for maintaining the reprocessing strategy. The pathways then diverge according to different hypotheses, with the main ones being as follows:

- the renewal[7] or non-renewal of the current nuclear power plant fleet;
- the choice in terms of fuel reprocessing: continuing (mono-recycling) or ending the recycling of spent enriched natural uranium (ENU) fuel, implementation of the recycling of ERU or MOX fuels (multi-recycling);
- the type, pace of deployment and nature of the fuels used (ENU, ERU or MOX fuels) in a potential future fleet of reactors (EPR2 and/or FNR).

The set of assumptions envisaged covers the main parameters that affect waste generation from the operation and dismantling of existing facilities, or the reclassification of certain materials, without pre-empting future industrial or commercial strategies.

Only existing reactors and facilities or those with construction licences as of 31 December 2021 are considered in order to assess the forecast quantities of radioactive waste material. Regarding the three scenarios including renewal of the nuclear fleet, the forecast estimates do not take account of waste and materials that would be generated by the possible fleet of reactors that would take over from them mentioned in the assumptions.

7 The gradual replacement of the reactors in the current nuclear power plant fleet with EPR2 reactors, which would eventually make up the entire future fleet, corresponds to one of the scenarios studied by RTE (scenario S2). https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques

FOCUS SPENT FUEL REPROCESSING

Spent fuel reprocessing allows for extraction of about 96% as recoverable materials (plutonium and uranium) and about 4% as radioactive waste.
The extracted plutonium is used to produce MOX fuel (mixed uranium and plutonium oxide fuel) while RepU (reprocessed uranium) is used to manufacture URE fuel (enriched reprocessed uranium). RepU use is expected to resume in 2023 after having stopped in 2013.

Mono-recycling consists of single recycling of plutonium and uranium from the processing of only the ENU fuel into the MOX and ERU fuel.
These fuels, once irradiated and unloaded from the PWR reactors, also contain materials such as plutonium.

Multi-recycling involves reprocessing of this irradiated MOX and ERU fuel to extract recoverable materials and then manufacture new fuel, in a cycle performed multiple times.

In line with theobjective of reducing the quantity and harmfulness of radioactive waste defined in Article L.542-1-2 of the French Environmental Code, the French energy policy provides for all fuel to be reprocessed after use. Under these terms, the French strategy recorded in the PPE2 is that of multi-recycling.

The reprocessing currently carried out at the Orano La Hague plant concerns spent natural uranium fuel (ENU). Mono-recycling is therefore the part of the reprocessing strategy that is currently already implemented in France.

SUMMARY OF PLANNING SCENARIO RESULTS

The table below summarises the assessments of volumes of radioactive materials and waste at term, according to the four scenarios studied.

Materials are associated with the waste category with which they have comparable typologies and physical-chemical characteristics. This does not determine the management solution that will be selected, particularly in the case of uranium. The PNGMDR 2022-2026 *"aims to bring greater visibility to recovery of materials and to define the State framework for analysis for the exercise of its capacity to reclassify materials as waste"*. As such, it provides for work relating to the recovery of materials and specifies that *"work will continue on the various materials in order to bring more detail to classification of the issues related to waste management in the event of reclassification as waste"*. As such, *"scenarios for disposal of depleted uranium, RepU and thorium-bearing materials"* are studied by Andra.

Waste quantities are expressed as "conditioned equivalent volume" ***(see the "unit of volume used" box on page 29).*** **Material quantities are expressed as "tonnes of heavy metal".**
In accordance with Article 4 of the PNGMDR decree of 9 December 2022, Andra initiated ***"discussions aimed at improving comparison of inventories of radioactive materials and waste".***
The first step in this approach concerns indication of an equivalence of the quantities of materials as "conditioned equivalent volume".
To do this, the conditioning assumptions used, on one hand, are those associated with storage of materials (for example depleted uranium), and on the other hand, are those used in adaptability studies of the Cigéo facility for disposal of spent fuels presented in the support file for the construction licence application (DAC) submitted on 16 January 2023, currently being examined by the Nuclear Safety Authority (ASN).

Chooz Nuclear Power Plant

SUMMARY OF SCENARIOS

		S1	S2	S3	S4
Total reactor operating life		60 years excluding closure of 12 reactors between 2027 and 2035 (see PPE 2019-2018)			
Nuclear power sector production		Continuation	Continuation	Continuation	No renewal
Type of reactor deployed in future fleet		EPR2 then FNR	EPR2	EPR2	-
Spent fuel reprocessing		Multi-recycling All: ENU at term, ERU, MOX, EL4, FNR Phénix and Superphénix, Research	Mono-recycling ENU at term, EL4	Reprocessing phased out ENU by 2040	Reprocessing phased out ENU by 2040
Reclassification of materials as waste		None	Spent fuel: ERU, MOX, FNR Phénix and Superphénix, Research excluding EL4 Depleted uranium, research plutonium	Spent fuel: ENU (after 2040), ERU, MOX, FNR Phénix and Superphénix, Research including EL4 Depleted uranium, research plutonium	Spent fuel: ENU (after 2040), ERU, MOX, FNR Phénix and Superphénix, Research including EL4 Depleted uranium, research plutonium
HLW	Spent ENU fuel	-	-	14,500 tHM *~ 7,000 m³*	14,500 tHM *~ 7,000 m³*
	Spent ERU fuel	-	6,110 tHM *~ 3,000 m³*	6,110 tHM *~ 3,000 m³*	6,110 tHM *~ 3,000 m³*
	Spent MOX fuel	-	5,030 tHM *~ 3,000 m³*	5,030 tHM *~ 3,000 m³*	5,030 tHM *~ 3,000 m³*
	MOX scrap	-	386 tHM *~ 200 m³*	386 tHM *~ 200 m³*	386 tHM *~ 200 m³*
	Spent FNR fuel	-	149 tHM *~ 100 m³*	149 tHM *~ 100 m³*	149 tHM *~ 100 m³*
	Spent fuel used in research	-	6.4 tHM *~ 10 m³*	56 tHM *~ 100 m³*	56 tHM *~ 100 m³*
	Non-irradiated separated plutonium	-	2 tHM *~ 20 m³*	2 tHM *~ 20 m³*	2 tHM *~ 20 m³*
	Other materials	-	70 tHM *~ 90 m³*	70 tHM *~ 90 m³*	70 tHM *~ 90 m³*
	Waste at term excluding materials reclassified as waste	11,800 m³	8,960 m³	6,890 m³	6,890 m³
	Total at term	11,800 m³	~ 15,000 m³	~ 20,100 m³	~20,100 m³
ILW-LL	Waste at term	68,800 m³	67,100 m³	63,200 m³	63,200 m³
LLW-LL	Depleted uranium	-	899,000 tHM* *~ 300,000 m³*	899,000 tHM* *~ 300,000 m³*	899,000 tHM* *~ 300,000 m³*
	Waste at term	218,000 m³	218,000 m³	218,000 m³	218,000 m³
LILW-SL	Waste at term	1,870,000 m³	1,870,000 m³	1,850,000 m³	1,850,000 m³
VLLW	Waste at term	2,430,000 m³	2,410,000 m³	2,400,000 m³	2,400,000 m³

Tonne of heavy metal: value rounded to three significant figures.

Volume of materials reclassified as waste: volume rounded to one significant figure.

Conditioned equivalent volume: value rounded to three significant figures for radioactive waste.

* *For Orano depleted uranium, the quantities indicated and the status of "reclassification as waste" do not take account of the recovery pathways already implemented and envisaged in nuclear power sectors in France or abroad and in innovative non-nuclear pathways, in accordance with the depleted uranium recovery plan developed as part of the PNGMDR 2022-2026.*

The expression "at term" here means at the end of dismantling of the nuclear installations licensed at end of 2021.

The lessons learned from comparing the different scenarios for each waste and material category are explained below.

MATERIALS RECLASSIFIED AS WASTE

Among the different assumptions considered in the scenarios, only the spent fuel reprocessing strategy impacts the quantities of material reclassified as waste. The multi-recycling strategy makes it possible to recover all radioactive materials contained in the spent fuels of the current fleet (ENU, ERU, MOX) while the mono-recycling strategy only makes it possible to recover the materials contained in the ERU type spent fuels. Consideration of thescenario with no more reprocessing therefore implies reclassification of all spent fuels as waste, as well as depleted uranium.

LONG-LIVED INTERMEDIATE-LEVEL AND HIGH-LEVEL WASTE (HLW AND ILW-LL)

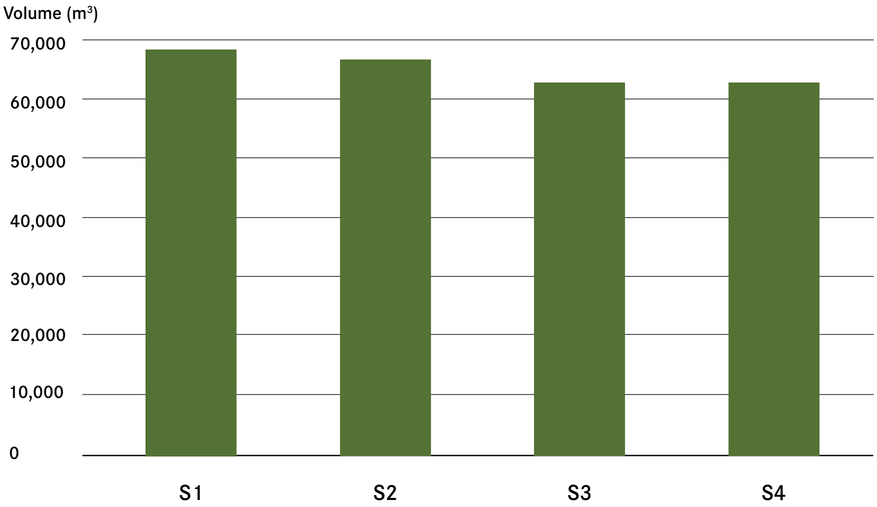
The operating life of the reactors in the current nuclear power plant fleet and the continuation of spent fuel reprocessing have a direct impact on the quantity of vitrified waste (HLW) and structural metallic waste surrounding the fuels (ILW-LL): the longer the plant fleet operates, the more fuel needs to be reprocessed, and the higher the volume of this waste at term.

The nature and quantity of HLW and ILW-LL waste at term for the current fleet are also impacted by the spent fuel management strategy for the current fleet, and in particular by the mono-recycling or multi-recycling strategies. It should be noted that spent fuel, because of its characteristics, would fall into the HLW category if it were reclassified as waste.

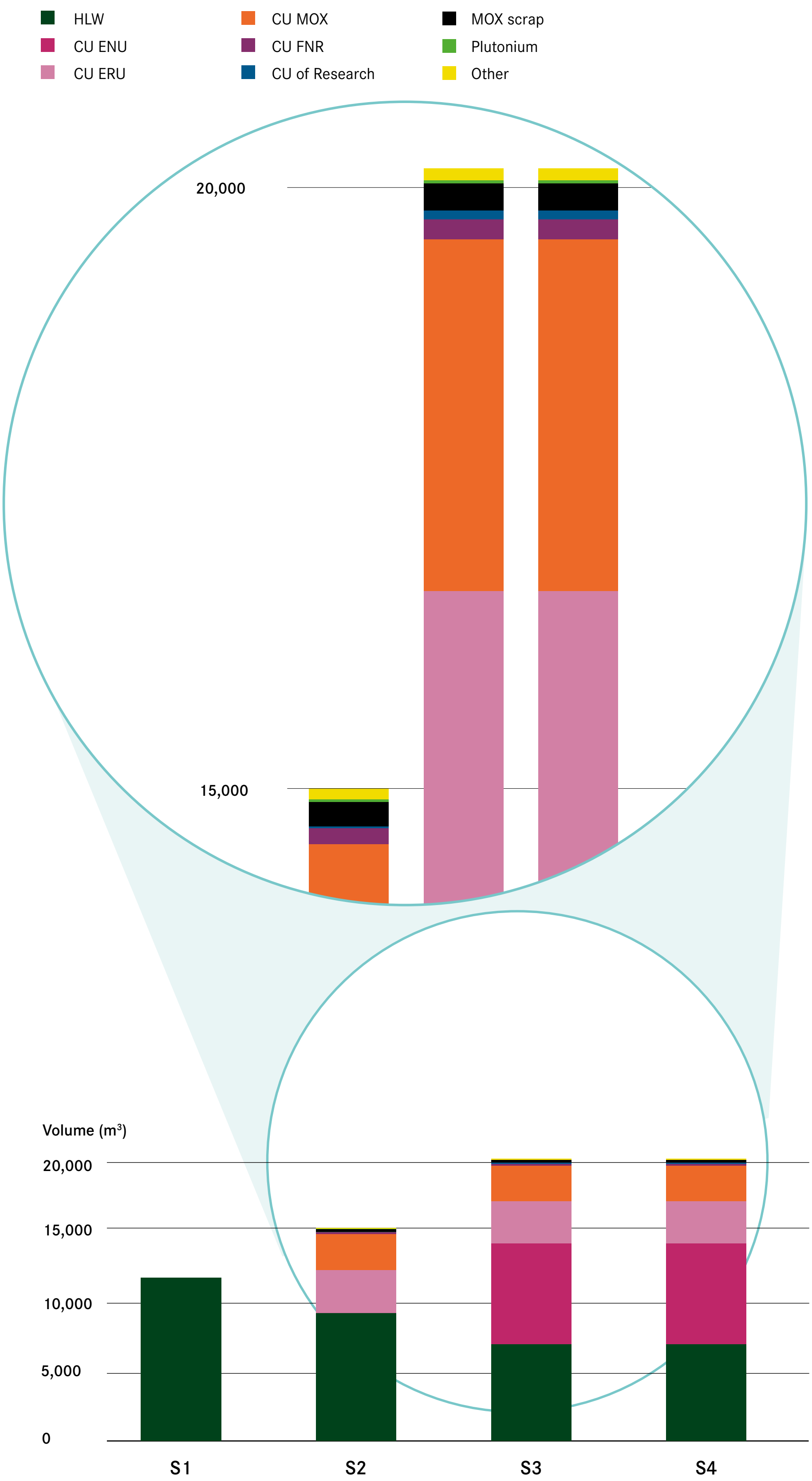
Therefore:

- **scenario S1:** assuming a renewal of the fleet with EPR2s then FNRs, the reprocessing of spent fuel from reactor operation leads to vitrified waste (HLW) and metal structural waste surrounding the fuels (ILW-LL) at term. The assumptions regarding the reprocessing of all spent fuel and deployment of EPR2 and then FNR reactors include the assumption that all the materials mentioned above are recovered: none of them are reclassified as waste;
- **scenario S2:** assuming a renewal of the fleet with EPR2 and a mono-recycling strategy, only the reprocessing of ENU fuels produces vitrified waste (HLW) and metal structural waste surrounding fuels (ILW-LL). The ERU, MOX and FNR fuels from the Phénix and Superphénix and research reactors are not reprocessed, so there is no vitrified waste generated. The volume of HLW and ILW-LL waste at term is therefore lower than the volume of waste in scenario S1. However, due to the reclassification of non-reprocessed spent fuels, the overall volume of waste and materials that would fall under the HLW management solution is greater than that of scenario S1;
- **scenarios S3 and S4:** the assumption that ENU spent fuel reprocessing stops by 2040 leads to an early end to generation of vitrified waste (HLW) and structural metallic waste surrounding fuels (ILW-LL) and therefore a smaller amount of HLW waste and ILW-LL waste. The remaining ENU spent fuels, ERU and MOX, Phénix and Superphénix FNR and research fuel would be reclassified as waste. The overall volume of waste and materials that would fall under the HLW management solution is therefore greater than that of scenarios S1 and S2.

INVENTORY OF WASTE FROM ILW-LL CATEGORIES AT TERM



INVENTORY OF HLW WASTE CATEGORIES AT TERM



LONG-LIVED LOW LEVEL WASTE (LLW-LL)

Most generation of LLW-LL waste is related to dismantling of existing facilities that have already shut down. This mainly involves dismantling of the reactor boxes of natural uranium graphite-moderated reactors (GCR) scheduled beyond 2040. As a result, the LLW-LL waste volume at term is independent of the forecast scenarios in the *National Inventory*.

The uranium conversion treatment residues (RTCU) produced after 2019 by the Orano Malvési plant and the radium-bearing waste produced by the Framatome zirconium sponge production facility in Jarrie also contribute to the volume of LLW-LL waste.

Given its prospects for reuse, the volume of uranium obtained from spent fuel reprocessing is considered as a material. Because of its typology, this volume of uranium could fall into the LLW-LL category if it were reclassified as waste.

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

The volume of LILW-SL and VLLW[8] waste generated, in these scenarios, is linked to the operating lives of the reactors (an increase in operating life actually leads to an increase in the volume of waste produced) and to dismantling of them. As the assumed operating life and the dismantling strategies are identical for all scenarios, the quantity of LILW-SL and VLLW waste at term is identical overall. The variability in quantities of fuels processed or cessation of their reprocessing has little influence on their inventory at term.

8 The production forecasts provided for the National Inventory scenarios do not take account of possible recovery of radioactive waste belonging to the VLLW category studied as part of the 2022-2026 PNGMDR.

DETAILED PLANNING SCENARIO RESULTS

The four scenarios envisage a shared pathway to 2040 and the equilibrium of material flows *through* use of MOX fuel and resumption of reprocessed uranium (RepU) recovery.

Consequently, the quantities of radioactive waste estimated on the intermediate dates 2030 and 2040 for scenario S1 can be extrapolated for scenarios S2, S3 and S4.

The tables showing the estimation of quantities of radioactive waste in these three scenarios include the balances at the end of 2030 and end of 2040 for scenario S1.

SCENARIO S1

RENEWAL OF THE NUCLEAR POWER FLEET WITH EPR2, THEN FNR REACTORS, AND MULTI-RECYCLING

In addition to the data common to all the scenarios presented in the introduction, scenario S1 applies the following key assumptions:

- the continuation of nuclear power generation, with gradual renewal of reactors in the current nuclear power plant fleet with EPR2 reactors from 2035, then gradually, by 2090, with FNRs, which could eventually make up the whole of the future fleet;
- continuation of spent fuel reprocessing: reprocessing of all spent fuel from the current nuclear power plant fleet and spent fuel from the Phénix and Superphénix FNRs, the Brennilis EL4 reactor and the research reactor.

By convention, this assumes that:

- the availability of spent fuel reprocessing plants (ENU, ERU and MOX) to perform these operations, as well as those for manufacture of new fuels (ERU and MOX) from recoverable materials obtained by reprocessing;
- the recovery of uranium and plutonium from the ENU spent fuel reprocessing in fuels intended for the reactors of the current power plant fleet, then in the EPR2 reactors of the future fleet.
  Separated plutonium obtained from spent fuel reprocessing is recycled as MOX fuel and reprocessed uranium (RepU) is used for manufacture of ERU fuels;
- from 2050, multi-recycling of spent fuel is implemented involving the recovery of materials from the MOX and ERU spent fuel reprocessing, allowing manufacture of fuel for the reactors of future fleets (EPR2 then FNR);
- the use of a proportion of depleted uranium (DU) for the manufacture of MOX fuels.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE ON INTERMEDIATE DATES 2030 AND 2040 AND AT END FOR SCENARIO S1

Radioactive waste	End of 2021	End of 2030	End of 2040	At the end of facility life
HLW	4,320	5,630	6,620	11,800
ILW-LL	39,500	43,500	48,300	68,800
LLW-LL	103,000	114,000	125,000	218,000
LILW-SL	981,000	1,100,000	1,260,000	1,870,000
VLLW	633,000	926,000	1,380,000	2,430,000
Total	~ 1,760,000	~ 2,190,000	~ 2,820,000	~ 4,590,000

Operation (operation and dismantling) of existing facilities or having obtained their construction licence decree on 31 December 2021 leads to an increase in the volume of waste until termination. This increase can be explained differently according to the radioactive waste categories:

- after 2040, the dismantling of the reactors in the current nuclear power plant fleet, the cycle plants and support workshops, and the research facilities lead to a significant increase in generation of LILW-SL waste, particularly VLLW waste;
- the increase in the volume of LLW-LL waste is related to the dismantling of GCR reactor boxes which will start beyond 2040;
- the increase in the amount of HLW and ILW-LL waste is modulated by the gradual shutdown of the reactors of the current fleet. Indeed, the reduction in number of units in operation between 2027 and 2035, resulting in a decrease in the amount of ENU fuel used, and the amount of fuel reprocessed from the current fleet, leads to a decrease in rate of generation of this radioactive waste after 2035.

The assumptions regarding reprocessing of all spent fuel and deployment of EPR2 and then FNR reactors include the assumption that all the materials are recovered. The materials obtained by reprocessing of spent fuel generated by the current nuclear power plant fleet are recovered in a future fleet of EPR2 then FNR reactors. No materials are reclassified as waste.

ESTIMATED QUANTITIES OF RADIOACTIVE MATERIALS IN tHM* AT INTERMEDIATE DATES 2030 AND 2040 FOR SCENARIO S1

No.	Radioactive materials	End of 2021	End of 2030	End of 2040
1	ENU fuels before use	733	341	286
2	ENU fuels in use in nuclear power plants	3,970	3,410	2,860
3	Spent ENU fuels pending reprocessing	11,200	11,200	8,900
4	ERU fuels before use	-	80	122
5	ERU fuels in use in nuclear power plants	-	805	1,220
6	Spent ERU fuels pending reprocessing	630	815	2,740
7	MOX fuels before use or during manufacture	11	44	50
8	MOX fuels in use in nuclear power plants	215	441	503
9	Spent MOX fuels pending reprocessing	2,390	2,980	4,010
10	Non-irradiated MOX fuel scrap pending reprocessing	337	328	377
11	Non-irradiated uranium fuel scrap pending reprocessing	-	-	-
12	Spent FNR fuels pending reprocessing	125	130	130
13	Research reactor fuels before use	0.04	0.03	0
14	Fuel currently in use in research reactors	1	0	0.1
15	Other civil spent fuel	61	59	59
16	National Defence spent fuel	202 t	260 t	335 t
17	Non-irradiated separated plutonium, in all its physical-chemical forms	65	59	43
18	Mined natural uranium, in all its physical-chemical forms	37,800	37,800	37,800
19	Enriched natural uranium, in all its physical-chemical forms	3,290	3,410	3,390
20	Enriched uranium from spent fuel reprocessing, in all its physical-chemical forms	-	-	-
21	Uranium from spent fuel reprocessing, in all its physical-chemical forms	34,200	29,900	17,700
22	Depleted uranium, in all its physical-chemical forms	324,000	471,000	569,000
23	Thorium, in the form of nitrates and hydroxides	8,510	8,020	7,540
24	Suspended particulate matter (by-products from processing of rare earth ore)	5	0	0
25	Other materials	70	70	70

* Excluding spent fuel from National Defence, expressed as tonnes of fuel assemblies

The changes in quantities of ENU, ERU and MOX fuels before use and during use (categories 1, 2, 4, 5, 7 and 8) in the current nuclear power fleet between 2021 and 2040 can be explained by gradual resumption of recycling of RepU and maintenance of the number of MOX reactors. Therefore, the quantity of ENU fuels (categories 1, 2) decreases in favour of the number of ERU (categories 4, 5) and MOX (categories 7, 8) fuels.

Continuation of the spent fuel reprocessing (maintenance of the current strategy) leads to a stabilisation over the period 2021-2040 of the quantity of spent ENU fuel (category 3) pending reprocessing. Spent ERU and MOX fuels (categories 6 and 9) will be stored pending recovery in the future EPR2 and then FNR fleet, resulting in an increase in their quantity between 2021 and 2040.

The gradual resumption of use of ERU fuel in EDF reactors has a direct impact on the amount of uranium obtained from spent fuel reprocessing, which, once enriched, is used in the manufacture of ERU fuel.

The volume of uranium from spent fuel reprocessing (category 21, RepU) therefore decreases. The volume of enriched uranium from reprocessing (category 20) is considered to be zero, as it is supposed to be immediately transformed into a fuel assembly (category 4).

Scrap from non-irradiated mixed uranium-plutonium fuel pending reprocessing (category 10) is intended to be treated and recycled in the current or future fleet. The variations observed result from a balance between generation of scrap, during the manufacture of new MOX fuels, and their treatment.

The continuation of nuclear power generation is reflected in particular by the continuation of uranium enrichment. The amount of depleted uranium in storage (category 22) continues to increase between 2021 and 2040. However, depleted uranium could be re-enriched according to economic market conditions or partially recovered for MOX fuels or in fourth generation fast neutron reactors or be recovered in sectors other than nuclear power *(see Chapter 1 – Focus on depleted uranium recovery)*.

The quantities of enriched natural uranium (category 19) and natural uranium extracted from the mine (category 18), in all its physical-chemical forms, are a projection based on current assumptions consistent with the number and operating life of reactors in the nuclear power plant fleet.

The decrease in the amount of plutonium (category 17) between 2021 and 2030 is due to the manufacture and return of MOX fuels abroad. During the same period, the French share of plutonium increases overall, due to the difficulties in MOX production encountered at the Melox plant. The restoration of the nominal production capacity of the Melox plant planned for 2025 will lead to a decrease in the amount of plutonium between 2031 and 2040.

The amounts of spent fuels from research and National Defence (categories 12, 15, 16 and 25) reflect the marginal nature of this reprocessing looking ahead to 2040.

The sale of thorium-bearing materials abroad by Solvay explains the gradual decrease in the volume of thorium (category 23). As for suspended particulate matter (containing oxides of rare earths and traces of thorium and uranium) (category 24), there is no amount of this from 2030, with recovery of this material being planned until 2025.

SCENARIO S2

RENEWAL OF THE NUCLEAR POWER PLANT FLEET WITH EPR2 ONLY, AND CONTINUATION OF MONO-RECYCLING

In addition to the data common to all the scenarios presented in the introduction, scenario S2 applies the following key assumptions:

- the continuation of nuclear power generation, with gradual renewal of reactors in the current nuclear power plant fleet with EPR2 reactors, which could eventually make up the whole of the future fleet;
- the ENU spent fuel reprocessing only (mono-recycling principle) and reprocessing of fuel from the Brennilis EL4 reactor.

By convention, this assumes that:

- there are ENU spent fuel reprocessing plants available to perform these operations and to manufacture new ERU and MOX fuel from the recoverable materials generated by processing;
- recovery of uranium and plutonium obtained by ENU spent fuel reprocessing in the reactors of the current power plant fleet and then in the reactors that will constitute the future fleet. Separated plutonium obtained from spent fuel reprocessing is recycled as MOX fuel and reprocessed uranium (RepU) obtained from fuel reprocessing is recycled as ERU fuel;
- spent MOX and ERU fuel is not reprocessed;
- FNR fuel from Superphénix and Phénix as well as spent fuel from research is not reprocessed;
- CEA materials containing plutonium as well as depleted uranium are reclassified as waste;
- depleted uranium from Orano is considered to be reclassified as waste. The quantities indicated do not take account of the recovery pathways already implemented and envisaged in nuclear power sectors in France or abroad and in innovative non-nuclear pathways, in accordance with the depleted uranium recovery plan developed as part of the PNGMDR 2022-2026.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE ON INTERMEDIATE DATES 2030 AND 2040 AND AT END FOR SCENARIO S2

Radioactive waste	End of 2021	End of 2030	End of 2040	At the end of facility life
HLW	4,320	5,630	6,620	8,960
ILW-LL	39,500	43,500	48,300	67,100
LLW-LL	103,000	114,000	125,000	218,000
LILW-SL	981,000	1,100,000	1,260,000	1,870,000
VLLW	633,000	926,000	1,380,000	2,410,000
Total	~ 1,760,000	~ 2,190,000	~ 2,820,000	~ 4,580,000

As with scenario S1, scenario S2 provides for an increase in the volume of waste due to the operation (operation and dismantling) of existing facilities or having obtained their construction licence decree by 31 December 2021.

The rate of generation of different radioactive waste categories varies over time depending, mainly, on the following:

- the gradual shutdown of the nuclear power reactors of the current fleet, in particular over the period 2027-2035 in accordance with the PPE2;
- the dismantling of GCR reactor boxes beyond 2040;
- the dismantling, after 2040, of the reactors in the current nuclear power plant fleet, the cycle plants and support workshops, and the research facilities.

ESTIMATED QUANTITIES OF RADIOACTIVE MATERIALS IN tHM* LIKELY TO BE RECLASSIFIED AS WASTE AT TERM FOR SCENARIO S2

No.	Radioactive materials that may be reclassified as waste at term	At the end of facility life
6	Spent ERU fuels pending reprocessing	6,110
9	Spent mixed uranium-plutonium fuels pending reprocessing	5,030
10	Non-irradiated MOX fuel scrap pending reprocessing	386
12	Spent FNR fuels pending reprocessing	149
15	Other civil spent fuel	6.4
17	Non-irradiated separated plutonium, in all its physical-chemical forms	2
22	Depleted uranium, in all its physical-chemical forms	899,000
25	Other materials	70
Total		911,000

* Excluding spent fuel from National Defence, expressed as tonnes of fuel assemblies

The total amount of radioactive waste in the LLW-LL, LILW-SL, and VLLW categories at term in S2 is globally equivalent to that of scenario S1. Forecast estimates are not significantly affected by the differences in assumptions made for these categories.

Regarding the HLW and ILW-LL categories, mono-recycling leads to a reduction in the amounts of reprocessed spent fuels compared to scenario S1 after 2040, when there is a difference between the assumptions of the scenarios.
The production of vitrified waste and structural metallic waste surrounding fuels (hulls and end caps) is therefore lower.
As a result, the forecast quantity of HLW and ILW-LL waste at term according to scenario S2 is lower than that of scenario S1.

In this scenario (fleet renewal and mono-recycling), the ERU, MOX and FNR spent fuels from Phénix and Superphénix and research would be reclassified as waste:

- approximately 6,110 tHM of spent ERU fuel, 5,030 tHM of spent MOX fuel and 386 tHM of MOX scrap;
- about 106 tHM of FNR spent fuel from Superphénix, 43 tHM of FNR spent fuel from Phénix, 6.4 tHM of civil spent fuel (excluding Brennilis EL4 reactor);
- 70 tHM of Superphénix new core ("other materials" category).

The amount of depleted uranium at term takes account of the inventory resulting from CEA research activities, equal to 109 tHM, with the addition of the recoverable inventory of Orano *(see Chapter 1 – Focus on depleted uranium recovery)*, evaluated at about 899,000 tHM.

The separated plutonium from the ENU spent fuel reprocessing from the current fleet is intended for the manufacture of MOX fuel. Only the waste resulting from CEA research activities is reclassified as waste at term.

The materials that would be reclassified as waste, if no other recovery pathway is identified, must be handled in dedicated long-term waste management pathways.

The reclassification of non-reprocessed spent fuel would involve an increase in volume of waste from the HLW sector by approximately 6,000 m³. The overall volume of waste and materials that would fall under this category, estimated at about 15,000 m³, would be greater than that of scenario S1.

SCENARIO S3

RENEWAL OF THE NUCLEAR POWER PLANT FLEET WITH EPR2S ONLY, AND NO RECYCLING

In addition to the data common to all the scenarios presented in the introduction, scenario S3 applies the following key assumptions:

- the continuation of nuclear power generation, with gradual renewal of reactors in the current nuclear power plant fleet with EPR2 reactors, which could eventually make up the whole of the future fleet;
- the end of spent fuel reprocessing by 2040.

By convention, this assumes that:

- the closure and dismantling of fuel reprocessing plants and plants for the manufacture of new fuels from recoverable materials obtained from processing;
- the ENU spent fuel produced after the end of reprocessing by 2040 and all the spent MOX and ERU fuel are not reprocessed. Spent FNR fuels from Superphénix and Phénix, CEA research reactors and Brennilis EL4 reactor are not reprocessed and thus considered as waste to be disposed of;
- all types of spent fuel (ENU, ERU, MOX) that are not reprocessed are considered as waste that must be disposed of;
- CEA materials containing plutonium as well as depleted uranium are reclassified as waste;
- all plutonium or RepU material (excluding volumes from CEA research activities) is recycled in the current fleet;
- Orano's depleted uranium is considered to be reclassified as waste. The quantities indicated do not take account of the recovery pathways already implemented and envisaged in nuclear power sectors in France or abroad and in innovative non-nuclear pathways, in accordance with the depleted uranium recovery plan developed as part of the PNGMDR 2022-2026.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE ON INTERMEDIATE DATES 2030 AND 2040 AND AT END FOR SCENARIO S3

Radioactive waste	End of 2021	End of 2030	End of 2040	At the end of facility life
HLW	4,320	5,630	6,620	6,890
ILW-LL	39,500	43,500	48,300	63,200
LLW-LL	103,000	114,000	125,000	218,000
LILW-SL	981,000	1,100,000	1,260,000	1,850,000
VLLW	633,000	926,000	1,380,000	2,400,000
Total	~ 1,760,000	~ 2,190,000	~ 2,820,000	~ 4,540,000

Scenario S3 provides for an increase in the volume of waste correlated with the continued operation of existing facilities or having obtained their construction licence decree by 31 December 2021.

Beyond 2040, the variations in rate of generation of the LILW-SL, VLLW and LLW-LL categories are largely due to the dismantling schedules for the GCR reactor boxes and reactors in the current nuclear power plant fleet, cycle plants and support workshops, and research facilities.

Ending reprocessing by 2040 results in a significant reduction in the quantities of HLW and ILW-LL waste categories after 2040.

Compared to the estimates for scenarios S1 and S2, the total amount of radioactive waste in the LLW-LL, LILW-SL, and VLLW categories at term in S3 is broadly equivalent. Forecast estimates are not significantly affected by differences in assumptions made for these categories.

On the other hand, with regard to the HLW and ILW-LL categories, ending reprocessing by 2040 leads to a reduction in the production of vitrified waste and structural metallic waste surrounding fuels (hulls and end caps). As a result, the forecast quantity of HLW and ILW-LL waste at term according to scenario S3 is lower than those in scenarios S1 and S2.

ESTIMATED QUANTITIES OF RADIOACTIVE MATERIALS IN tHM* LIKELY TO BE RECLASSIFIED AS WASTE AT TERM FOR SCENARIO S3

No.	Radioactive materials that may be reclassified as waste at term	At the end of facility life
3	Spent ENU fuels pending reprocessing	14,500
6	Spent ERU fuels pending reprocessing	6,110
9	Spent mixed uranium-plutonium fuels pending reprocessing	5,030
10	Non-irradiated MOX fuel scrap pending reprocessing	386
12	Spent FNR fuels pending reprocessing	149
15	Other civil spent fuel	56
17	Non-irradiated separated plutonium, in all its physical-chemical forms	2
22	Depleted uranium, in all its physical-chemical forms	899,000
25	Other materials	70
Total		926,000

* Excluding spent fuel from National Defence, expressed as tonnes of fuel assemblies

In this scenario (renewal of the fleet with stopping of treatment by 2040), the ERU, MOX and FNR spent fuels from Phénix and Superphénix and the research reactor would be reclassified as waste, as well as the ENU fuels after reprocessing ends:

- approximately 14,500 tHM of spent fuel, 6,110 tHM of spent ERU fuel, 5,030 tHM of spent MOX fuel and 386 tHM of MOX scrap;
- about 106 tHM of FNR spent fuel from Superphénix, 43 tHM of FNR spent fuel from Phénix, 56 tHM of civilian spent fuel (including the EL4 reactor in Brennilis);
- 70 tHM of Superphénix new core (category "other materials").

The quantity of depleted uranium at term takes account of the inventory resulting from CEA research activities, equal to 109 tHM, with the addition of the recoverable inventory of Orano *(see Chapter 1 – Focus on depleted uranium recovery)*, estimated at about 899,000 tHM.

The separated plutonium from the fuel reprocessing is intended for the manufacture of MOX fuel. Only the waste resulting from CEA research activities is reclassified as waste at term.

The materials that would be reclassified as waste, if no other recovery pathway is identified, must be handled in dedicated long-term waste management pathways.

The reclassification of non-reprocessed spent fuel would involve an increase in volume of waste from the HLW sector by approximately 13,200 m^3. The overall volume of waste and materials that would fall under this category is estimated at about 20,100 m^3, and would be greater than that of Scenarios S1 and S2.

SCENARIO S4

NON-RENEWAL OF THE NUCLEAR POWER PLANT FLEET

In addition to the data common to all the scenarios presented in the introduction, scenario S4 applies the following key assumptions:

- the non-renewal of the existing fleet;
- ENU spent fuels treated until 2040 generate vitrified waste and structural metallic waste surrounding fuels (hulls and end caps);
- the end of spent fuel reprocessing by 2040. By convention, this assumes that:
  - untreated ENU fuels after 2040 and all ERU and MOX fuels from the current fleet are considered as waste to be disposed of;
  - the closure and dismantling of fuel reprocessing plants and plants for the manufacture of new fuels from recoverable materials obtained from processing;
  - ENU spent fuel produced after the end of reprocessing by 2040, all unprocessed MOX and ERU spent fuel and the entire CEA Civil material inventory are considered as waste intended to be disposed of;
  - fuels for Phénix and Superphénix, CEA research reactors and Brennilis EL4 are not treated and thus considered as waste intended to be disposed of;
- all plutonium or RepU materials (excluding the volume from CEA research activities) is recycled in the current fleet;
- Orano's depleted uranium is considered to be reclassified as waste. The quantities indicated do not take account of the recovery pathways already implemented and envisaged in nuclear power sectors in France or abroad and in innovative non-nuclear pathways, in accordance with the depleted uranium recovery plan developed as part of the PNGMDR 2022-2026.

ESTIMATED QUANTITIES OF RADIOACTIVE WASTE ON INTERMEDIATE DATES 2030 AND 2040 AND AT END FOR SCENARIO S4

Radioactive waste	End of 2021	End of 2030	End of 2040	At the end of facility life
HLW	4,320	5,630	6,620	6,890
ILW-LL	39,500	43,500	48,300	63,200
LLW-LL	103,000	114,000	125,000	218,000
LILW-SL	981,000	1,100,000	1,260,000	1,850,000
VLLW	633,000	926,000	1,380,000	2,400,000
Total	~ 1,760,000	~ 2,190,000	~ 2,820,000	~ 4,540,000

Scenarios S3 and S4 both take account of the assumption of stopping reprocessing by 2040, and only differ in terms of renewal of the nuclear power plant fleet in the case of scenario S3, and non-renewal in the case of scenario S4.

The volumes of waste produced at term, with all categories combined, are identical for these two scenarios. These two scenarios, in comparison with scenarios S1 and S2, show that changes in the volumes of waste at term are largely impacted by the continuation or stopping of spent fuel reprocessing.

It should be noted that the volumes of waste that would be produced by the new fleet stipulated by scenario S3 are not counted.

ESTIMATED QUANTITIES OF RADIOACTIVE MATERIALS IN tHM* LIKELY TO BE RECLASSIFIED AS WASTE AT TERM FOR SCENARIO S4

No.	Radioactive materials that may be reclassified as waste at term	At the end of facility life
3	Spent ENU fuels pending reprocessing	14,500
6	Spent ERU fuels pending reprocessing	6,110
9	Spent mixed uranium-plutonium fuels pending reprocessing	5,030
10	Non-irradiated mixed uranium-plutonium fuel scrap pending reprocessing	386
12	Spent FNR fuels pending reprocessing	149
15	Other civil spent fuel	56
17	Non-irradiated separated plutonium, in all its physical-chemical forms	2
22	Depleted uranium, in all its physical-chemical forms	899,000
25	Other materials	70
Total		926,000

* Excluding spent fuel from National Defence, expressed as tonnes of fuel assemblies

In this scenario (non-renewal of the fleet and stopping of recycling by 2040), the nature of the materials, as well as the quantities, that would be reclassified as waste, are similar to those in scenario S3.

FOCUS RECLASSIFICATION OF MATERIALS AS RADIOACTIVE WASTE

The fate of radioactive substances considered as radioactive material by their owners should be subject to regular review.

In the case where the possibilities of recovery of a radioactive substance may be called into question, it must be ensured that the necessary guarantees, particularly financial, are put in place for management of these substances by means of dedicated management solutions.

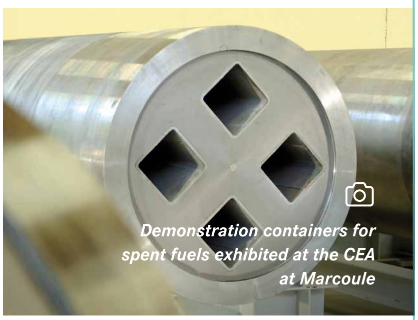
The legislative framework allows the State, in particular, after an ASN opinion, to reclassify all or part of the radioactive material as radioactive waste, or vice versa. In addition to studies relating to recovery, the PNGMDR 2022-2026 provides that *"work will continue on the various materials in order to bring more detail to classification of the issues related to waste management in the event of reclassification as waste"*. As such, *"scenarios for disposal of depleted uranium (DU), reprocessed uranium (RepU) and thorium-bearing materials"* are being studied by Andra.

A reassessment of the effectively recoverable nature of radioactive materials has been requested under the PNGMDR 2013-2015 and the PNGMDR 2016-2018. The owners of radioactive materials, Orano, the CEA, EDF and Solvay submitted their descriptions of the proposed recovery processes, including their analysis of the suitability of the prospects for recovery and the quantities held and to be held. This information has been subject to an opinion by ASN and ASND[1].

As part of the 2016-2018 PNGMDR, Andra has brought more detail, for spent fuels, depleted uranium, RepU and thorium, to studies concerning the disposal of these substances in cases where they would be classified as waste in the future, in consultation with their owner.

The 2022-2026 edition of the PNGMDR prescribed a strengthening of control of the recoverability of radioactive materials, in particular for those that are not currently recovered. To achieve this, the Plan calls for development of recovery plans, support for research into recovery of materials and continuation of studies of possible scenarios for disposal of different materials in the event of reclassification as waste.

1 ASN opinions no. 2016-Av-0256 of 9 February 2016 and no. 2020-AV-0363 of 8 October 2020 on the assessment of the recoverability of radioactive materials are available on the website: asn.fr



Demonstration containers for spent fuels exhibited at the CEA at Marcoule

VOLUMES OF DISMANTLING WASTE

As the nuclear power industry is a relatively young industry (born in the early 1960s), the main dismantling worksites of nuclear facilities for the fuel cycle as well as nuclear power plants are still ahead.

There are two types of waste generated by dismantling operations: conventional or radioactive. To identify the waste falling into one or other of these categories, the facilities are divided into zones, which take account of the history of the facility and the operations that have been carried out there:

- waste from Conventional Waste Zones (ZDC) is non-radioactive waste, which is therefore eliminated after inspection through approved conventional waste management solutions;
- the waste from the Potential Nuclear Waste Generation Areas (ZppDNs) are all managed as if they were radioactive, even if no radioactivity is detected, and are conditioned and characterised for management by Andra in consideration of their long-term management.

Waste zoning can be reviewed between the operation and dismantling of the facility to take account of the specific features of the different phases of operation and to allow optimised waste management.

The dismantling of a nuclear facility generates radioactive waste mainly in the VLLW and LILW-SL categories. Studies are underway with the aim of optimising management of this waste and in particular reducing its volume.

DISMANTLING WASTE MANAGEMENT PRINCIPLES

As for other waste, the management policy for radioactive waste from dismantling is based on:

- ensuring the traceability of waste from nuclear installations (waste zoning, characterisation, inspection);
- minimising waste volume;
- optimising waste categorisation;
- sending waste directly to existing disposal facilities as much as possible. If the waste does not have an outlet, it is stored in dedicated facilities.

Dismantling of the Chooz A power plant

NATURE OF WASTE GENERATED BY DISMANTLING

The waste generated by dismantling is mostly conventional waste, including rubble and metals. For example, with the dismantling of the Chooz A nuclear power plant, 60% of the 50,000 tonnes of waste generated can be sent to conventional management solutions and only 40% is radioactive waste.

Most radioactive waste from dismantling (> 99%) is very low level (VLLW) or short-lived low- and intermediate-level waste (LILW-SL). This covers:

- materials related to the demolition of installations (concrete, rubble, scrap metal, glove box walls, piping, etc.);
- process equipment (e.g. metal parts);
- tools and work clothes (gloves, vinyl work clothes, etc.);
- effluents that have been used to rinse equipment.

In addition, there is long-lived low-level waste (LLW-LL), in particular graphite waste related to the dismantling of GCR reactors, but also a small amount of long-lived intermediate-level waste (ILW-LL). It is mainly activated waste, including some metal parts located in the core of the reactors or waste from the dismantling of the cycle facilities.

Radioactive waste generated by dismantling is managed in the same way as the operating waste from the facilities. They are sorted, treated if appropriate and then conditioned (*see Chapter 6 - Special Report 2*), before being transported to the existing disposal facility suitable for their level of radioactivity (currently Cires for VLLW waste and CSA for LILW-SL waste) or stored pending the opening of the appropriate disposal facility.

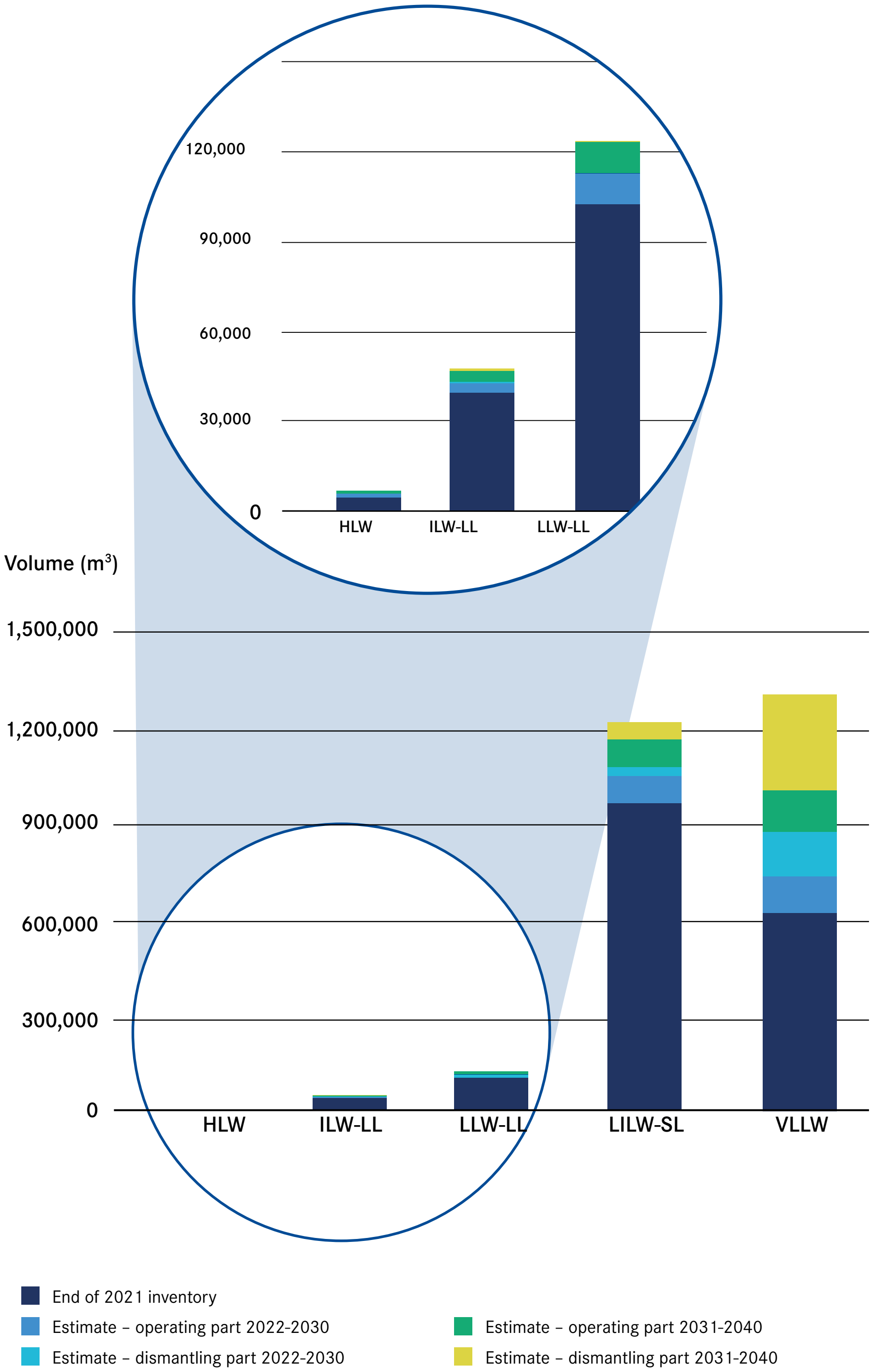
ESTIMATED QUANTITIES OF WASTE GENERATED BY DISMANTLING

During the preparation for dismantling operations, the quantity and nature of waste to be produced are evaluated as accurately as possible, and the treatment and conditioning methods to be used are defined. These assessments take account of all the waste produced by the operation, including secondary waste generated, for example the conditioned volumes of effluent generated by decontamination.

To achieve this, a rigorous inventory is performed, examining the facilities to be cleaned up, the equipment that they contain and their level of residual contamination. This constitutes the initial state inventory and requires a good knowledge of the operating history of the facility. The quantities of waste that will be generated are subsequently assessed in relation to the final state envisaged, using "technical ratios" that have been established and are regularly updated on the basis of feedback from dismantling operations carried out previously. These ratios make it possible to calculate the quantity of waste resulting from the dismantling of each part of an installation according to the nature and technical characteristics of the facility and the radiological contamination measurements taken there (*see Chapter 6 - Special Report 3*).

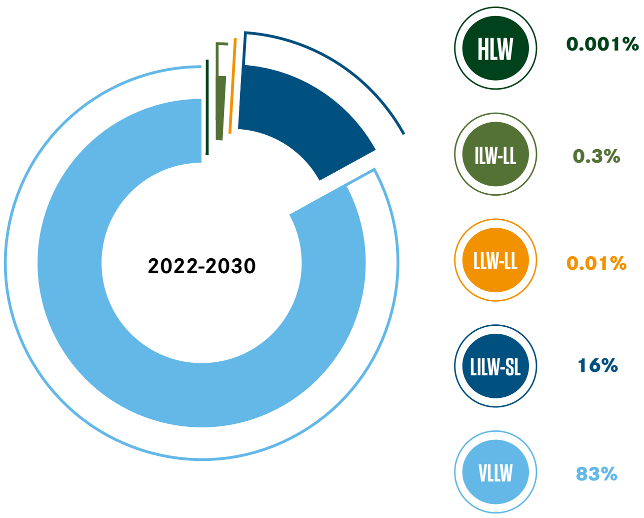
The graphs opposite show the forecast quantities of waste at the end of 2030 and 2040 for scenario S1 according to the categories, used to differentiate the volumes of waste produced at the end of 2021, the forecasts of waste generated by dismantling and the forecasts of waste generated by the operation of the facilities.

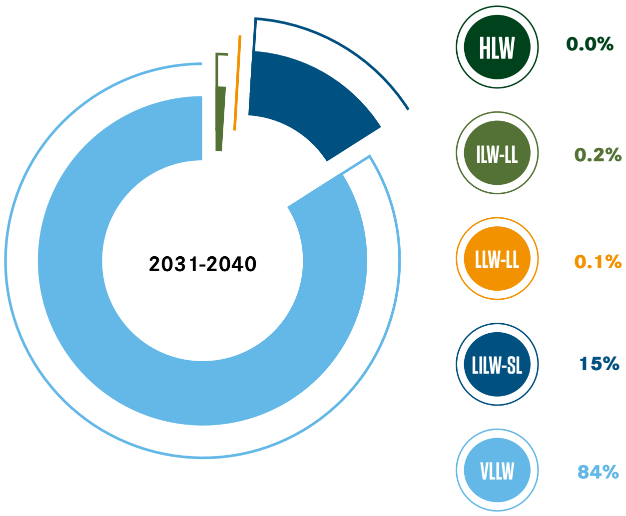
ESTIMATED QUANTITIES OF WASTE AT THE END OF 2030 AND 2040 FOR SCENARIO S1

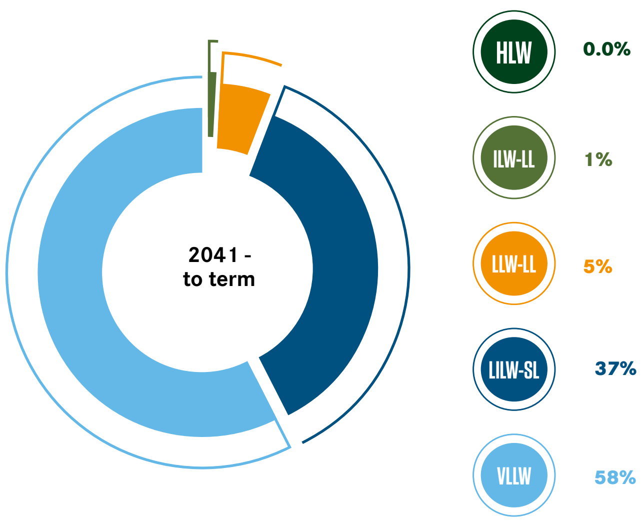


The graphs below show the distribution between the different categories of the dismantling waste generated from 2022 to 2030, from 2031 to 2040 and from 2041 to term. Until 2040, the majority of radioactive waste from dismantling operations is VLLW, and to a lesser extent in the LILW-SL category. In certain special cases, depending on the nature of the installation, the waste may also fall under the LLW-LL or ILW-LL categories. From 2041 to term, the proportion of radioactive waste generated by the dismantling operations belonging to the LILW-SL category increases. In addition, the dismantling of the GCR reactors will produce LLW-LL waste.

PRODUCTION OF DISMANTLING WASTE FROM 2022 TO 2030, FROM 2031 TO 2040, AND FROM 2041 TO TERM







OUTLOOK

In order to fully highlight the challenges of the radioactive waste management solutions, the chapter concerning forecast scenarios of the 2023 edition of the National Inventory is supplemented by this section: "Prospects".

This section describes the results of studies carried out by Andra on the volume of radioactive waste generated by the potential deployment of 6 new reactors or the extended operating life of current reactors. It therefore adds to the assessment carried out for the currently authorised installations, according to scenarios based on the key principles of the currently applicable multi-annual energy programming (PPE2). The inclusion in the *National Inventory* of these studies, which are also part of the PPE2, therefore makes it possible to assess the forecast volumes of radioactive waste by covering all current energy policy guidelines.

WASTE GENERATED BY A NEW FLEET OF SIX EPR2 REACTORS

At the request of the Government in relation to *the New Nuclear Works*[9] *report published in February 2022, Andra carried out an initial technical assessment of the impact of the potential deployment of 6 new EPR2 reactors on the current or planned radioactive waste disposal facilities.*

This work was part of the PPE2, which asked to set out the Government's thoughts concerning technical and economic conditions for a decision to build new EPR2 technology high-power nuclear reactors.

Andra's preliminary assessment was based on the assumptions included in the government report: six EPR2 reactors, deployed in pairs four years apart from 2035 and operating for 60 years.

The estimated volumes of materials and waste included in this preliminary assessment are not accounted for in the forecast scenarios mentioned in the preamble for this chapter, as these are only related to facilities that are already licensed. They can therefore be integrated into the following versions, subject to obtaining the construction licence for these new reactors.

ESTIMATED QUANTITIES OF WASTE

HLW and ILW-LL waste
The volumes of ILW-LL and HLW waste generated by operation of six EPR2 reactors vary according to the fuel reprocessing strategy considered and are shown in the table below.

9 https://www.ecologie.gouv.fr/sites/default/files/2022.02.18_Rapport_nucleaire.pdf

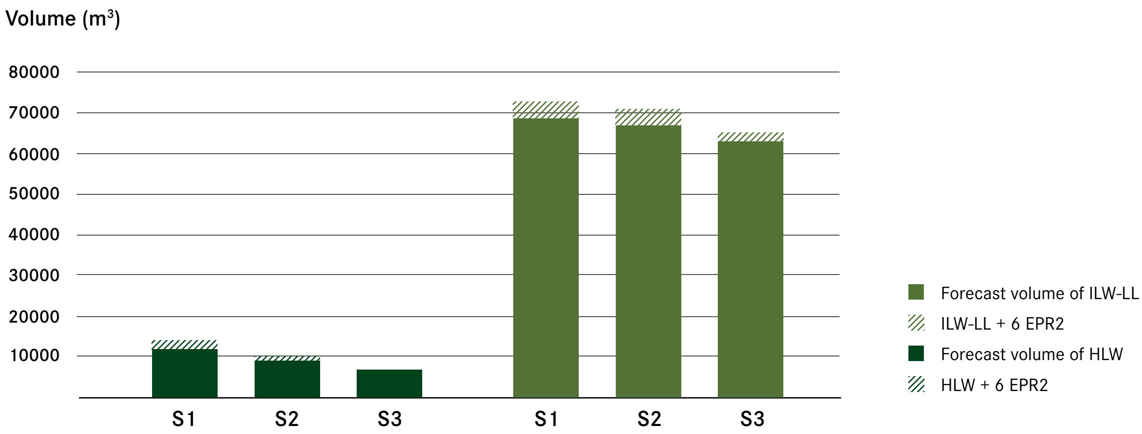
ESTIMATED VOLUMES OF HLW ET ILW-LL WASTE GENERATED BY OPERATION OF SIX EPR2S

HLW waste	Multi-recycling	Mono-recycling	End of recycling
CSD-V	1,872 m³	971 m³	0 m³
ILW-LL waste			
CSD-C	1,273 m³	710 m³	0 m³
Activated and/or contaminated waste from operation and dismantling of EPR2 reactors and other cycle facilities	2,678 m³	3,219 m³	2,574 m³
Total	3,951 m³	3,929 m³	2,574 m³

By way of comparison, the assessment of the volume of HLW and ILW-LL waste to be generated by facilities that obtained their construction licence decree on 31 December 2021, for a 60-year operating life of the nuclear power plant reactors, except for the 12 units due to be closed between 2027 and 2035 (in accordance with PPE2) is:

- **for HLW waste:**
  - 11,800 m³ for scenario S1 in this edition of the *National Inventory*. In the context where multi-recycling would be implemented, the volume of HLW waste from operation of 6 EPR2s would represent an additional volume of waste of 16%;
  - 8,960 m³ for scenario S2 in this edition of the *National Inventory*. In the context where mono-recycling would be implemented, the volume of HLW waste from the operation of 6 EPR2s would represent an additional volume of waste of 11%;
  - 6,890 m³ for scenario S3 in this edition of the *National Inventory*. In the context where recycling would be stopped, the absence of reprocessing does not generate an additional volume of HLW waste, but leads to reclassification of spent fuels as waste.
- **for ILW-LL waste:**
  - 68,800 m³ for scenario S1 in this edition of the *National Inventory*. In the context where multi-recycling would be implemented, the volume of ILW-LL waste from the operation of 6 EPR2s would represent an additional volume of waste of 6%;
  - 67,100 m³ for scenario S2 in this edition of the *National Inventory*. In the context where mono-recycling would be implemented, the volume of ILW-LL waste from the operation of 6 EPR2s would represent an additional volume of waste of 6%;
  - 63,200 m³ for scenario S3 in this edition of the *National Inventory*. In the context where recycling would be stopped, the volume of ILW-LL waste from the operation of 6 EPR2s would represent an additional volume of waste of 4%.

ESTIMATED VOLUMES OF HLW ET ILW-LL WASTE GENERATED BY OPERATION OF SIX EPR2S



The volumes of spent fuel produced by 6 EPR2 reactors, able to be reclassified as waste under the strategy with recycling stopped and mono-recycling are shown in the following table:

ESTIMATED NUMBER of FUEL ASSEMBLIES PRODUCED BY SIX EPR2 TYPE REACTORS THAT MAY BE RECLASSIFIED AS WASTE

Fuel types	Mono-recycling	End of recycling
ENU	Not applicable	18,720
ERU	5,295	1,358
MOX	3,712	0
Total	9,007	20,078

VLLW and LILW-SL waste

The radiological and physical-chemical characteristics of the waste that would be generated by the 6 new EPR2 reactors would be almost similar to the waste currently produced by the most recent reactors in the fleet. Given these similarities, the ratios of LILW-SL and VLLW operating waste generated by the EPR2 type reactors are considered identical to those of the reactors in the current fleet.

These volumes of waste are also independent of the spent fuel reprocessing strategy considered.

The estimated volumes of conditioned LILW-SL and VLLW radioactive waste that would be produced over the entire life cycle of six EPR2 reactors, considering 60 years of operation, are shown opposite.

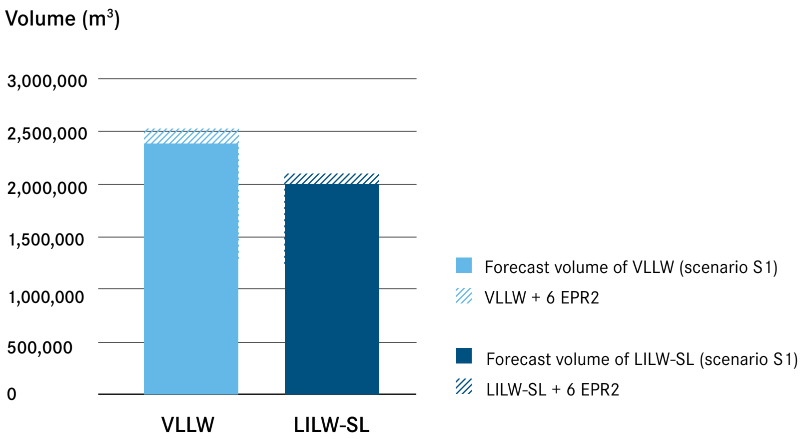
By way of comparison, the assessment of the volume of LILW-SL waste to be generated by facilities that obtained their construction licence decree on 31 December 2021, for a 60-year operating life of the nuclear power plant reactors, except for the 12 units due to be closed between 2027 and 2035 (in accordance with PPE2) is:

- concerning LILW-SL waste close to 2,000,000 m³, regardless of the scenario of this edition of the *National Inventory*. The volume of LILW-SL waste generated by operation of 6 EPR2s would represent an additional volume of waste of 5%;
- concerning VLLW waste close to 2,400,000 m³, regardless of the scenario of this edition of the *National Inventory*. The volume of VLLW waste resulting from the operation of 6 EPR2s would represent an additional volume of waste of 5%.

ESTIMATED VOLUMES OF LILW-SL AND VLLW WASTE GENERATED BY OPERATION OF SIX EPR2S

Category	LILW-SL	VLLW
Operation	40,200 m³	23,400 m³
Dismantling	58,200 m³	96,000 m³
Total	98,400 m³	120,000 m³

ESTIMATED VOLUMES OF LILW-SL AND VLLW WASTE GENERATED BY OPERATION OF SIX EPR2S



THE IMPACT OF EXTENDING THE OPERATING LIFE OF THE CURRENT FLEET

The operating life of nuclear power reactors is one of the elements of French energy policy. In the forecast inventory provided in detail at the beginning of this chapter, the operating life assumptions have been taken in accordance with the Multi-annual Energy Programming for 2019-2028 (PPE2) and therefore include the shutdown of 12 reactors by 2035. The purpose of this paragraph is to estimate the influence of current energy policy guidelines on extending the lifetime of the reactors in the current fleet to 60 years. Nevertheless, it does not pre-empt ASN's position regarding the continued operation of these facilities.

In order to highlight the impact of reactor operating life on quantities of waste, this chapter presents the orders of magnitude, for each category, of the quantities of waste related to operation of nuclear power reactors.
The continued operation actually primarily impacts the generation of operating waste, with no impact on the waste related to the dismantling of the facilities.

These values were calculated on the basis of the data provided by EDF and Orano to the *National Inventory*, which allow the distinction to be made between waste related to operation and waste related to dismantling, and which presents an assessment of production over the periods 2022-2030 and 2031-2040. The information was obtained by considering the types of waste related to the operation of the reactors, i.e.:

- **ILW-LL waste** (activated waste from EDF reactors excluding sodium-containing waste), **LILW-SL** and **VLLW** from nuclear power plants;
- **HLW and ILW-LL waste** from fuel processing. This is vitrified waste and structural metallic waste surrounding the fuels (hulls and end caps) generated at the Orano La Hague facility.

CONDITIONED VOLUME OF OPERATING WASTE FOR ONE REACTOR IN ONE YEAR

Category	
HLW	About 3 m³
ILW-LL	About 3 m³
LILW-SL	Between 110 and 150 m³
VLLW	Between 60 and 80 m³

IMPACT OF QUANTITIES OF WASTE GENERATED BY OPERATION OF 12 REACTORS OVER 10 YEARS

Category	
HLW	Between 2% and 5% depending on the scenarios
ILW-LL	Less than 1%
LILW-SL	Less than 1%
VLLW	Less than 1%

These estimates therefore make it possible to assess the effect of extending the 10-year operating life of 12 reactors on waste generation, showing that this impact is no more than a few percent of the inventory of waste at term for each category, regardless of the scenario considered.

04

Storage

STORAGE OF RADIOACTIVE WASTE

In France, a regulatory framework was put in place to ensure that the existing and future storage capacities would be sufficient [1] with regard to the current and the forecast quantities of radioactive materials and waste. Regarding this, with each edition of the National Radioactive Material and Waste Management Plan (PNGMDR), requests and recommendations are sent to the holders of radioactive material, the producers of radioactive waste and the organisations responsible for conditioning, storage or disposal of waste in order to identify the specific requirements and define their capacities and their provisional closure dates.

The National Inventory *of Radioactive Materials and Waste* returns the storage-related information in accordance with:

- Article 3 of the amended Order of 9 October 2008. This requires waste producers to provide Andra with information concerning storage facilities (fill factor of the storage facilities, any planned extensions and construction work as of 31 December 2021) intended to receive radioactive waste packages for which no final management solutions exist or such solutions are currently not complete;
- Article 3 of the Decree of 9 December 2022 in application of Decree No.2022-1547 of 9 December 2022 stipulated by Article L. 542-1-2 of the French Environmental Code and establishing the requirements of PNGMDR. The purpose is to anticipate requirements for storage and disposal facility capacities and to improve the overall view of the choices to be made in terms of management of radioactive materials and waste according to the four forecast scenarios presented in Chapter 3.

This chapter presents the data concerning storage of radioactive materials and waste, provided to Andra by the CEA, EDF, Orano, Framatome and Solvay in accordance with the regulations. This data is presented as follows:

- fill factors of storage facilities and their locations as of end of 2021;
- planned storage facility extension or construction work as of end of 2021;
- additional storage requirements based on forecast scenarios.

Radioactive waste is stored at different industrial sites in facilities dedicated to this purpose. This waste is intended to be stored by Andra in existing or planned specialist facilities or in accordance with solutions that remain to be defined as appropriate.

This covers:

- for waste intended for **existing disposal facilities**:
  - intermediate storage of waste conditioned in packages, of a logistical nature, used to manage flows to Andra facilities;
  - storage of waste, in particular old waste, pending treatment, conditioning, before removal to Andra facilities;
- for waste intended for **planned disposal facilities**:
  - storage of waste, in particular old waste, pending retrieval (RCD), before removal to other storage facilities;
  - storage pending the availability of disposal solutions;
  - storage for high-level waste (HLW), which must be stored for several decades in decay, before it can be dealt with in a deep disposal facility.

FILL FACTORS OF STORAGE SITES FOR RADIOACTIVE WASTE AT END OF 2021

The table opposite lists storage facilities in operation at the end of 2021 with their fill factor. In accordance with Article 3 of the amended Order of 9 October 2008, it shows the facilities in which radioactive waste packages are stored, for which no final management solutions exist or such solutions are currently not complete.

New facilities are commissioned to take over from older ones, either because they are reaching saturation point or because they need to be dismantled. In this way,all waste packages, such as those in production, have an existing storage capacity.

ICEDA (EDF facility for conditioning and storage of radioactive waste)

1 The French Environmental Code defines storage in Article L. 542-1-1 as "the operation consisting in temporarily placing these radioactive substances in a surface or near-surface facility specially designed for this purpose, with the intention of retrieving them at a later date".

DISPOSAL FACILITIES AUTHORISED AT THE END OF 2021 TO RECEIVE RADIOACTIVE WASTE PACKAGES FOR WHICH DISPOSAL SOLUTIONS DO NOT EXIST OR ARE NOT COMPLETE

Registrant	Site	Stored waste typology	Date of commis-sioning	Total capacity	Capacity used at end of 2021	Fill factor at end of 2021
Andra	Cires, Storage building (Morvilliers)	Waste generated by activities outside the nuclear power sector	2012	6,000 m^3	945 m^3	16%
Framatome	CEZUS (Jarrie)	Radium-bearing waste	2005	24,000 packages	18,393 packages	77%
Orano	Building S (La Hague)	Bituminised sludge packages	1987	20,000 packages	11,928 packages	60%
Orano	Building ES (La Hague)	Alpha drums	1995	30,704 packages	14,483 packages	47%
Orano	Building R7 (La Hague)	CSD-V, CSD-B package	1989	4,500 packages	4,094 packages	91%
Orano	Building T7 (La Hague)	CSD-V package	1992	3,600 packages	3,179 packages	88%
Orano	Building EEV/SE (La Hague)	CSD-V, CSD-B package	1996	4,320 packages	4,316 packages	100%
Orano	Building EEV/LH Pit 30 (La Hague)	CSD-V, CSD-B package	2013	4,212 packages	4,201 packages	100%
Orano	Building EEV/LH Pit 40 (La Hague)	CSD-V, CSD-B package	2017	4,212 packages	4200 packages	100%
Orano	Building ECC (La Hague)	CSD-C package	2002	23,584 packages	18,195 packages	77%
Orano	Building EDS/EDT (La Hague)	CBF-C '2 and CAC packages	1990	6,512 packages	6,208 packages	95%
Orano	Building EDS/ADT2 (La Hague)	CBF-C '2 package	2008	2,759 packages	1,200 packages	43%
Orano	Building EDS/EDC-A (La Hague)	Package of cemented hulls and end caps	2009	1,125 packages	1,125 packages	100%
Orano	Building EDS/EDC-B and C (La Hague)	Package of cemented hulls and end caps	1990	1,656 packages	822 packages	50%
Orano	Building D/E EDS (La Hague)	Package of cemented hulls and end caps	1995	5,280 packages	4,548 packages	86%
CEA DAM	Tritium waste storage (Valduc)	Tritium-bearing waste	1995	5,000 packages	3,732 packages	75%
			2012	16,620 packages	13,036 packages	78%
CEA civil	Storage of asphalt packages (new generation) (Marcoule)	Bituminised sludge packages	2000	11,500 packages	11,257 packages	98%
CEA civil	Storage of vitrified waste packages (production) (Marcoule)	Vitrified waste packages and production plant operating waste packages	1978	3,800 packages	3,473 packages	91%
CEA civil	DIADEM (Marcoule)	Irradiating waste and dismantling alpha package	2025	2,430 packages	0 packages	0%
CEA civil	BNI 56 (Cadarache)	Miscellaneous package	1968	25,999 m^3	6,197 m^3	24%
CEA civil	BNI 164 (Cadarache)	500L, 870L packages, concrete hulls 500L of filtration sludge	2006	7,488 packages	4,309 packages	58%
CEA civil	ICPE 420 and 465 (Cadarache)	Radium-bearing waste	1992	26,800 packages	25,302 packages	94%
CEA civil	Storage of vitrified waste packages (pilot) (Marcoule)	Pilot glass package	1976	640 packages	216 packages	34%
CEA civil	Storage of asphalt packages (old generation) (Marcoule)	Bituminised sludge packages	1966	60,000 packages	52,173 packages	87%
EDF	ICEDA (Bugey)	Cemented packages	2020	2,180 packages	0 packages	0%
EDF	SILOS (Saint-Laurent A)	Graphite waste	1971	2,000 tonnes	2,000 tonnes	100%
Solvay	Chef de Baie Plant (La Rochelle)	Radium-bearing waste	1988	56,980 m^3	7,593 m^3	13%

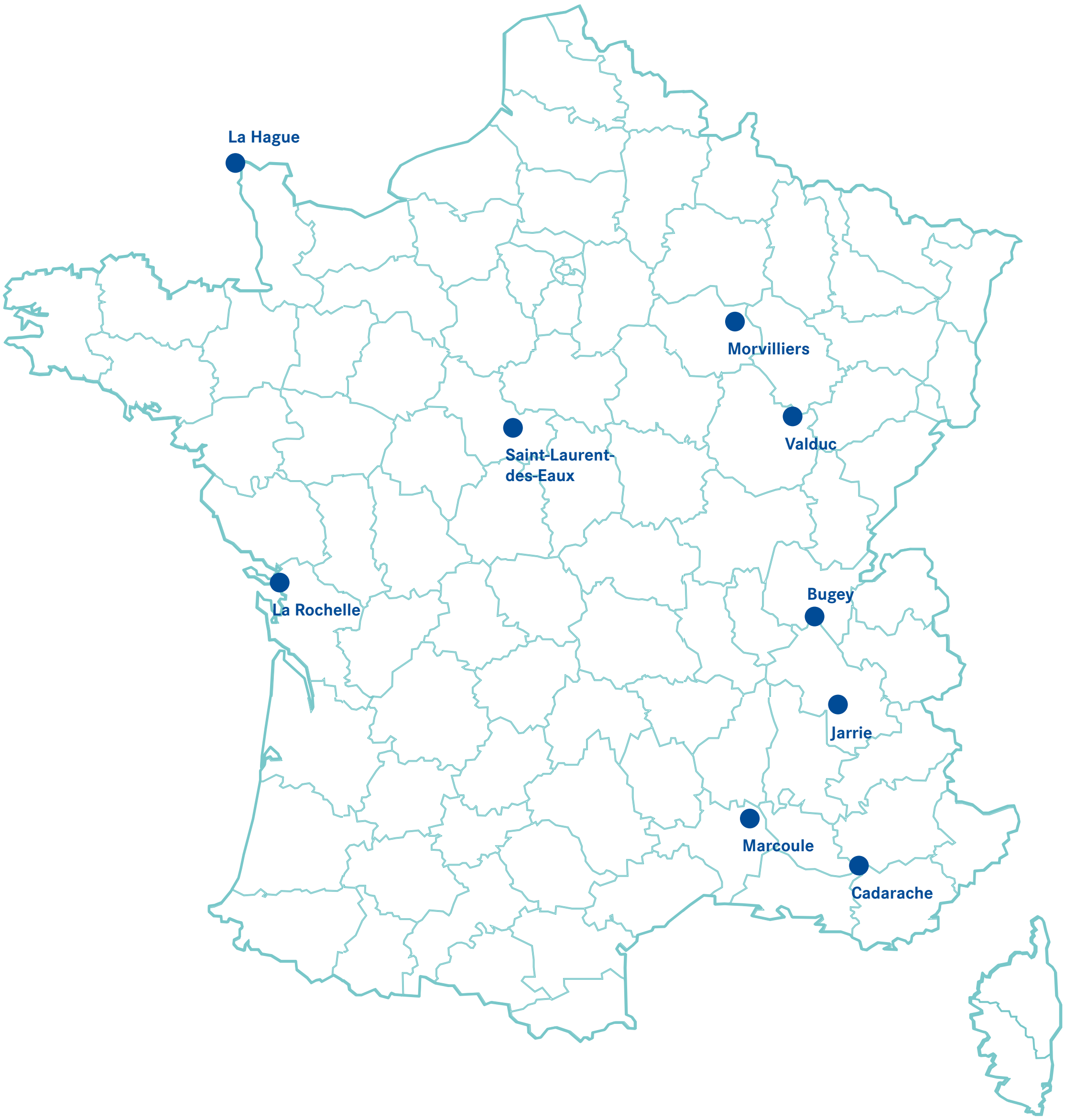
LOCATIONS OF STORAGE SITES FOR RADIOACTIVE WASTE

The location of the storage facilities intended to receive radioactive waste packages for which the disposal solutions do not exist or are not complete, as of 31 December 2021, is shown below.

The nature, quantity of waste stored and the storage locations are described in the *Geographical Inventory* available on the *National Inventory* website. inventaire.andra.fr

Storage of high-level waste packages at the Orano La Hague site

STORAGE FACILITIES FOR RADIOACTIVE WASTE AS OF 31 DECEMBER 2021



FORECASTS OF EXTENSION OR CONSTRUCTION OF RADIOACTIVE WASTE STORAGE SITES AT END OF 2021

Producers are planning extensions or the deployment of new facilities in order to have sufficient capacity to store waste packages generated as a result of production, recovery and reconditioning of radioactive waste.

In accordance with Article 3 of the amended decree of 9 October 2008, the table opposite presents the forecast extensions or construction of storage facilities for the decade ahead, as planned at the end of 2021.

FORECAST EXTENSION OR CONSTRUCTION OF STORAGE SITES

Registrant	Site	Planned waste packages	Provisional commissioning date	Total capacity
Orano	Building S (La Hague)	Bituminised sludge packages	2025	1,008 packages
Orano	Building ES (La Hague)	Alpha drums	2022*	6,880 packages
Orano	Building EEV/LH Pit 50 (La Hague)	CSD-V, CSD-B package	2022*	4,212 packages
Orano	Building EEV/LH Pit 60 (La Hague)	CSD-V, CSD-B package	2027	4,212 packages
Orano	Building EDS/EDT (La Hague)	CBF-C'2 and CAC packages	2022*	173 packages
Orano	Building EDS/EDC-A (La Hague)	Package of cemented hulls and end caps	2022*	140 packages
Orano	Building ECC (La Hague)	CSD-C package	2025	5,928 packages
CEA civil	BNI 164-CEDRA (Cadarache)	500 L, 870 L packages, concrete hulls 500 L of filtration sludge	2029	7,488 packages
CEA civil	Storage of asphalt packages (new generation) (Marcoule)	Bituminised sludge packages	2027	11,500 packages
CEA DAM	Tritium waste storage (Valduc)	Tritium-bearing waste	2026	2,700 packages
			2027	7,200 packages

* Planned at the end of 2021, the extension was actually commissioned during 2022.

ADDITIONAL REQUIREMENTS

In accordance with Article 3 of the PNGMDR decree of 9 December 2022, additional data is provided by producers to be able, by 2050, to assess the rates of reaching maximum authorised capacities of facilities and to provide for deployment of new storage capacities according to the forecast scenarios (S1, S2, S3 and S4).

The table opposite shows the additional requirements previously identified to meet the future needs assessed by the producers.

Additional requirements for radioactive waste storage capacity over the next three decades may depend on the forecast scenarios studied as part of the *National Inventory*. For certain types of radioactive waste, estimates of waste generation may indeed differ depending on the assumptions made, particularly with regard to the strategy for reprocessing of spent fuel.

ADDITIONAL RADIOACTIVE WASTE STORAGE CAPACITY REQUIREMENTS

<table>
<tr><th rowspan="2">Registrant</th><th rowspan="2">Site</th><th rowspan="2">Planned waste packages</th><th colspan="4">Provisional commissioning date</th><th rowspan="2">Total capacity</th></tr>
<tr><th>S1</th><th>S2</th><th>S3</th><th>S4</th></tr>
<tr><td>Orano</td><td>Building EEV/LH Pit 70 (La Hague)</td><td>CSD-V, CSD-B package</td><td colspan="4">2032</td><td>4,212 packages</td></tr>
<tr><td>Orano</td><td>Building EEV/LH Pit 80 (La Hague)</td><td>CSD-V, CSD-B package</td><td colspan="4">2037</td><td>4,212 packages</td></tr>
<tr><td>Orano</td><td>Building EEV/LH Pit 90 (La Hague)</td><td>CSD-V, CSD-B package</td><td colspan="2">2042</td><td colspan="2">No requirements</td><td>4,212 packages</td></tr>
<tr><td>Orano</td><td>Building EEV/LH Pit 100 (La Hague)</td><td>CSD-V, CSD-B package</td><td colspan="2">2047</td><td colspan="2">No requirements</td><td>4,212 packages</td></tr>
<tr><td>Orano</td><td>Building ECC2 (La Hague)</td><td>CSD-C package</td><td colspan="4">2033</td><td>23,000 packages</td></tr>
<tr><td>Orano</td><td>Building EDS (La Hague)</td><td>CBF-C'2 package</td><td colspan="4">2035</td><td>to be defined</td></tr>
<tr><td>Orano</td><td>Building ES (La Hague)</td><td>Alpha drums</td><td colspan="4">2042</td><td>7,318 packages</td></tr>
<tr><td>EDF</td><td>Storage of graphite waste (Saint-Laurent)</td><td>Graphite sleeves package</td><td colspan="4">Start of 2030s</td><td>2,000 tonnes</td></tr>
<tr><td>Framatome</td><td>CEZUS (Jarrie)</td><td>Radium-bearing waste</td><td colspan="4">to be defined</td><td>to be defined</td></tr>
<tr><td>CEA civil</td><td>Storage of asphalt packages (new generation) (Marcoule)</td><td>Bituminised sludge packages</td><td colspan="4">2040</td><td>45,000 packages</td></tr>
</table>

This is the case for the Orano La Hague site. In order to cover all potential storage requirements, Orano is implementing two strategies:

- the first concerns cemented solid operating waste packages (CBFC'2) and compacted waste packages (CSD-C). It aims to define a capacity for extensions of the EDS and ECC buildings to cover the highest future production, as evaluated in scenario S1[2];
- the second concerns vitrified waste packages (CSD-V). The gradual deployment of pits in building EEV/LH, at a rate of two per decade, makes it possible to adapt to possible changes in strategy with regard to spent fuel reprocessing, particularly in the event of a shutdown by 2040, as envisaged in scenarios S3 and S4. The choice to build pits 90 and 100 between 2040 and 2050 will therefore be determined by the French energy strategy.

Regarding the EDF and Framatome sites, as the assumption concerning the operating lives of the reactors in the current fleet is the same, regardless of the scenario, the forecasts for radioactive waste generation are equivalent. Consequently, their additional storage capacity requirements are independent of the scenarios.

For the civil CEA, since its research activities are equivalent in all scenarios studied, the additional storage capacity requirements are identical regardless of scenario.

EXAMPLE 1:
DISMANTLING OF SAINT-LAURENT-DES-EAUX SILOS (EDF)

In addition to the two former GCR reactors currently in the dismantling phase, the EDF Saint-Laurent-des-Eaux site has two storage silos for irradiated graphite sleeves (long-lived low-level waste) generated by operation of these reactors, authorised by the decree of 14 June 1971 (BNI 74). This storage site is shown in the table on page 85 under theheading "SILOS".

As part of the planned dismantling of these silos, EDF has decided to create a new storage facility at the Saint-Laurent-des-Eaux site to accommodate packages of irradiated graphite sleeves, at the start of the 2030s (see the second table *on page 87 - storage of graphite waste).*

Saint-Laurent-des-Eaux Silos (EDF)

EXAMPLE 2:
RECOVERY OF ASPHALT DRUMS FROM THE CEA SITE IN MARCOULE

Since May 1966, the bitumen coating process for sludge generated by treatment of medium- and high-activity liquid effluents has been implemented at the CEA site in Marcoule and has led to production of more than 60,000 drums. As there is no associated disposal site, the drums have been stored on the site, initially in pits (North Zone) and bunkers (South Zone). This storage is shown in the table on page 85 under theheading *Storage of asphalt packages (old generation).*

From 2000 until 2018, more than 10,000 drums stored in the North Zone pits and bunkers 1 and 2 have been retrieved, reconditioned and stored in the Multipurpose Storage (EIP) building. This building is currently composed of two cells and has a capacity of 11,500 packages (see table on page 85 - *storage of asphalt packages - new generation*).

From 2027, two additional cells, with an approximate capacity of 11,500 drums, will be commissioned, allowing the retrieval and storage of the drums currently stored in bunkers 3 and 4. This storage extension is shown in the first table on page 87 under the title *Storage of asphalt packages (new generation).*

Finally, as part of retrieval from the last bunkers, a third phase, from 2034 to 2055 approximately, could follow, with deployment, by 2040, of an extension of the EIP with an additional capacity of about 45,000 drums (see second table on page 87 - *storage of asphalt packages - new generation).*

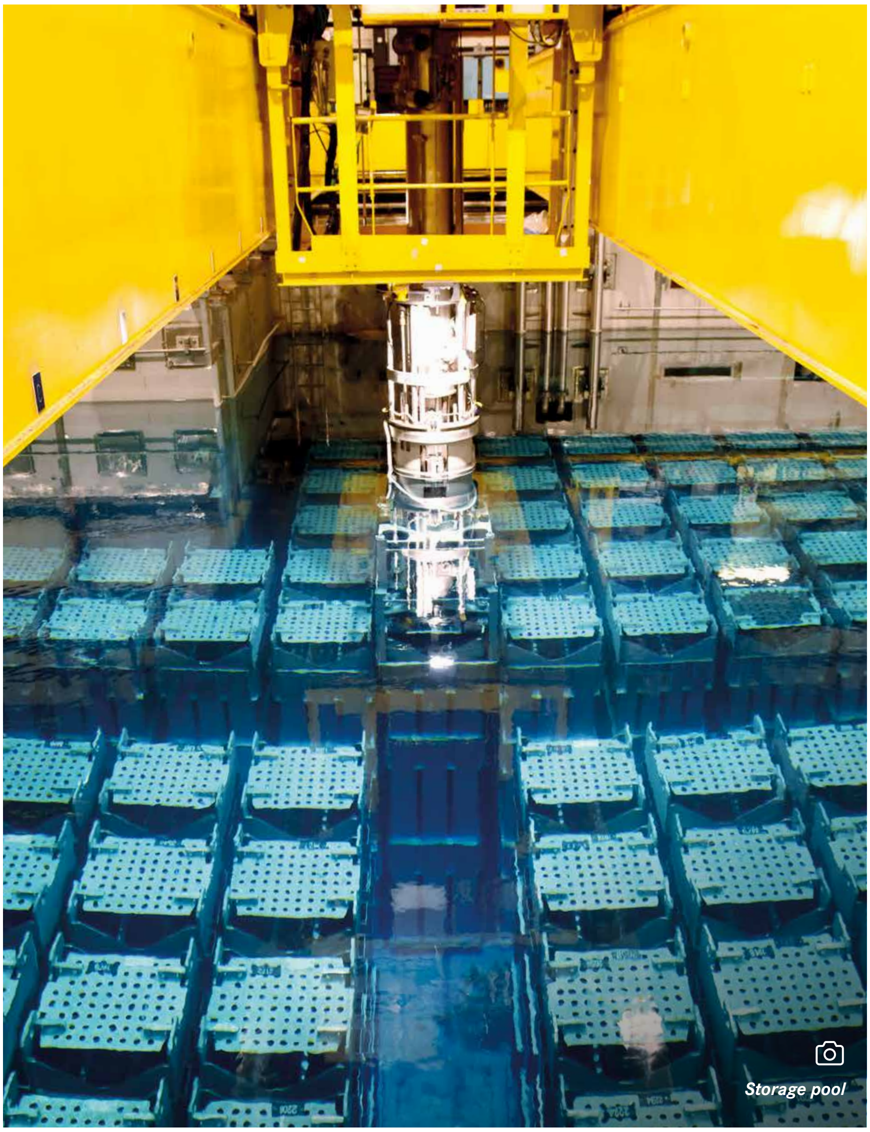
2 Presented in Chapter 3.

STORAGE OF RADIOACTIVE MATERIALS

By its nature, a radioactive material is a substance for which there is a future use planned *(see Article L. 542-1-1 of the French Environmental Code)*. Pending this future use, the waste management goes through a storage period according to the intended or envisaged use *(see Article L. 542-1-1 of the French Environmental Code)* before recovery. The recovery solutions implemented or envisaged differ according to the radioactive material concerned.

In accordance with Article 3 of the PNGMDR decree of 9 December 2022, producers provide Andra with information concerning the storage of radioactive materials. This information concerns:

- as of 31 December 2021, the fill factor of the storage facilities as well as their location and forecasts for expansion and construction of storage facilities;
- storage capacity requirements according to forecast scenarios (S1, S2, S3 and S4).



Storage pool

FILL FACTORS OF STORAGE SITES FOR RADIOACTIVE MATERIALS AT END OF 2021

STORAGE FACILITIES AUTHORISED AT THE END OF 2021 INTENDED FOR RADIOACTIVE MATERIALS

Regis-trant	Site	Categories of materials stored	Date of commissioning	Total capacity [3]	Fill factor at end of 2021
EDF	BK pools* 900 MWe series - CP0	Spent ENU fuel pending reprocessing (3)	According to NPP concerned	416 assemblies	78%
EDF	BK pools* 900 MWe series - CPY		According to NPP concerned	5,180 assemblies	82%
EDF	BK pools* 1300 MWe series - P4	Spent ERU fuel pending reprocessing (6)	According to NPP concerned	1,616 assemblies	83%
EDF	BK Pools* 1300 MWe series - P'4		According to NPP concerned	4,350 assemblies	66%
EDF	BK pools* 1450 MWe series - N4	Mixed uranium-plutonium fuel spent fuel, pending reprocessing (9)	According to NPP concerned	1,356 assemblies	64%
EDF	BK Pool* Flamanville 3		2020	635 assemblies	42%
EDF	APEC Pool (Creys-Malville)	Spent FNR fuels pending reprocessing (12) Other materials -SPX (25)	2000	1,344 assemblies	99.6%
CEA	CASCAD (Cadarache)	Other civilian spent fuel (15)	1990	315 shafts	85%
CEA	MAGENTA (Cadarache)	Enriched uranium from spent fuel reprocessing, in all its physical-chemical forms (20)		1,486 cells	76%
		Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22) Non-irradiated separated plutonium, in all its physical-chemical forms (17) Thorium, in the form of nitrates and hydroxides (23)	2011	1,110 drums	73%
CEA	MMB (Cadarache)	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22)	1961	102 sets[4]	90%
Orano	Pu storage facilities at La Hague	Non-irradiated separated plutonium, in all its physical-chemical forms (17)	1966	6,632 containers	95%
Orano	Spent fuel storage at La Hague	Spent ENU fuels pending reprocessing (3) Spent ERU fuels pending reprocessing (6) Spent mixed uranium-plutonium fuels pending reprocessing (9) Non-irradiated mixed uranium-plutonium fuel scrap pending reprocessing (10) Other civilian spent fuel (15)	1980	2,851 basket slots	93%
Orano	Workshop T5 (La Hague)	Uranium from spent fuel reprocessing, in all its physical-chemical forms (21)	1980	2,000 m^3	37%
Orano	AC MOX storage facilities at Melox	Mixed uranium-plutonium fuels before use or under manufacture (7)	Before 2000	149 assemblies	95%
Orano	Pu storage facilities at Melox	Non-irradiated separated plutonium, in all its physical-chemical forms (17)	Before 2000	192 canisters	82%
Orano	Malvési	Mined natural uranium, in all its physical-chemical forms (18)	1958	40,000 tU[5]	82%
Orano	BNI 93 (Tricastin)	Natural, enriched or depleted uranium (18, 19, 22)	1998	50,000 tU	20%

* For reasons of reactor safety and availability, the total capacity of the BK pools considered in operation is the total capacity of the pools minus the capacity corresponding to 1 complete core and minus 1 new refill.

3 The storage capacities are expressed in various units, depending on the type of material, the conditioning and the nature of the facility.

4 MMB consists of six storage halls, and each of these halls is divided into areas or bays.

5 tU: tonne of uranium.

Regis-trant	Site	Categories of materials stored	Date of commissioning	Total capacity [3]	Fill factor at end of 2021
Orano	BNI 178 excluding P17 (Tricastin)	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Depleted uranium, in all its physical-chemical forms (22)	1998	46,000 tU	20%
Orano	P17 (Tricastin)	Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Depleted uranium, in all its physical-chemical forms (22)	1998	16,000 tU including 3,820 for biological protection [6]	21%
Orano	P35 (Tricastin)	Mined natural uranium, in all its physical-chemical forms (18) Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Depleted uranium, in all its physical-chemical forms (22)	1998	93,500 tU including 60,000 for biological protection [6]	86%
Orano	P18 (Tricastin)	Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Depleted uranium, in all its physical-chemical forms (22)	1998	48,002 tU including 41,761 for biological protection [6]	61%
Orano	P09 (Tricastin)	Depleted uranium, in all its physical-chemical forms (22)	1998	2 184 DV70	100%[7]
Orano	P19 (Tricastin)	Depleted uranium, in all its physical-chemical forms (22)	1998	134,835 tU	41%
Orano	Bessines fleet	Depleted uranium, in all its physical-chemical forms (22)	1998	24 762 DV70[8]	75%
Framatome	Research (CERCA, Romans-sur-Isère)	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22) Thorium in the form of nitrates or hydroxides (23)	1960s	33.031 tonnes	27%
Framatome	Puissance (Romans-sur-Isère)	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22)	1990s	1,805.052 tonnes	26%

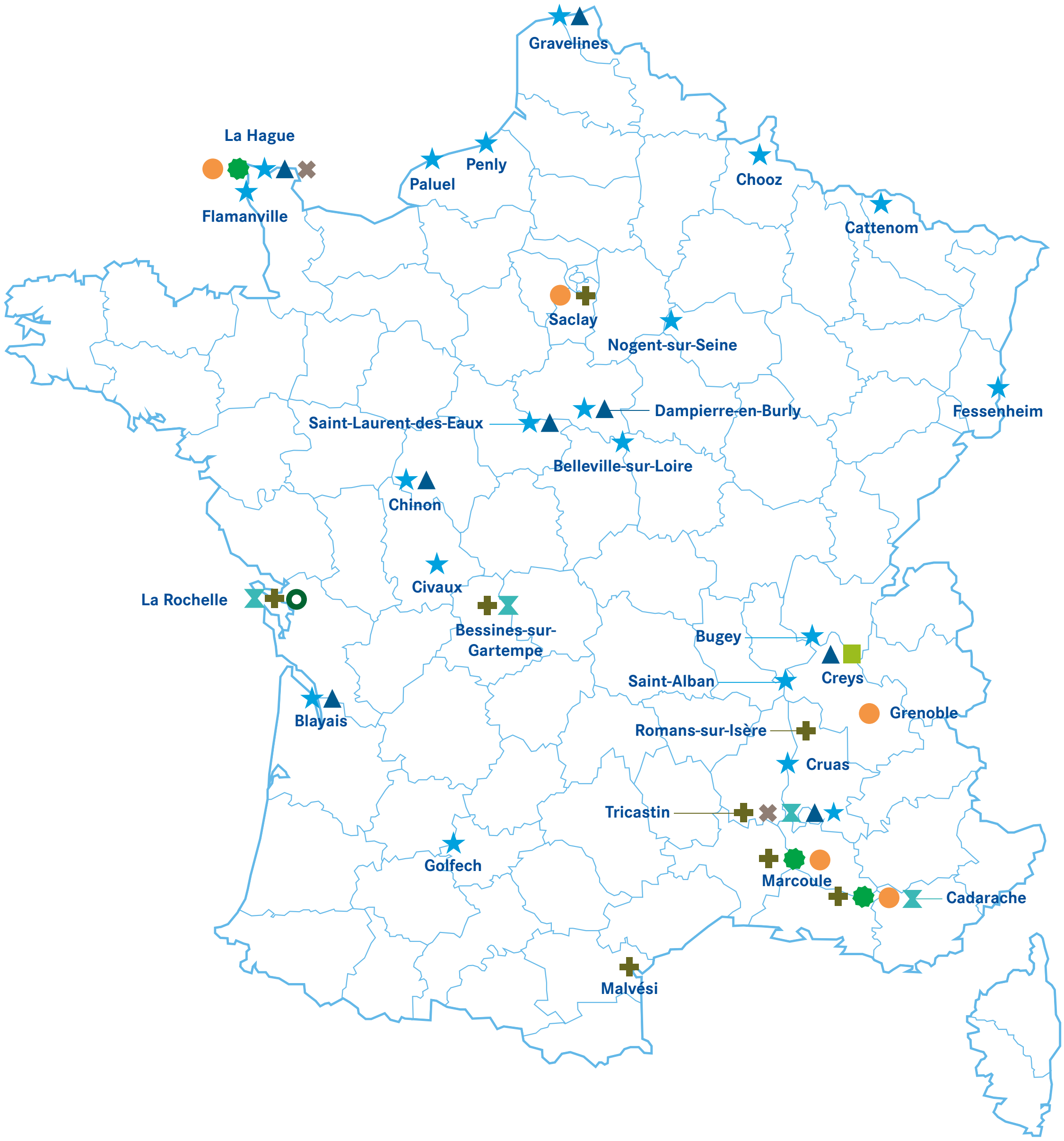
6 Depleted uranium is used for radiation protection, due to the attenuating properties of this material.

7 Although 100% of the capacity of this storage facility is occupied, other depleted uranium storage facilities are currently in operation and there is no risk of saturation being reached for this category of material.

8 DV 70 containers are steel cubes measuring 3 m^3

LOCATIONS OF STORAGE SITES FOR RADIOACTIVE MATERIALS

STORAGE SITES FOR RADIOACTIVE MATERIALS AS OF 31 DECEMBER 2021



- Natural uranium
- Uranium from spent fuel reprocessing
- Uranium oxide fuel (ENU, ERU)
- Mixed oxide fuel (MOX, FBR)
- Research reactor fuel
- Thorium
- Materials in suspension
- Plutonium
- Other materials

FORECASTS OF EXTENSION OR CONSTRUCTION OF RADIOACTIVE MATERIALS STORAGE SITES AT END OF 2021

Holders of radioactive materials plan the extension or development of new facilities in order to have sufficient capacities to store the materials that are used or will be used in the fuel cycle.

In accordance with Article 3 of the PNGMDR decree of 9 December 2022, the table below presents the forecasts for extension or construction of storage.

Most of the storage facilities concerned are already licensed, commissioned in 2022 or will be commissioned in 2023.

Orano's Fleur 1 and Fleur 2 facilities at the Tricastin site will be used to store reprocessed uranium prior to enrichment, while Framatome's S9 facility will be used to store enriched uranium obtained by reprocessing.

The increase in Framatome Puissance's licence, up to 2,164,406 kg, will make it possible to keep up with the increase in fuel assembly manufacturing activity.

The construction licence application for EDF's centralised storage pool project must be submitted at the end of 2023.

If it is authorised, commissioning is planned for 2034. Pending its operation, an operation to densify the swimming pools at the Orano La Hague plant is being examined by the nuclear safety authority and will increase the capacity approximately by an additional 3,200 tHM. The decision on this project is expected in 2024. Dry storage of fuels will also be studied if this becomes necessary and could start in 2029 for a potential capacity of 650 tHM.

Finally, since plutonium is used to make MOX fuel assemblies and these are delivered to the EDF customer as they are produced, the Melox plant does not require additional storage capacity for the radioactive materials used.

FORECASTS OF FUTURE EXTENSION OR CONSTRUCTION OF STORAGE

Registrant	Site	Type	Planned categories of materials	Provisional commissioning date	Total capacity
EDF	Central storage pool (La Hague)	Construction	Spent ENU fuels pending reprocessing (3) Spent ERU fuels pending reprocessing (6) Spent mixed uranium-plutonium fuels pending reprocessing (9)	2034	13,000 assemblies
Orano	P36 – Fleur 1 and Fleur 2 (Tricastin)	Construction	Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Depleted uranium, in all its physical-chemical forms (22)	2023	42,093 drums
Framatome	Puissance (Romans-sur-Isère)	Increase in licence to hold	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22)	2022	359,354 kg
Framatome	Area S9 (Romans-sur-Isère)	Construction	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Enriched uranium from spent fuel reprocessing, in all its physical-chemical forms (20) Depleted uranium, in all its physical-chemical forms (22)	2022	113.85 tonnes
Framatome	New Uranium Zone (Romans-sur-Isère)	Construction	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22)	2022	46 tonnes

ADDITIONAL REQUIREMENTS

In accordance with Article 3 of the PNGMDR decree of 9 December 2022, additional data is provided by producers in order to be able, by 2050, to assess the rates of reaching the authorised capacities of the facilities, in order to provide for the deployment of new storage capacities according to the forecast scenarios.

The table below shows the additional requirements previously identified to meet the future needs assessed by the holders (S1, S2, S3 and S4).

The additional requirement for spent ENU, ERU and MOX fuel storage capacities depends on the energy policy scenario: the requirement is identified in scenarios S3 and S4, which provide for an early shutdown of reprocessing, which would result in the maximum allowable capacities of existing facilities being reached.

The Orano additional requirements for the storage of reprocessed uranium depend largely on the resumption of the RepU activity (manufacture and use of ERU fuels) by nuclear power plants, leading to removal of this uranium from storage for enrichment with the aim of manufacturing fuel.

ADDITIONAL STORAGE CAPACITY REQUIREMENTS FOR STORAGE OF RADIOACTIVE MATERIALS

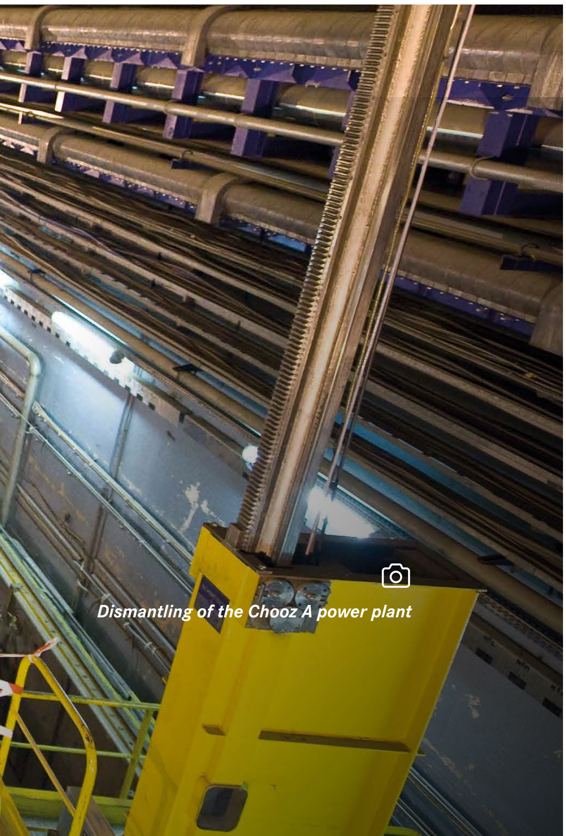
Registrant	Site	Planned categories of materials	Provisional commissioning date S1 S2	Provisional commissioning date S3 S4	Total storage capacity
EDF	Storage of spent fuel to be defined	Spent ENU fuels pending reprocessing (3) Spent ERU fuels pending reprocessing (6) Spent mixed uranium-plutonium fuels pending reprocessing (9)	No requirements	Before 2050	to be defined
Orano	Tricastin – Fleur 3 (Tricastin)	Uranium from spent fuel reprocessing, in all its physical-chemical forms (21) Depleted uranium, in all its physical-chemical forms (22)	Around 2040	No requirements	to be defined
Framatome	Puissance (Romans-sur-Isère)	Mined natural uranium, in all its physical-chemical forms (18) Enriched natural uranium, in all its physical-chemical forms (19) Depleted uranium, in all its physical-chemical forms (22)	Before 2030		3,030,168 kg of uranium

SPENT FUEL from EDF

Current forecasts of the quantity of ENU, ERU and MOX spent fuels to be stored indicate that the La Hague plant's current capacities would be reached by 2030, regardless of the energy policy scenario studied.

For this reason, EDF is carrying out a development project to create a centralised underwater storage pool, to complement the capacities already present at the La Hague plant. The maximum allowable capacity for this pool (13,000 fuel assemblies – 6,500 tHM) could be reached by 2050 with the scenarios that involve stopping the reprocessing activity. An additional capacity requirement would therefore be necessary by that time, for example in the form of a second pool.

A densification of the current pools at La Hague is also being examined by the French Nuclear Safety Authority to cover the requirement until the commissioning of the central storage pool which is planned to take place in 2034.



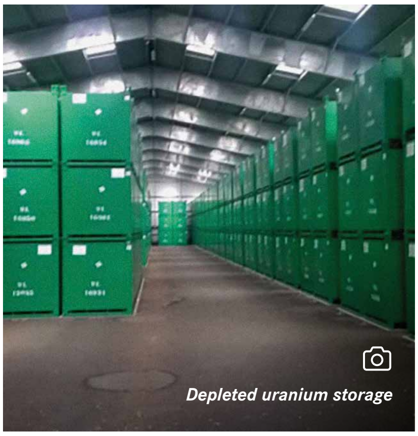
Dismantling of the Chooz A power plant

ADDITIONAL REQUIREMENT FOR STORAGE OF SPENT FUEL FROM EDF

		End 2030	End 2040	End 2050
Fill factor of existing pools at Orano La Hague		93%	100%	100%
Fill factor of the 1st basin of the future central storage pool	S1	EDF central storage pool not yet commissioned	14%	72%
	S2		12%	85%
	S3		14%	100%
	S4		17%	100%
Additional requirement after filling the 1st basin of the central storage pool	S1	EDF central storage pool not yet commissioned	-	-
	S2		-	-
	S3		-	3,012 tHM
	S4		-	1,774 tHM

FLEUR 3 (ORANO)

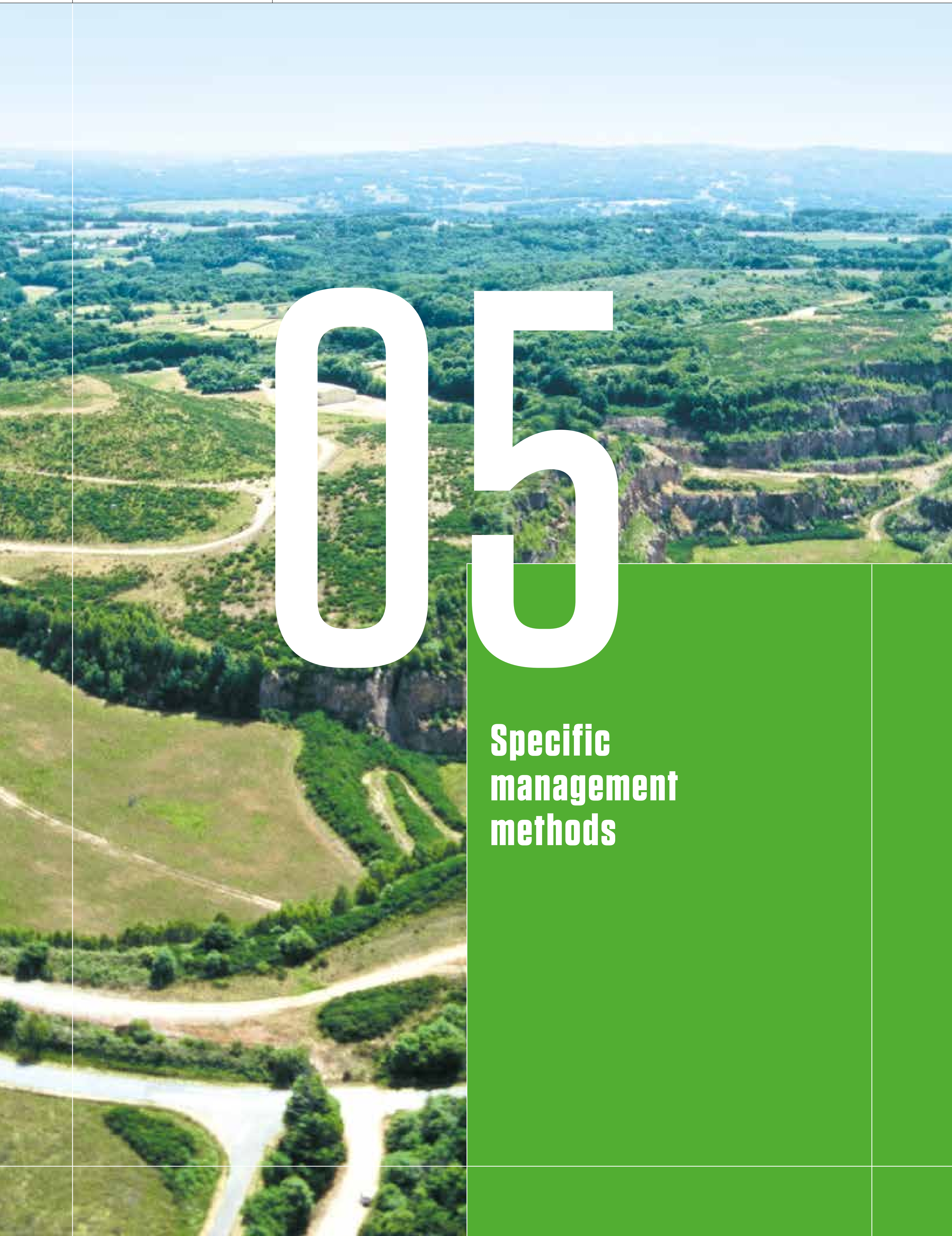
The Tricastin Fleur 1 and 2 Orano site is estimated to reach its full storage capacity (42,096 drums) by 2050. The requirement for an increase in capacity would be an additional 25%. Although part of the reprocessed uranium (RepU) is used in the form of ERU fuel, this removal from storage has not been taken into account in estimation of additional requirements (Fleur 3).



Depleted uranium storage

FRAMATOME PUISSANCE (ROMANS-SUR-ISÈRE)

After approving an increase in the total storage capacity in 2022, from about 1,800 tonnes of uranium to about 2,100 tonnes of uranium, Framatome is estimating an additional 40% requirement by 2030. This corresponds to approximately 900 kg of additional uranium, bringing the total storage capacity to approximately 3,000 tonnes of uranium.



05

Specific management methods

Some radioactive waste is subject to specific management methods.

These may involve:
- radioactive waste where the waste management choices were made at the time the waste was generated, and has not been changed since. These are legacy waste situations. This waste was able to be disposed of within or near nuclear facilities, in conventional waste disposal facilities, on or close to former or currently operational industrial sites, or dumped at sea;
- tailings from processing at uranium mines, which, due to their large volume, are subject to *in-situ* management;
- waste containing naturally occurring radioactive material which, depending on the radiological characteristics, can be stored *in-situ*, recovered, removed to conventional waste disposal facilities or to Andra disposal facilities.

All sites where radioactive waste is stored (excluding international disposal areas at sea) are subject to appropriate environmental monitoring, which makes it possible to check that the impact of the waste is negligible, or, if not, to take appropriate measures to protect the environment and the population.

The sites mentioned here are referenced in the *Geographical Inventory*. The quantities of waste presented in this chapter are not included in the inventory records provided in chapters 2, 3 and 4, because the corresponding waste is not intended to be dealt with by current or future Andra disposal facilities, due to its legacy waste status and the fact that it has already gone through waste management.

MANAGEMENT OF LEGACY WASTE SITUATIONS

Some radioactive waste in the past was managed using methods that have since evolved.

Radioactive waste has been stored in the past by waste producers or holders at sites classified as "legacy disposal" sites, which do not come under Andra's responsibility.

This mainly requires:
- conventional waste disposal facilities that have received VLLW waste from the conventional or nuclear industry;
- legacy waste disposal facilities within or close to nuclear installations;
- deposits of waste containing naturally-occurring radioactive material on or near former industrial sites or even operational industrial sites;
- defence disposal facilities in French Polynesia;
- waste disposal areas at sea.

LEGACY DISPOSAL OF RADIOACTIVE WASTE IN CONVENTIONAL WASTE DISPOSAL FACILITIES

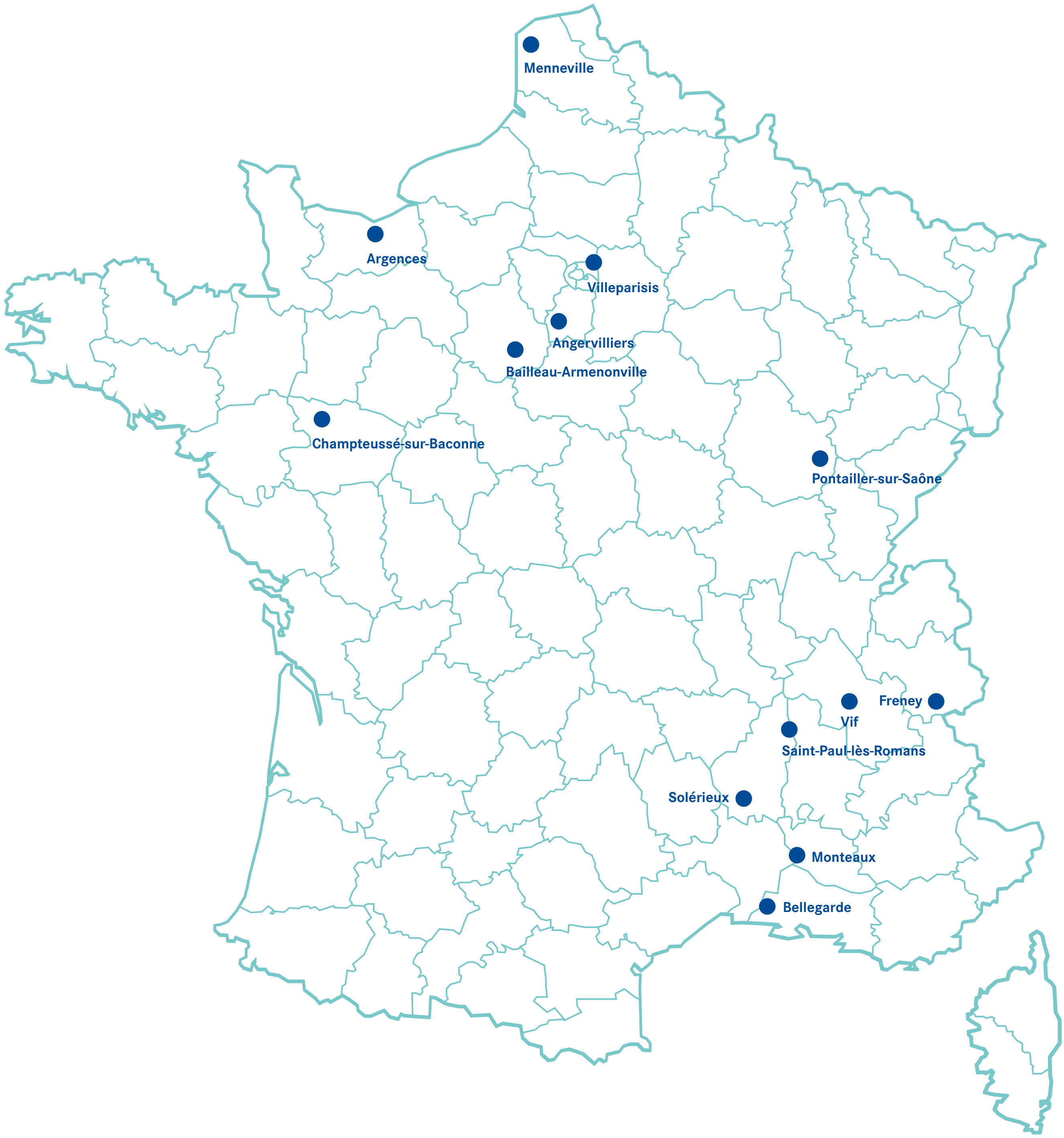
Conventional waste disposal centres have either occasionally or regularly received waste with very low levels of radioactivity, around a few becquerels per gramme. This is mainly sludge, soil, industrial residues, rubble and scrap from conventional industry or from the civilian or military nuclear industry.

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

There are a total of 13 conventional waste disposal facilities that have received radioactive waste on a regular or occasional basis, and these are referenced in the *Geographical Inventory*.

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

CONVENTIONAL WASTE DISPOSAL FACILITIES THAT HAVE RECEIVED RADIOACTIVE WASTE



LEGACY WASTE DISPOSAL FACILITIES LOCATED WITHIN OR CLOSE TO BASIC OR SECRET BASIC NUCLEAR INSTALLATIONS

Waste disposal facilities located within or near nuclear installations have been able to regularly or occasionally receive waste that contains, for the most part, added radioactivity of about a few becquerels per gramme. A total of a dozen legacy waste disposal facilities have been identified to date.

CHILLY-MAZARIN A126 MOTORWAY

Soil (1,700 m^3) and very low-level radioactive materials (2,200 m^3) were used on the construction site for this motorway in the 1970s. The soil came from the clean-up of the site of the old Société Nouvelle du Radium (SNR) plant in Gif-sur-Yvette and the very low-level radioactive materials were generated by the clean-up operations for the former Bouchet plant. The average radium and uranium content in this soil is comparable to that found in nature (up to 3 becquerels per gramme).

MONTBOUCHER MOUND (BUTTE DE MONTBOUCHER)

This mound largely contains waste that would now be categorised as VLLW (24,600 m^3), which was generated during the clean-up of the former Bouchet plant between May 1975 and March 1977.

BUILDING 133 OF THE CEA SACLAY CENTRE

Waste backfill that would now be categorised as VLLW (17 m^3 of sandstone debris from old piping and 57 m^3 of rubble and earth) was laid down in the north and south foundations of building 133 at the Saclay Centre.

THE CONCRETE BASIN OF THE FORMER PILOT DECLADDING CENTRE AT CEA MARCOULE

This is an old basin that was equipped for underwater fuel cladding removal, for a few months prior to commissioning of a dedicated workshop in 1959. This partially underground basin, containing some machinery and equipment, was then filled with concrete. This basin has a total volume of 1,116 m^3 and is fully insulated from the process, with all piping having been removed. It has been sealed at the top. It is subject to quarterly surface contamination checks carried out by the radiation protection department as part of routine inspections.

INTERNAL DISPOSAL AT MARCOULE

The current volume is estimated at approximately 126,000 m^3 of waste which largely consists of soil mixed with rubble. In order to characterise this volume, 32 uniformly distributed holes were drilled into the disposal site, going down to the natural land level at a depth between 5 and 12 m.

It should be noted that the investigations carried out have not shown up any radiological marking, nevertheless, the consistency in the management practices implemented has led this disposal site to be considered similar to those at Cadarache (ZEDI) and Valduc.

TRENCHES AT MARCOULE

Four trenches were operated in succession, from 1963 to 1993, to hold very low-level and low-level nuclear waste. These types of waste mainly consist of rubble, scrap metal, concrete, ash, sludge and earth from site earthworks, which could not be conditioned in drums at that time and could not be disposed of in landfills. At the end of operation of each of the trenches, embankments were raised 1 m to 1.5 m above the waste. The four trenches contain approximately 50,000 m^3 of waste.

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

This waste disposal site was created when the facility first opened. 192,000 m^3 of inert waste has been disposed of there between 1961 and 2007, including 1,650 m^3 of contaminated waste (4,600 MBq) between 1963 and 1991. The chemical and radiological monitoring plan provides for monitoring of the aquifer using piezometers with semi-annual or annual sampling, depending on the parameters measured.

EXPERIMENTAL WELLS AT PEM – MORONVILLIERS EXPERIMENTATION CENTRE

There are about a hundred wells containing residues from the experiments carried out at the Moronvilliers Experimentation Centre. These wells have been filled in and plugged. As part of the survey of polluted sites and soils, the CEA declared the PEM site in the Basol database in May 1997. The whole site, including the hundred wells, is subject to enhanced environmental monitoring, with results sent regularly to the Prefect by the Delegate for Nuclear Safety and Radiation Protection for defence-related activities and installations (DSND). Finally, radiometric mapping of the site by helicopter confirmed the control of the radiological reference system for this site.

THE FIRST SIX CONVENTIONAL WASTE DISPOSAL SITES AT THE CEA VALDUC CENTRE

Until the early 1990s, due to the isolation of this site, ordinary household and industrial waste along with rubble was dumped in six places at the facility, in line with the standards of the time and the practices of all French municipalities then. These disposal sites mainly dealt with ordinary, non-hazardous materials deposited in hollow places, such as valley areas. The waste and rubble were therefore used to flatten the areas concerned. Radiological marking cannot be completely ruled out because of the old decontamination practices. The volumes concerned are estimated between 100,000 and 150,000 m^3 and the level of radioactive contamination is estimated by the CEA to be zero or very low. These disposal sites are monitored with use of piezometers located downstream of the areas concerned.

THE AREA 045 DISPOSAL FACILITY AT THE CEA VALDUC CENTRE

This area mainly held contaminated soil resulting from the clean-up operation of the valley nearby, carried out in 1995. It consists of a silo, with the bottom and walls lined with a membrane consisting of welded HDPE, sandwiched between two layers of geotextile fabric, all covered over with sand. This ensures containment. This soil has low-level activity (an average of 1 Bq/g and never more than 10 Bq/g). The volume involved is 8,990 m^3. This disposal area is monitored. Piezometers located downstream are used to monitor the site.

PIERRELATTE CENTRE MOUND

This mound, with a surface area of about 37,000 m^2, was formed in the early 1960s. Between 1964 and 1977, trenches were constructed for disposal of about 14,000 m^3 of waste including fluorines from uranium processing and chromated sludge. A water table quality monitoring plan has been in place since 1998 and the integrity of the structure has also been monitored.

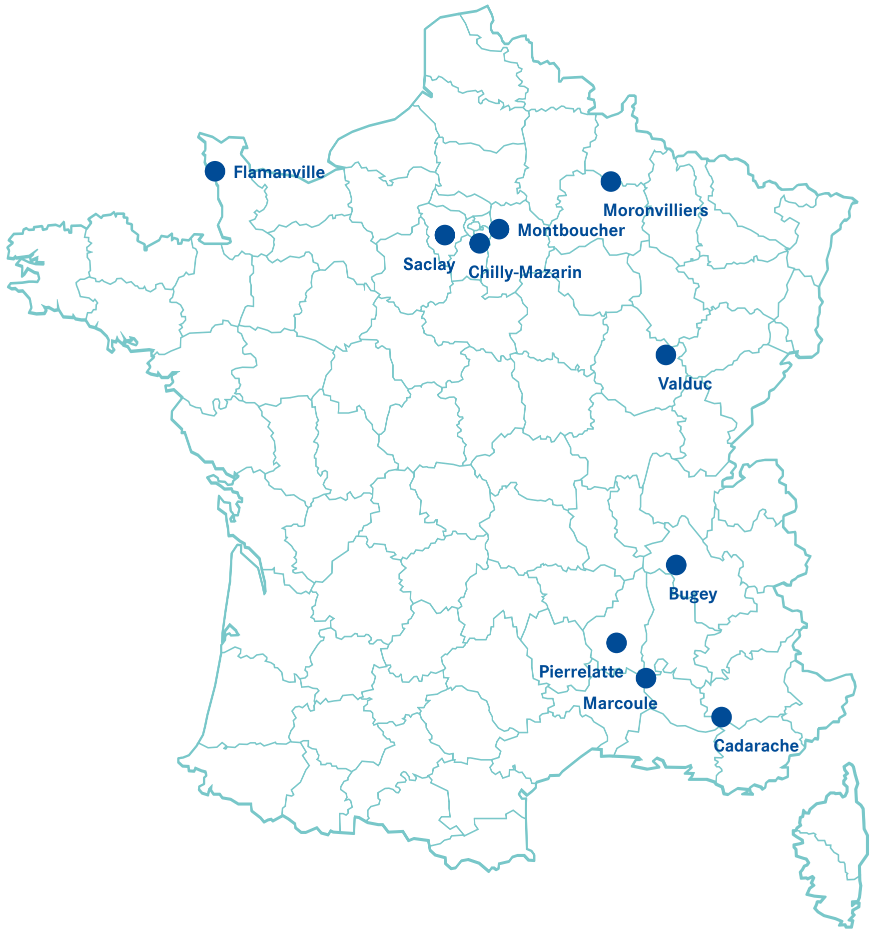
BUGEY HILL

The presence of about 130 m^3 of ion-exchange resins (not radioactive by the criteria of the time), buried here between 1979 and 1984 in an artificial mound of about 1 million cubic metres of backfill, was highlighted in 2005 during the first siting studies for the Iceda facility south of the Bugey site. This mound is formed of various natural excavation materials with non-radioactive waste from the construction of the various production units. Groundwater quality in this area is monitored using 11 piezometers distributed around the mound.

LEGACY WASTE DISPOSAL SITE AT FLAMANVILLE

Located by the current EPR car park, this former worksite waste disposal site dates from the construction of the first 2 units in the 1980s. It consisted of various natural excavation materials and some non-radioactive waste, which was found to include around 3 m^3 of waste (cotton work clothes, overshoes, vinyl) with traces of Cobalt 60 (mass activity < 0.1 Bq/g). The excavation work removed 9,000 tonnes of material, including this radioactive waste. Radiochemical analyses of soil and rubble samples and those carried out in piezometric wells have confirmed the absence of any marking of soils or water. The radioactive waste has been removed and directed to the appropriate waste management solution.

LEGACY WASTE DISPOSAL FACILITIES LOCATED WITHIN OR CLOSE TO BASIC OR SECRET BASIC NUCLEAR INSTALLATIONS



LEGACY WASTE DISPOSAL SITES WITH NATURALLY OCCURRING RADIOACTIVITY

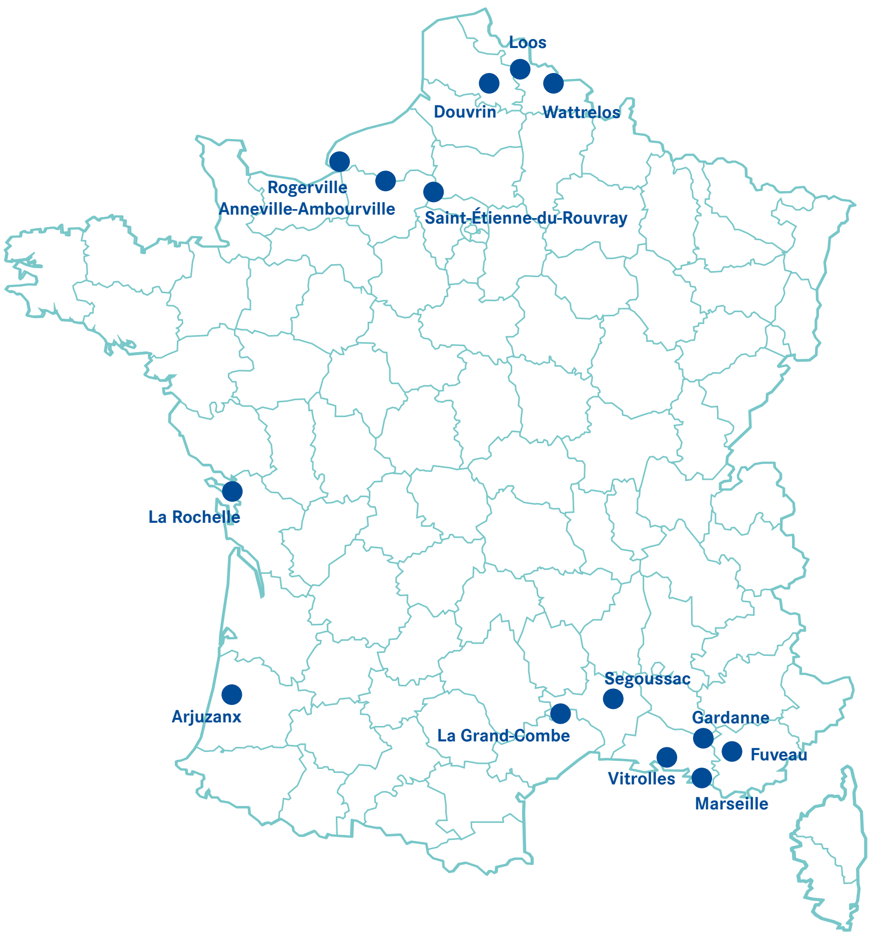
There are several dozen waste disposal sites containing naturally occurring radioactive materials referenced in the *Geographical Inventory*. They include phosphogypsum waste deposits generated by fertiliser production, residues from alumina production and coal ash from thermal power plants, some of which could still be recovered. The French Environmental Code applies to these deposits, including organisation of monitoring to check that there is no significant environmental pollution.
Most of these legacy NORM waste disposal sites could be compared to very low-level waste (VLLW) with extremely low radioactivity or none at all.

The main disposal sites for waste that contain naturally occurring radioactive material are:

- disposal sites for residues from alumina production: **Gardanne, Vitrolles, Marseille** (Aygalades, La Barasse-Saint-Cyr, La Barasse-Montgrand), **Segoussac**;
- coal ash disposal from thermal power plants, which is not recoverable: **La Grand-Combe, Fuveau, Arjuzanx**;
- disposal of phosphogypsum from the phosphoric acid production process used in manufacturing fertiliser. These sites are no longer in operation and are monitored: **Anneville-Ambourville, Douvrin, Rogerville, Saint-Étienne-du-Rouvray, Wattrelos**;
- Vernay lagoon in **Loos**. This is an ore processing site that has generated filtration sludge which was stored (3,600 m^3) at the site;
- the port areas of **La Rochelle** where the facilities have been backfilled with residues from legacy rare earth production operations using monazite ore: the site of the Chef-de-Baie plant in La Rochelle has 35,000 m^3 of solid residues from the monazite treatment used as backfill. There is also the port of La Palice in La Rochelle: the Solvay plant produced residues generated by processing of very slightly radioactive natural materials, 50,000 m^3 of which were used as backfill here.

It should be noted that some recovery operations on the coal ash heaps have produced building materials (concrete).

LEGACY WASTE DISPOSAL SITES WITH NATURALLY OCCURRING RADIOACTIVE MATERIALS



DEFENCE DISPOSAL FACILITIES IN FRENCH POLYNESIA

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

These nuclear tests were initially carried out in the open air (1966-1974), then they moved underground, taking place in shafts drilled vertically into the rocks of the coral reefs (1975-1987) or under the lagoons (1981-1996).

The waste produced by these experiments and by the dismantling of the related facilities was disposed of in-situ in shafts or dumped in French territorial waters *(see section on Disposal at Sea, opposite)*.

The waste disposed of *in-situ* as part of these operations is presented in the *Geographical Inventory* (overseas).

When French nuclear tests in the Pacific were finally halted in 1996, France asked the IAEA to conduct radiological surveying of the Mururoa and Fangataufa test sites and nearby areas. Their assessment constitutes the reference baseline for levels of radioactivity in the environment around these two atolls.

Although IAEA experts concluded that there was no need to continue radiological monitoring of Mururoa and Hao, it was decided to maintain a monitoring programme in order to be able to detect any potential releases of radionuclides from lagoon cavities and sediments.

This monitoring concerns the environment of the two atolls and has two parts:
- continuous monitoring of atmospheric aerosols and integrated dose;
- annual sampling. To date, no releases have been detected.

Mururoa Atoll

Dumping of radioactive waste at sea in the 1960s

WASTE DISPOSAL AT SEA

Dumping at sea has always been a means of managing all types of waste. Radioactive waste was no exception to this rule. The solution of simply dumping waste at sea was actually considered safe by the scientific community, due to the dilution and the presumed period of isolation involved, which were thought to be sufficient. This practice was implemented by many countries for more than four decades, starting in 1946.

Dumping waste at sea was initially organised by the countries that generated the waste, before it became coordinated by international bodies, in the 1960s onwards. This was the context in which France dumped radioactive waste in the Atlantic, participating in campaigns organised by the NEA in 1967 and 1969. During these two operations, France dumped 14,200 tonnes of conditioned radioactive waste, with a total activity of approximately 350 TBq, all from the Marcoule site.

Since the commissioning of the Manche disposal facility in 1969, France has abandoned disposal at sea in the management of most of its radioactive waste.

However, this management solution continued to be used by France until 1982, for waste generated by activities related to nuclear testing in French Polynesia: 3,200 tonnes of radioactive waste, with a total activity of less than 0.1 TBq, were dumped in French territorial waters in Polynesia.

It should be noted that France never disposed of radioactive waste in the Channel: only the United Kingdom and Belgium have used the Casquets trench northwest of Cap de La Hague.

MANAGEMENT OF URANIUM MINE TAILINGS

The operation of uranium mines in France between 1948 and 2001 (open-cast or underground) produced 76,000 tonnes of natural uranium. The exploration, extraction and processing activities involved about 250 sites varying in size (from simple survey work to large-scale operational mining activities) spread over 27 departments in France. Ore processing was largely carried out by 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) developed by IRSN.

There are two categories of waste generated by uranium mining operations:

- mining waste, which is made up of the soil and rocks excavated to access the relevant deposits.
  The volume of mine waste rock extracted can be estimated at around 170 million tonnes. Most of the waste rock has remained on its production site. It has been used to fill open-cast mines or underground mining structures such as shafts, for redevelopment work, covering disposal sites or placed in heaps of waste. About 2 million tonnes of mine waste, or 1-2% of the amount extracted, could be used as backfill, earthwork materials or road foundations in locations near the mine sites;
- uranium mine processing tailings (RTMU) are the waste remaining after extraction of the uranium contained in the ore by static or dynamic processing. These tailings are actually the process waste, forming an estimated volume of 50 million tonnes. These residues correspond to process waste as defined in the French Environmental Code, which is why disposal facilities for these tailings are subject to the ICPE nomenclature and classified under heading 1735.

The processing tailings are stored at 16 sites, all close to uranium ore processing facilities and correspond to VLLW or LLW-LL waste characterised by particle size and mass activity:

- tailings from the processing of low-grade ores (on the order of 300 to 600 ppm of uranium) with a total average mass activity of 44 Bq/g (including about 4 Bq/g of radium 226). These residues, resulting from static leaching (approximately 20 million tonnes), are stored either in heaps, or in open-cast mines, or used as an initial covering layer for dynamic leaching treatment residue disposal sites;
- tailings from the processing of high-grade ores (in the range of 1,000 to 10,000 ppm or 0.1 to 1% uranium) with a total average mass activity of 312 Bq/g (including approximately 29 Bq/g of radium 226). These residues, from dynamic leaching (about 30 million tonnes), are stored either in old open-cast mines sometimes with a complementary dyke, or in basins enclosed by a belt dyke or behind a dyke damming a thalweg.

The 16 disposal sites concerned are:

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

At some of these sites, there is very low-level waste related to use or dismantling of facilities (ore treatment or upstream of the cycle) also stored on site. These sites are the following: Bauzot, Saint-Pierre-du-Cantal, Bessines-sur-Gartempe, Gueugnon, Lodève, Jouac, L'Escarpière, Les-Bois-Noirs-Limouzat and Le Cellier.

In addition, 3 sites in the Crouzille Mining Division (Orano, formerly Cogema then Areva) were used in the 1970s and 1980s as landfills for very low-level waste from various upstream facilities in the cycle:

- **Fanay**;
- **Margnac**;
- **Peny**.

As part of the PNGMDR, Orano submitted studies relating to the assessment of the long-term impact on health and the environment of tailings disposal sites (physical-chemical characterisation of tailings, geomechanical resistance of dykes and long-term radiological impact of disposal sites), as well as former mining extraction sites (management of diffuse discharges and water treatment, long-term impact of mine waste). The studies submitted as part of the PNGMDR 2013-2015 and 2016-2018 made it possible to:

- provide information about the modelling of the impact of disposal of mine tailings;
- improve knowledge of the phenomena of uranium transport from tailings dumps to the environment;
- improve knowledge of the mechanisms governing mobility of uranium and radium within uranium mine tailings.

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

Finally, in accordance with the circular of 22 July 2009[2], environmental assessments are taking place for all Orano mine sites, including tailings disposal sites. A diagnosis of orphan sites (for which the responsible entity is unknown or insolvent) is also in progress.

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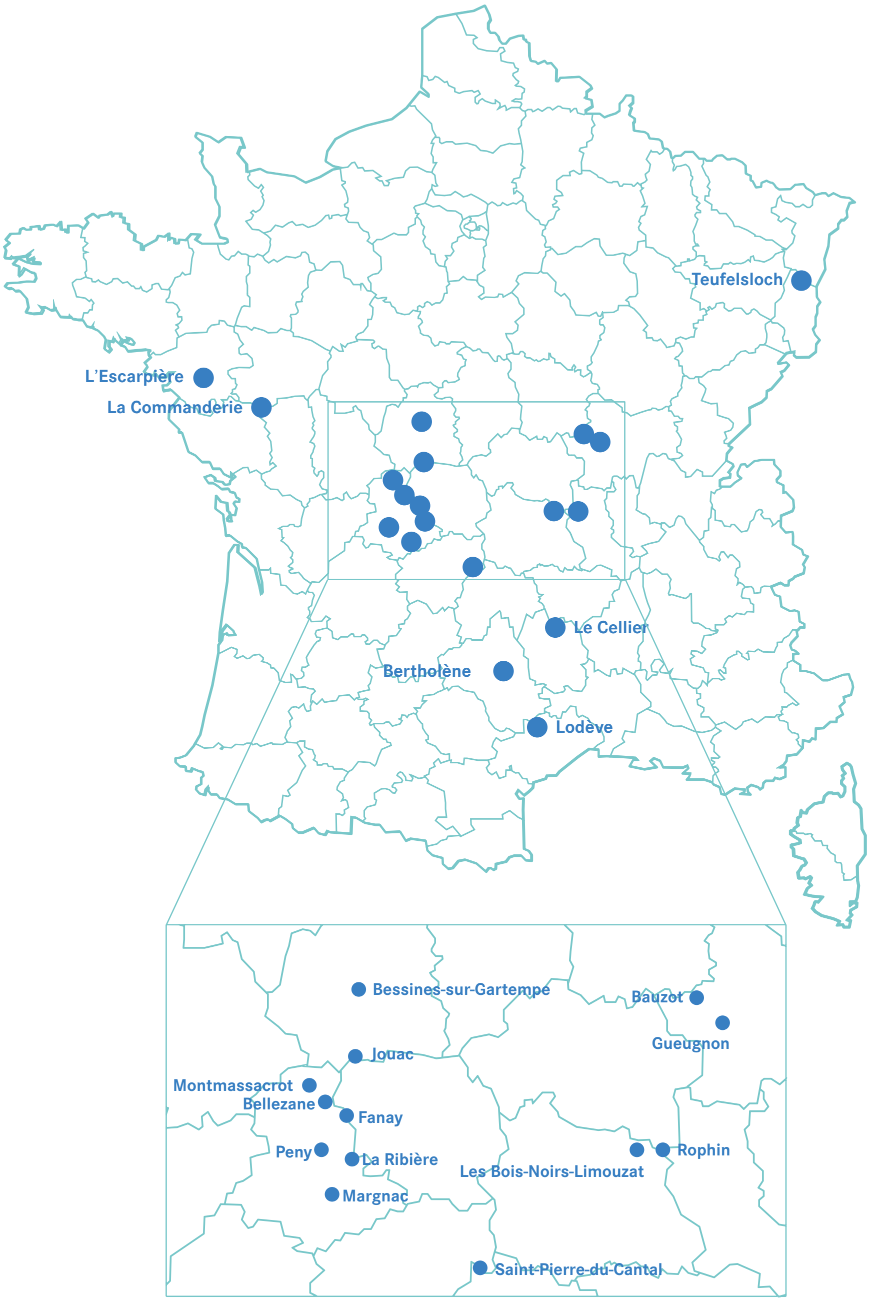
1 Recommendations for the management of former uranium mining sites in France. From the Limousin sites to other sites, from the short to the medium and long terms, the final report of the Limousin uranium mine interdisciplinary expert group (GEP), September 2010.

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

Former Bellezane uranium mine in operation...

... and after remediation

MINING SITES



CURRENT MANAGEMENT OF WASTE CONTAINING NATURALLY OCCURRING RADIOACTIVE MATERIAL

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

Waste containing naturally-occurring radioactive material has been subject to specific management procedures since the decree of 25 May 2005[3]. Depending on its radiological characteristics, waste containing naturally-occurring radioactive material may be:

- managed *in-situ*;
- upgraded due to its physical-chemical properties, in particular for use in manufacturing construction materials;
- disposed of in conventional waste disposal facilities (ISD). The regulations provide for the possibility of storing waste containing naturally occurring radioactive material in hazardous waste disposal facilities (ISDD), non-hazardous waste disposal facilities (ISDnD) and inert waste disposal facilities (ISDI). Four facilities have been authorised to handle waste with high naturally occurring radioactivity.These are the hazardous waste disposal facilities at Villeparisis, Bellegarde, Champteussé-sur-Baconne and Argences. These hazardous waste disposal facilities (ISDD) have taken steps to be able to accept this type of waste in accordance with the terms of the circular of 25 July 2006[4]. Among other things, the circular specifies procedures for reception and inspection of waste in waste disposal facilities, the conditions for monitoring the radiological impact of the admission of this waste on the environment and the procedures for informing the inspection of classified facilities through the annual operating report. The quantities of waste containing naturally occurring radioactive material received at these facilities are well below the authorised capacity (less than 10% of the authorised capacity);
- disposed of at Andra disposal facilities. Waste containing naturally occurring radioactive material with very low activity 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 identified (excluding waste generated by coal-fired power plants, paper mills and biomass combustion). In addition, there are stockpiles of waste with naturally-occurring radioactivity, falling under the LLW-LL category, amounting to approximately 21,000 m^3.

The management of waste containing naturally occurring radioactive material has been thoroughly overhauled by Decree No. 2018-434 of 4 June 2018[5] which came into effect on 1 July 2018 and which transposes the provisions of Council Directive 2013/59/Euratom of 5 December 2013 setting out basic safety standards for protection against the dangers arising from exposure to ionising radiation.

at THE end of 2023, only the hazardous waste disposal facilities of Villeparisis, Bellegarde and Argences continue to store waste that contains naturally occurring radioactive material.

FOCUS — THE ORFLAM-PLAST SITE IN PARGNY-SUR-SAULX

In the 1930s, a monazite processing plant, later to become the Orflam-Plast plant, was established at Pargny-sur-Saulx to manufacture lighter flints from monazite. The plant operated until 1967, before being permanently decommissioned in 1997.

The extraction of monazite, an ore rich in thorium, generated low-level radioactive residue, concentrating the radioactivity initially present in monazite. This residue polluted the site, which was cleaned up at a later date.

Much of the waste and earth collected during the cleanup operation was disposed of at Cires. Another fraction, mainly consisting of rubble with very low radioactivity, was contained on site (3,000 m^3).

Former Orflam site before...

... and after remediation

3 Order of 25 May 2005 concerning professional activities involving raw materials containing naturally-occurring radionuclides not used for their radioactive properties.

4 Circular of 25 July 2006 on the conditions of acceptance of waste with enhanced or concentrated natural radioactivity in waste disposal facilities.

5 Decree No. 2018-434 of 4 June 2018 establishing various provisions concerning nuclear matters.

06

Special reports

Report 1

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

INTRODUCTION

Like many countries, France has chosen to implement long-term management for all radioactive waste. This management is based on disposal (surface, near-surface, or deep geological disposal), the only viable solution to confine waste for the time necessary for decay of the radioactive elements it contains, until they no longer pose a risk to humans and the environment.

Confinement consists in isolating contaminants, so as to sustainably prevent them from spreading, and to ensure the monitoring and maintenance of the measures implemented during the design of each disposal facility. This design is adapted to the types of waste received, according to three components.

Today, there are three surface disposal facilities in France (two in the operational phase and one in the closure phase), which make it possible to store the majority of the volumes of radioactive waste produced each year in France (VLLW and LILW-SL waste). For other types of waste (LLW-LL, ILW-LL and HLW), suitable disposal facilities are planned or under study. In the meantime, the corresponding waste is stored in specific facilities, mainly at its production site.

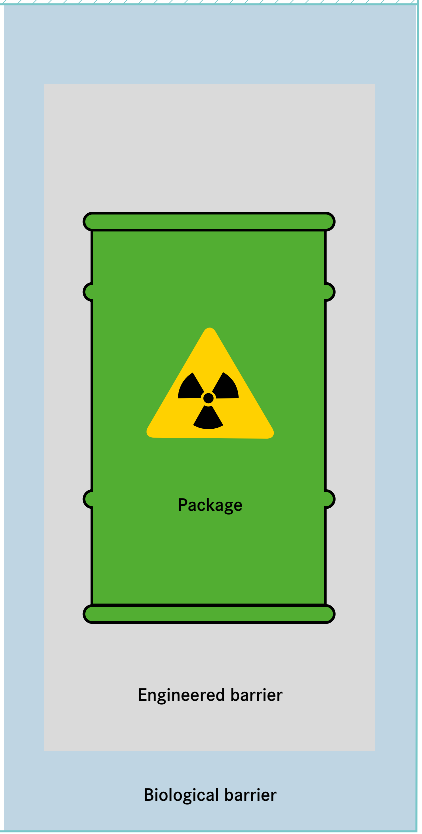
FOCUS — DISPOSAL STRUCTURES

Historically, the safety of any nuclear installation is based on the concept of redundancy of protection means. This concept translates into the establishment of successive barriers between radioelements and the biosphere. Their role is to slow down and, if possible, prevent the dispersal of radionuclides in the ecosystem by:

- limiting water influx;
- delaying the release of radioelements in the aqueous phase;
- Retaining any radioelements released.

In the case of a nuclear waste disposal facility, the confinement system consists of three components:

- the packages containing the waste;
- the disposal structures containing the packages;
- The site geology, which forms a natural barrier.



DEEP GEOLOGICAL DISPOSAL OF HLW AND ILW-LL WASTE

After 15 years of research on the management of HLW and ILW-LL and a public debate, the Programme Act no. 2006-739 of 28 June 2006, now codified in the French Environmental Code, adopted the principle of deep disposal as the only safe long-term solution to manage waste that cannot be disposed of on the surface or near-surface for safety or radiation protection reasons, without transferring the burden to future generations. In view of implementing this solution, this law instructed Andra to conduct studies and research to select a site and design a reversible deep geological disposal facility for HLW and ILW-LL waste.

Andra is thus developing a project for the industrial geological disposal facility, Cigéo, designed to store all HLW and ILW-LL waste produced by all current nuclear installations, or those that had obtained a construction licence by the end of 2016, including waste resulting from their dismantling, and the reprocessing of spent fuel used in nuclear power plants.

If its construction is authorised, the Cigéo centre will be located in eastern France, at the boundary between the Meuse and Haute-Marne.

Cigéo will be composed of surface facilities, in particular to accommodate waste packages and to carry out excavation and construction of the underground structures. The waste will be stored in underground installations located at a depth of approximately 500 metres, in a layer of impermeable clay rock chosen for its confinement properties over very long time scales.

Cigéo is to be operated for at least 100 years, and to be reversible, in order to leave a maximum of options open for future generations.

In April 2016, Andra submitted a series of documents to ASN for instruction, including a proposal for a master plan for operation of Cigéo, a Safety Options File and a Retrievability Technical Options Report. ASN issued its opinion on these files in January 2018[1].

In July 2022, a government decree recognised the public utility of the Cigéo[2] project. Then, in January 2023, Andra submitted the Construction Licence Application (DAC) for the disposal facility to the Ministry for the Ecological Transition and Territorial Cohesion, which then referred the matter to ASN.

The initial construction of Cigéo may begin after examination of this application by ASN, a public inquiry, and on condition that a construction licence decree is obtained.

If Cigéo is authorised, it will start with an industrial pilot phase, during which the first phase of the disposal facility will be built and will start operation. Cigéo will then gradually expand over more than a century.

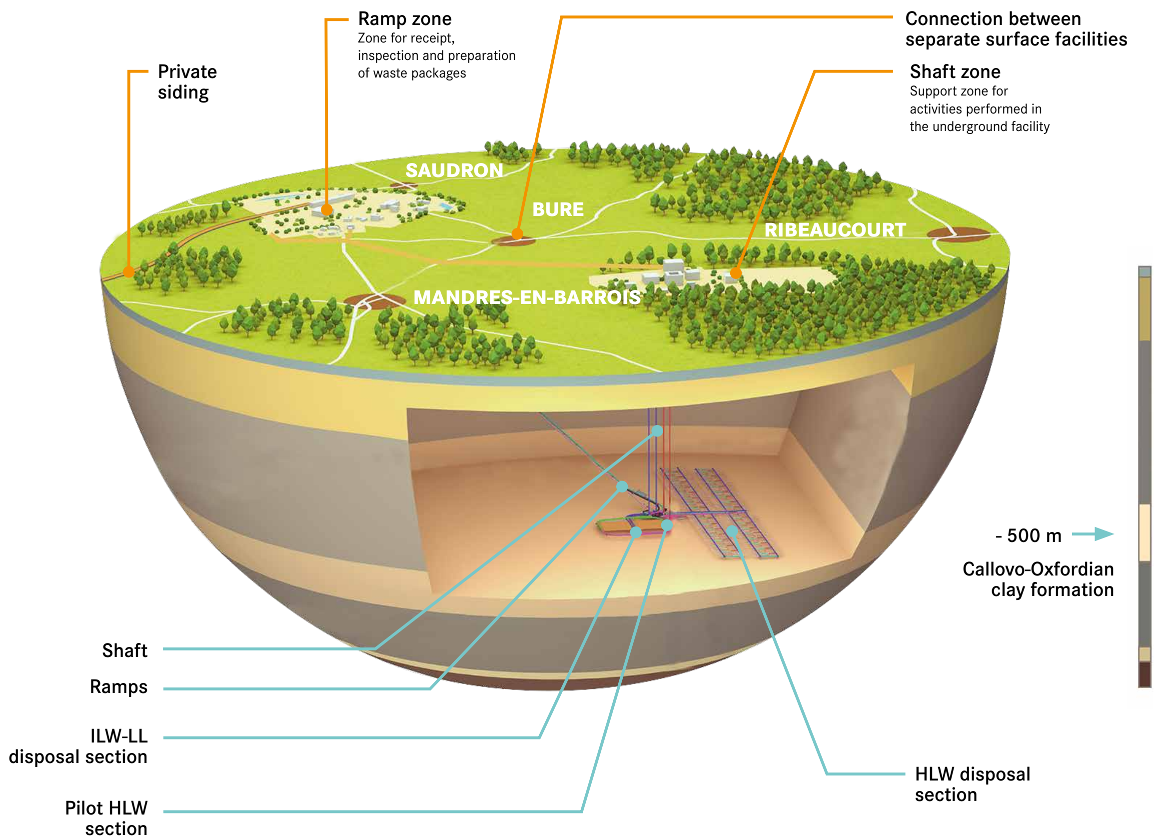
Pending the disposal of this waste at Cigéo, storage of this waste on waste producer sites is an essential tool for the management of HLW and ILW-LL waste.

FOCUS — STORAGE BEFORE DISPOSAL

Unlike disposal, storage is, by definition, temporary. Before being disposed of, waste is stored on sites in dedicated facilities. These facilities include:

- For waste destined for existing disposal facilities:
  - buffer storage of conditioned waste, for logistical reasons, to manage flows to Andra facilities;
  - storage of waste, in particular old waste, awaiting treatment or conditioning, before evacuation;
- For waste destined for future disposal facilities:
  - storage of waste, in particular old waste, awaiting recovery, before evacuation to other storage facilities or to future Andra facilities;
  - storage pending the availability of disposal solutions;
  - decay storage for high-level waste (HLW), which must be stored for several decades as it decays, before it can be moved to deep disposal.

DIAGRAM OF CIGÉO'S SURFACE AND UNDERGROUND FACILITIES



1 Opinion No. 2018-AV-0300 from the Nuclear Safety Authority on 11 January 2018 concerning the Safety Options File presented by Andra for Cigéo, the deep geological disposal project for radioactive waste.

2 Decree No. 2022-993 dated 7 July 2022 declaring the Cigéo deep geological disposal facility of public interest, available at https://www.legifrance.gouv.fr

ONGOING STUDY FOR MANAGEMENT OF LLW-LL WASTE

Law No. 2006-739 of 28 June 2006 governing the sustainable management of radioactive materials and waste, now codified in the Environmental Code, instructed Andra to develop disposal solutions for graphite waste, mainly from the operation and dismantling of first-generation GCR nuclear power reactors (Gas-cooled graphite-moderated), and for radium-bearing waste. The State also requested that Andra examine the possibility of taking into account other types of long-lived low-level waste (LLW-LL) in these studies.

The disposal solution studied for LLW-LL waste is a near-surface disposal in a layer ofclay. The community of municipalities of Vendeuvre-Soulaines in the Aube département, which already hosts the surface disposal facilities operated by Andra, gave its agreement in 2013 to carry out geological investigations on its land and is expected to host this type of disposal facility. In accordance with the request of local elected officials, a consultation process was implemented before any presence in the field. The geological investigations that were carried out in the Aube between mid-2013 and mid-2015 aimed to acquire a better knowledge of the local geology, in order to determine whether the nature of the subsoil was suitable for the possible establishment of a disposal facility for long-lived low-level waste.

In accordance with the request of the PNGMDR 2013-2015, Andra submitted a progress report on the management of LLW-LL waste in 2015. This report made it possible to draw lessons from the first geological investigations carried out, as well as from advances in studies and research carried out on waste by Andra and waste producers (EDF, CEA, Orano, Solvay). Preliminary concept design of the disposal facility has been carried out and has been the subject of an initial safety assessment. The 2015 progress report identifies a geographical area in which the project will be continued. It also identifies the subjects to be explored further in the programme of studies. The report was referred to ASN, which published its recommendations in Opinion No. 2016-AV-264[3].

Work is continuing within the framework of the PNGMDR 2022-2026, where Andra is asked to finalise the characterisation of the safety issues related to the Vendeuvre-Soulaines community of municipalities site, highlighting the associated ethical choices. In particular,Andra must submit a file presenting the technical and safety options selected for a disposal facility on this site.

In addition, due to the heterogeneity of LLW-LL waste, the PNGMDR 2022-2026 asks Andra to propose management scenarios, then, in conjunction with waste producers, to develop a global LLW-LL waste management plan.

Pending the creation by Andra of a suitable disposal facility, LLW-LL waste is stored, most often on the sites where it is produced or at Andra's Industrial facility for grouping, storage and disposal (Cires), especially waste from industries other than nuclear power generation.

Campaign for additional LLW-LL geological investigations in 2017


Campaign for additional LLW-LL geological investigations in 2017

3 Opinion No. 2016-AV-264 of the French Nuclear Safety Authority dated 29 March 2016 on studies relating to the management of long-lived low-level waste (LLW-LL) submitted pursuant to the French National Radioactive Materials and Waste Management Plan 2013-2015, for development of the French National Radioactive Materials and Waste Management Plan 2016-2018.

SURFACE DISPOSAL FOR LILW-SL AND VLLW WASTE

LILW-SL WASTE

Surface disposal of short-lived low- and intermediate-level waste (LILW-SL) has been practised in France since 1969. There are two waste disposal facilities in France dedicated to this category of waste: the Manche Disposal Facility (CSM) and the Aube Disposal Facility (CSA).

Approximately 527,000 m^3 of waste was disposed of at the Manche Disposal Facility, located in the municipality of La Hague, between 1969 and 1994. This facility has been in the closure phase since 1994 and therefore no longer accepts waste.

The Aube Disposal Facility, in operation since 1992, is located in the municipalities of Soulaines-Dhuys, Épothémont and La Ville-aux-Bois. It covers an area of 95 ha, 30 of which are reserved for disposal, and has an authorised capacity of one million cubic metres of radioactive waste packages.

Waste stored at the CSA is conditioned in concrete or metal packages. These packages are stored in reinforced concrete structures with 25 m sides and a height of 8 m, built on a geological zone consisting of a clay layer with a sandy layer on top. The clay layer forms a natural barrier, which retains the radioactive elements in the subsoil. Above the clay, the sandy layer drains rainwater to a single outlet, which facilitates environmental monitoring.

The spaces between the packages in a structure are filled with concrete or gravel, depending on whether it contains metal or concrete packages. The structure is then closed with a concrete slab and covered with a layer of waterproof polyurethane. At end of operation of the centre, a cap composed mainly of clay will be placed on the structures to ensure containment of the waste in the long term, then the site will be monitored for at least 300 years.

The leaktightness of the structures is checked via a network of underground galleries which are regularly inspected.

Disposal of LILW-SL waste packages at the CSA

VLLW WASTE

At the request of the public authorities, Andra has developed a specific solution for very low-level waste.

In many countries, below a certain level of radioactivity called "clearance level", waste is managed as conventional waste. In France, all waste produced by basic nuclear installations, ICPEs, or installations authorised under the public health code, containing or likely to contain radioactive elements is managed using dedicated solutions.

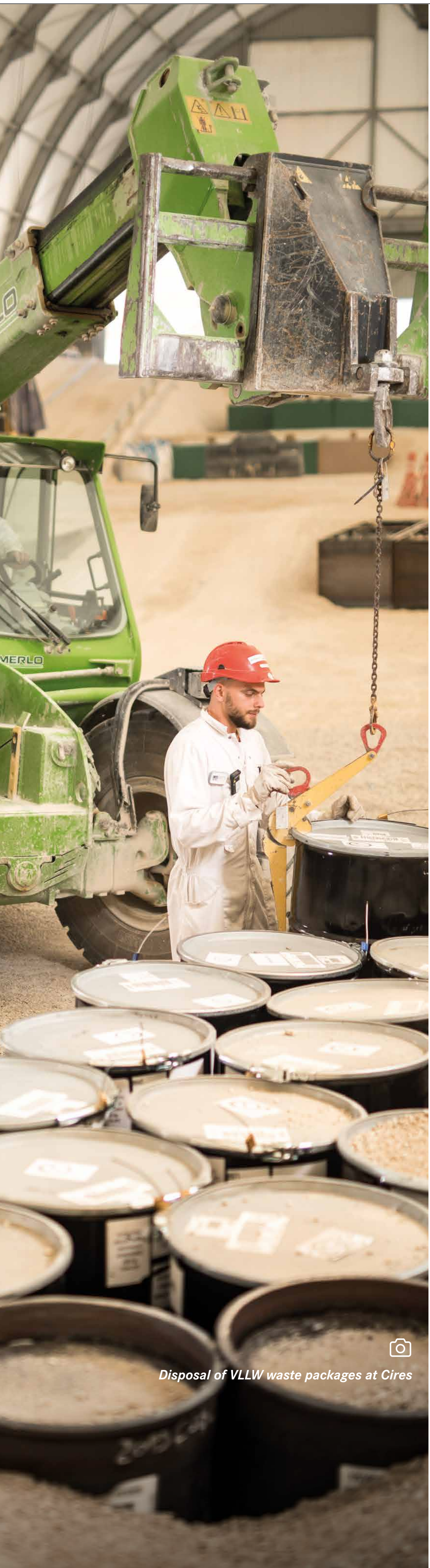
Since 2003, this waste has been disposed of at the Industrial facility for grouping, storage and disposal (Cires), located in the municipalities of Morvilliers and La Chaise. This facility, which is a Classified Environmental Protection Facility (ICPE), covers an area of 46 ha, 18 of which are dedicated to disposal.

Today, it is intended to receive 650,000 m^3 of waste, mainly from the dismantling of French nuclear facilities. The principle of this facility is based on disposal facilities for hazardous waste from the chemical industry.

The waste packages, which are inspected on arrival at the site, are disposed of in cells dug into the clay, the bottom of which are designed to collect any infiltrated water. They are isolated from the environment by a system comprising:

- a synthetic membrane surrounding the waste cells, associated with a leak test system;
- the clay layer under and on the sides of the disposal cells.

During operation, the cells are protected by removable roofs forming a tunnel and equipped with monitoring devices. Once filled, the cells are covered with a layer of clay associated with a leachate collection and inspection system.



Disposal of VLLW waste packages at Cires

FOCUS PROJECT TO INCREASE THE AUTHORISED CAPACITY OF CIRES (ACACI)

As of the end of 2021, Cires had reached approximately 66% of its total licensed disposal capacity of 650,000 m³. In its current configuration, Cires will not be sufficient to dispose of the VLLW waste volumes to be produced by dismantling in the coming years. Additional management solutions are therefore currently being studied.

The medium-term solution consists in increasing the licensed disposal capacity of Cires to 950,000 m³, without changing the current footprint of the disposal zone and while maintaining its safety level (Acaci project). If licensed, this increase in capacity will allow Cires operation to be extended by ten or so years, i.e. up to around 2040.

FOCUS A TECHNOCENTRE FOR MELTING VERY LOW-LEVEL RADIOACTIVE STEELS

A significant proportion of the steels present in VLLW waste could be recycled as part of the "Technocentre" project. Led by EDF and Orano, it aims to create a melting treatment centre for metallic VLLW waste near the nuclear power plant Fessenheim, which is in the dismantling phase.

The steels will be decontaminated by melting and separating the "slag" which forms on the surface of the molten steel and makes it possible to concentrate the radioactive substances. This process would make it possible to recycle, subject to compliance with regulations (decree of 14 February 2022), most of the tonnage of metallic VLLW waste. The remainder would be conditioned and sent to Andra's industrial centres in the Aube.

FOCUS CIRES STORAGE INSTALLATION

In 2012, ANDRA commissioned a long-lived radioactive waste storage building at Cires, intended in particular for waste from industries other than the nuclear power industry, with a surface area of 2,000 m².

This waste, which falls into the LLW-LL (for the most part) and ILW-LL categories, is grouped in various halls according to its radiological characteristics. It will be recovered gradually to be disposed of when the disposal facilities are commissioned.

The main types of waste stored at Cires at the end of 2021 are:

- radioactive lightning conductors;
- radioactive objects from individuals (radium fountains, radioluminescent objects, etc.);
- radioactive objects for medical use between the two world wars kept as collector's items (radium needles, tubes, and compresses);
- waste (e.g. soil, rubble) resulting from the clean-up of sites polluted by radioactivity containing long-lived radioactive elements (radium, thorium).

SPECIAL CASES

In addition to waste subject to specific management methods (*see Chapter 5*), certain cases are subject to special management methods due to their physical-chemical characteristics.

TRITIUM-BEARING WASTE

Tritium is a short-lived radionuclide (radioactive half-life of about 13 years), which is difficult to contain and can easily migrate into the environment. Waste containing tritium ("tritium-bearing waste") is therefore subject to specific management methods: it is stored for a sufficiently long period, around fifty years or so, to allow for radioactive decay of the tritium in the packages before being directed to one of the Andra disposal facilities, depending on the level of radioactivity and the residual gas release rate of the package. Tritium-bearing waste where the tritium radioactivity or gas release rate is too high may be subjected to heat treatment in order to reduce its activity or gas release rate before storage.

At the end of 2021, the volume of tritium-bearing waste in storage was approximately 5,870 m^3. This waste is most often in solid form. However, there are small quantities of tritium-bearing waste in liquid and gaseous form.

The vast majority of tritium-bearing waste (around 99%, or approximately 5,810 m^3 at the end of 2021) comes from the French Defence sector, almost entirely from activities related to the deterrence force. Industrial actors and medical and pharmaceutical research laboratories have also used tritium in the past and still use it today, therefore generating tritium-bearing waste: at the end of 2021, the corresponding volume was 60 m^3. Finally, the ITER facility will also generate tritium-bearing waste and will become the highest producer of tritium-bearing waste, first in its operating phase and then in its dismantling phase. Currently, tritium-bearing waste is stored at production sites.
In 2012, the CEA commissioned a storage centre in Valduc to accommodate its own very low level tritium-bearing waste.

As part of the PNGMDR 2022-2026, Andra, in conjunction with the CEA and ITER organisation, is responsible for developing management scenarios for all tritium-bearing waste present in France, on the basis of a consolidated inventory. These scenarios foresee the implementation of sufficient storage capacities, in particular for highly tritiated waste and tritium-bearing sources from small-scale producers.

Subsequently, a management plan for all tritium-bearing waste will be produced, presenting the foreseeable waste flows to be managed and the associated implementation schedule, detailing the report submission dates for the construction of new facilities or the modification of existing facilities.

VERY SHORT-LIVED WASTE

Most very short-lived waste is hospital waste containing radionuclides with a radioactive half-life of less than 100 days, used for diagnostic or therapeutic purposes *(see chapter 6 - special report 5)*.

This waste is managed through decay on its production site: it is stored for more than 10 times the longest half-life of the radionuclides it contains.

The radioactivity of the waste has then decreased by a factor of 1,000 and it can be evacuated to a conventional waste management solution following inspection.

International Thermonuclear Experimental Reactor (ITER)

WASTE FROM THE ORANO MALVÉSI SITE

Since 1960, the Orano Malvési industrial site has been carrying out the first conversion step of uranium needed for the nuclear fuel cycle. The process used to convert uranium generates solid waste stored in settling ponds at the Malvési site.

The specificity and volume of this waste, known as legacy waste, explains why it is not integrated into existing or planned disposal solutions. This waste corresponds to the uranium conversion treatment residue (RTCU) stream of the *National Inventory*. On-site disposal studies are under way to define a final management solution for this waste.

For waste produced since January 1, 2019, Orano has worked on two projects intended, on the one hand, to reduce the volume of solid waste produced and to favour existing management solutions, and on the other hand, to treat liquid process effluents using a thermal process, together with effluents already stored in the evaporation ponds. These changes in the process lead to the differentiation of two categories of waste that will be produced:

- solid waste, composed of fluorines and gypsums, which is produced by the plant in the form of densified sludge and stored in cells on the site;
- solid waste resulting from the heat treatment of nitrated liquid effluents produced by the operation of conversion installations, but also by the recovery of the inventory already stored in evaporation ponds.

Waste produced after January 1, 2019 is no longer considered as historic RTCU and is integrated, after treatment and conditioning, into the VLLW and LLW-LL management solutions.

As part of the PNGMDR 2022-2026, Orano is requested to submit a report defining the technical and safety options for the disposal of waste stored at basic nuclear facility No. 175, known as ÉCRIN. The report is to be of a maturity level corresponding to a pre-feasibility study.

WASTE WITHOUT A SPECIFIC DISPOSAL SOLUTION

The majority of radioactive waste has an existing or planned management solution. However, a small amount of waste, an estimated 350 m^3 at the end of 2021 (compared to 1,800 m^3 in 2016 and 3,800 m^3 in 2013), cannot be assigned to one of these solutions. This waste is referred to as "waste without a solution" for management (or disposal). This waste is defined as waste that does not fit into any of the existing or planned disposal solutions, at the current state of knowledge, due in particular to its specific physical or chemical characteristics. It is the subject of studies aimed at defining suitable management solutions for each type of waste.

In this context, a working group was set up as part of the PNGMDR 2010-2012. In addition to consolidating the inventory of waste without a solution, this working group made it possible to identify three waste categories classified as "priority" in the search for a shared solution.

Among others, these waste types include waste containing free asbestos, mercury, or organic oils and liquids.

The studies carried out as part of the 2013-2015 and 2016-2018 PNGMDRs made it possible to find solutions for asbestos waste and for mercury-containing waste.

With regard to contaminated organic oils and liquids, management solutions are currently being studied. An inventory of the volumes of organic oils and liquids has therefore been requested as part of the PNGMDR 2022-2026, distinguishing them according to their compatibility with the identified processes, as well as an action plan for treating them.

Work is continuing within the framework of the PNGMDR 2022-2026 and will make it possible to define and implement management solutions for waste without a solution that is produced in nuclear facilities and that does not fall within the above categories. In particular, waste producers will draw up an inventory of waste still subject to management difficulties and will establish a work programme with Andra to develop the associated management solutions. These solutions will be established in accordance with the French Environmental Code and ASN recommendations.

Aerial view of the Orano Malvési site

Report 2

Treatment and conditioning of radioactive waste

GENERAL INFORMATION ON THE TREATMENT AND CONDITIONING OF RADIOACTIVE WASTE

When it is produced, radioactive waste is in a raw form that can be gaseous, liquid, or solid. To manage this waste, it is most often necessary to condition it, meaning to create "waste packages" aiming to ensure the containment of radionuclides and allow for handling. Depending on the nature of the waste, the conditioning operation may follow a preliminary treatment process to obtain waste with characteristics suitable for its long-term management.

Conditioning can therefore be defined as all operations consisting in the introduction of waste, which has potentially undergone prior treatment, into a container where it may or may not be incorporated into an encapsulating or immobilising material, to form a waste package.

The choices of treatment, a possible matrix (encapsulation or immobilisation), and container are mainly linked to the radiological and physical-chemical characteristics of the raw waste. They also aim to optimise the conditioned volume of waste, in particular by increasing its rate of incorporation into the dedicated matrix and/or by reducing the dimensions of containers.

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

- the cement matrix for sludge, evaporation concentrates, or incineration ashes;
- bitumen, in particular for the encapsulation of sludge and evaporation concentrates resulting from the treatment of liquid effluents;
- the glass matrix, in particular for fission product solutions;
- the polymer matrix comprising epoxy resins for ion exchange resins (REI).

For solid waste, two processes are commonly used:

- encapsulation or immobilisation, in particular with a hydraulic binder, of compacted or uncompacted waste after it has been placed in a container;
- direct stacking of compacted drums in a container, without the addition of an hydraulic binder.

Containers are of different shapes (cylindrical or parallelepipedal), according to their contents and their storage or disposal locations. These containers can be made of various different materials. The most commonly used today are concrete (fibrous or non-fibrous) and stainless steel.

To be accepted at a storage or disposal facility, the waste package must meet the acceptance specifications defined for that facility. These specifications are established according to the characteristics of the expected waste packages and those of the facility in question, and they specify the expected performance of the package according to the waste it contains. For example, they may prohibit the presence of perishable or liquid waste, or limit the amount of gaseous releases accepted from a waste package.

***"Conditioned waste** is waste that is either accepted without further treatment in a currently operational disposal facility; complies with the acceptance specifications for disposal at the operational facility to which it is to be sent; or for which no further treatment is planned by its producer before disposal, in the event that there is no disposal facility currently in operation 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, especially if it is stored in tanks, pits, or silos".*

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

THE MAIN INDUSTRIAL PROCESSES FOR TREATMENT AND CONDITIONING

Since the 1950s and the commissioning of the first nuclear reactors in France, numerous treatment and conditioning processes have been studied and developed to manage the waste produced by all nuclear installations. The main treatment and conditioning processes implemented are presented below.


Baling press at the Aube disposal facility (CSA)

TREATMENT PROCESSES

COMPACTION

Compaction is intended to reduce the volume of certain types of solid waste, in particular metal or plastic waste. This process uses presses with different technologies and capacities, ranging from a few hundred tonnes to a few thousand tonnes, depending on the nature of the waste to be compacted. After compaction, the waste is placed in a container and possibly immobilised with an hydraulic binder.

Compaction is generally implemented by waste producers (at sites in La Hague, Cadarache, etc.), but also by Andra at disposal facilities currently in operation (Industrial facility for grouping, storage and disposal (Cires) of very low-level waste and the Aube disposal facility (CSA) dedicated to low- and intermediate-level waste, mainly short-lived).

FOCUS — COMPACTED RADIOACTIVE WASTE PACKAGES

The spent fuel assembly structural elements from light water reactors: cladding tubes, assembly end pieces, grids, springs, etc., are compacted and conditioned at the Hull Compaction Workshop (ACC) in La Hague, commissioned in 2002. The packages also contain solid metal operating waste that has been compacted.

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


Example of ILW-LL package

EVAPORATION

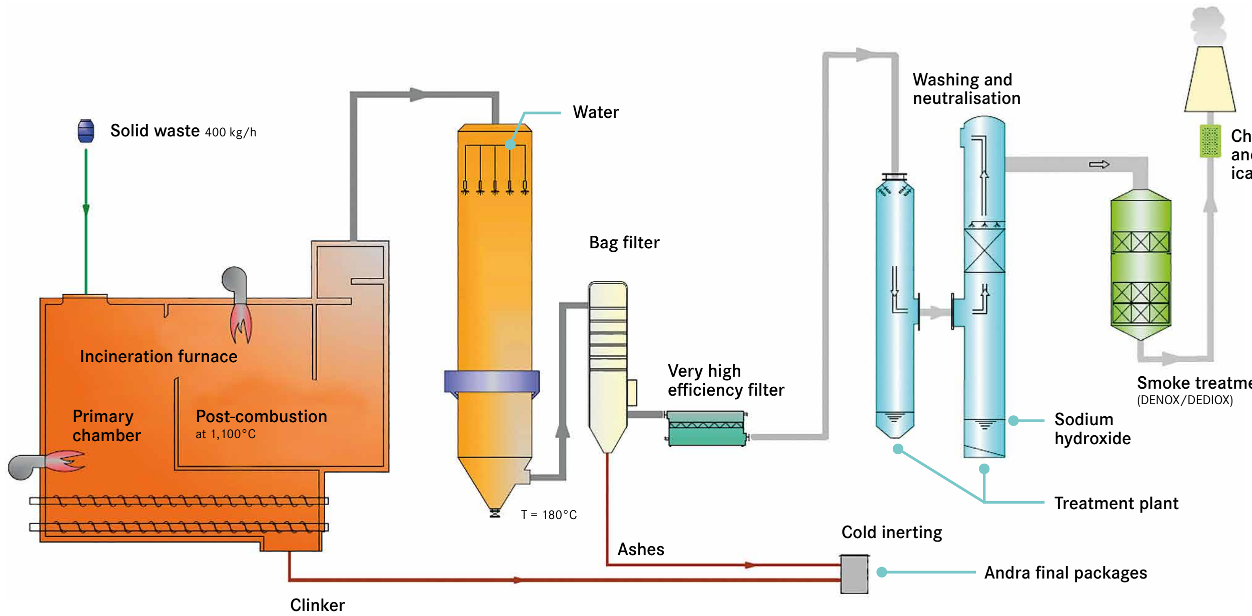
Before conditioning, liquid waste is sometimes concentrated by heating and evaporation, when its chemical characteristics allow it, which reduces its volume. The concentrates obtained through this process are then conditioned directly, for example by cementation or bituminisation.

On the waste producer's site, evaporation is generally integrated into the installation implementing the conditioning method selected for the concentrates.

INCINERATION

Incineration significantly reduces the mass and volume of waste and concentrates its radioactivity in the ashes. It is particularly suitable for aqueous and organic liquid waste, solvents or scintillation liquids, as well as organic solid waste, very low-level (VLLW) or short-lived low- and intermediate-level waste (LILW-SL). As an example, the Cyclife France Centraco facility in Codolet, which has been in operation since 1999, makes it possible to incinerate liquid and solid waste.

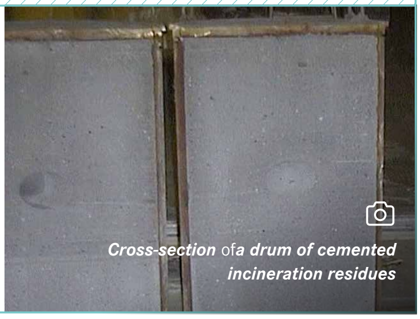
SCHEMATIC DIAGRAM OF THE INCINERATION PROCESS



FOCUS WASTE PACKAGES OF CEMENTED INCINERATION RESIDUES

The incineration residues are in the form of clinker, slag, and ash. These raw incineration residues are crushed and mixed with a cement-based material, to then be poured into a non-alloy steel drum to which the lid is welded.

The drums are short-lived low- and intermediate-level waste packages (LILW-SL), belonging to the F3-7-01 stream of waste. The mass of the finished package is about 1.5 t for a volume of 450 L. Such a package contains about 370 kg of raw incineration residues.



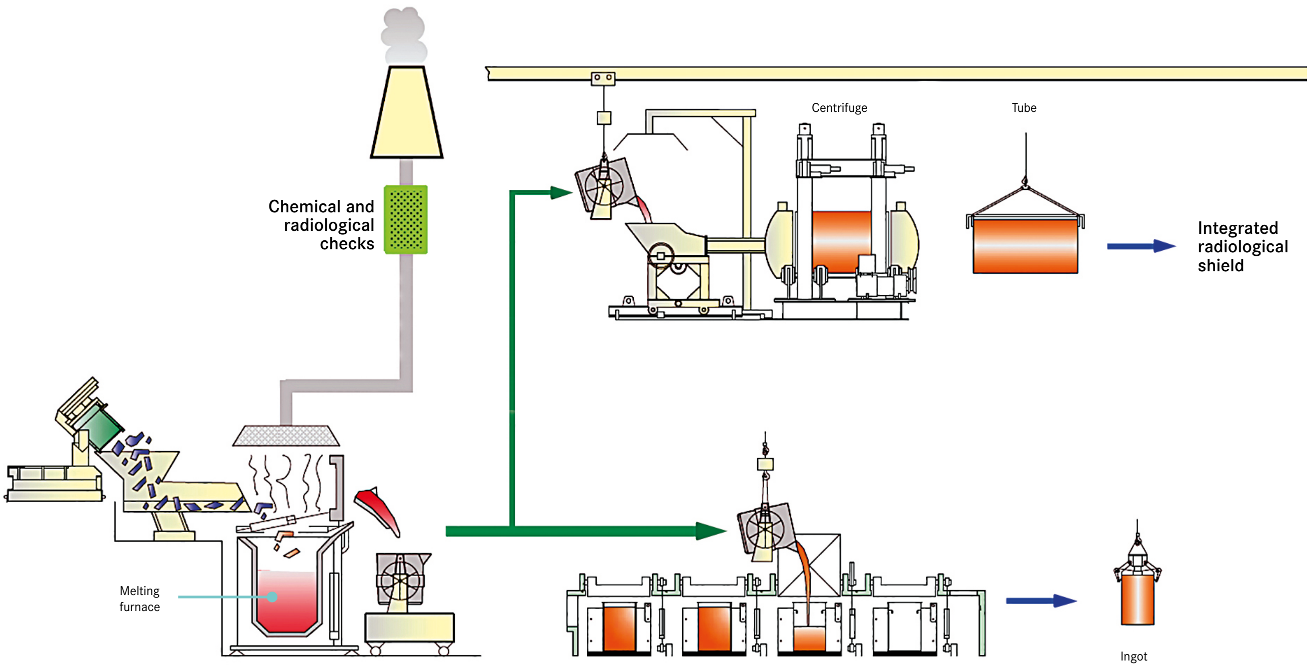
Cross-section ofa drum of cemented incineration residues

MELTING

Like incineration, melting makes it possible to reduce the volume of waste and partially decontaminate waste, which 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 France Centraco facility to treat steel or non-ferrous metal waste produced by maintenance or dismantling operations on nuclear facilities.

SCHEMATIC DIAGRAM OF THE MELTING PROCESS



CONDITIONING PROCESSES

CEMENTATION

The cementation process is used to:

- immobilise solid waste such as technological waste, activated waste and structural waste. In this case, it produces so-called heterogeneous waste packages;
- encapsulating waste in solution or in powder form: evaporation concentrates, chemical treatment sludges, ion exchange resins, etc. The waste packages thus produced are said to be homogeneous.

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

Cementation is therefore widely implemented on the sites of waste producers (on the La Hague, Cadarache, Marcoule sites, etc.). This process is also practised at Andra's Cires and CSA sites.

BITUMINISATION

The bitumen encapsulation process consists in mixing hot waste, in the form of sludge, with bitumen. The mixture obtained is dehydrated and poured into a container where it is cooled. Bitumen has advantageous properties due to its high binding power, impermeability, low solubility in water, high containment power, moderate cost and, finally, its availability. Disposal of bitumens may require reinforced design provisions with regard to operational safety.

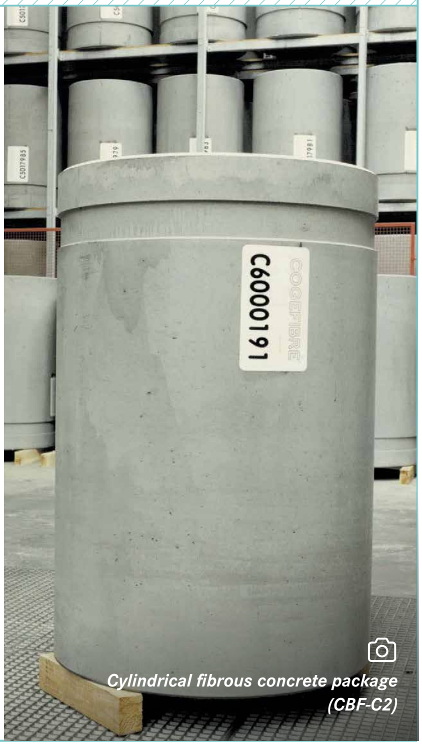
This process is implemented on the sites of waste producers, essentially to condition the precipitation sludge resulting from the treatment of liquid effluents. It has now been largely replaced by cementation or vitrification, depending on the nature of the waste to be treated.

FOCUS

CEMENTED WASTE PACKAGES

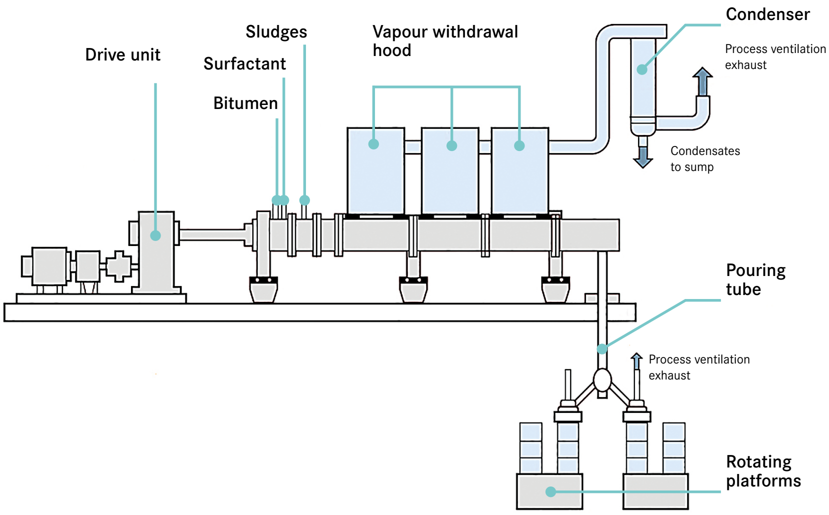
Waste generated during normal operation of the various workshops and laboratories, maintenance operations, or dismantling of facilities at the La Hague site are conditioned in cylindrical fibrous concrete containers. Depending on the activity of the waste, these packages are either disposed of at the CSA (for short-lived low- and intermediate-level waste, LILW-SL, which belongs to the F3-3-11 stream), or stored pending the availability of a suitable disposal facility (for long-lived intermediate-level waste, ILW-LL, and long-lived low-level waste, LLW-LL which belong to the F2-3-08 and F9-3-03 streams, respectively).

The mass of the finished package is about 2.5 t for a volume of 1.18 m³. A package like this contains about 450 kg of waste.



Cylindrical fibrous concrete package (CBF-C2)

SCHEMATIC DIAGRAM OF THE BITUMINISATION PROCESS

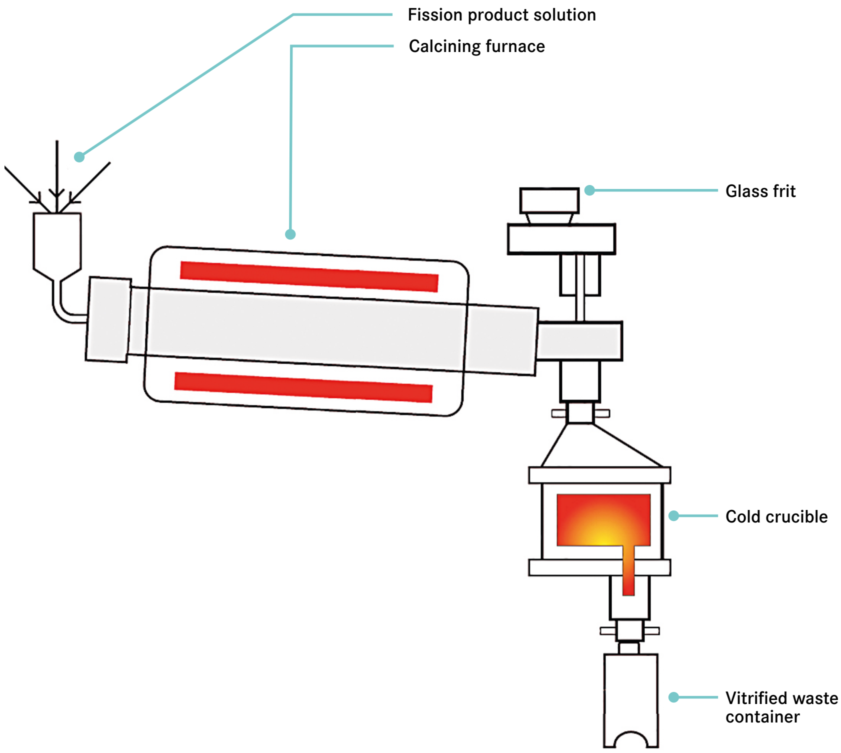


VITRIFICATION

Vitrification consists in mixing, in a crucible and at high temperature, generally liquid radioactive waste (that has first been calcined) with a glass frit. The composition of the glass frit is adapted to the chemical nature of the waste in order to integrate, at the atomic scale, all the radionuclides present in the waste into the vitreous network in a homogeneous manner. The mixture obtained 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 has good chemical durability over long periods of time.

Implemented for several decades at the Marcoule and La Hague sites, this process is now the industrial reference for conditioning of fission product solutions resulting from the reprocessing of spent fuel. Technological developments, in particular around the use of a cold crucible, have made it possible to limit the waste produced by the process and to potentially extend its application to other types of waste.

SCHEMATIC DIAGRAM OF THE VITRIFICATION PROCESS



FOCUS VITRIFIED WASTE PACKAGES

The first industrial implementation of vitrification took place at the Marcoule site in 1978. The vitrification workshop, which has been shut down since 2012, produced high-level vitrified waste packages belonging to the F1-4-01 stream.

These packages are in the form of a stainless steel container approximately 1 m high and 50 cm in diameter, containing around 360 kg of vitrified waste.

AVM vitrified waste packages

ENCAPSULATION IN POLYMER RESINS

Depending on its radiological and physical-chemical characteristics, solid waste can also be encapsulated using a polymer resin. This process is used in particular to condition ion exchange resins (REI) that are used in the chemical and volume control systems of nuclear reactor coolant systems, for the treatment and purification of pool water and the treatment of effluents.

This process involves mixing the ion exchange resins with an epoxy matrix and then conditioning them in cylindrical concrete containers.

Some ion exchange resins are not easily transportable due to their radiological or physical-chemical characteristics. The treatment process is carried out *in situ* using mobile machines designed by Cyclife France's Centraco, which allow the resins to be conditioned in accordance with Andra specifications.

RESEARCH AND DEVELOPMENT ON TREATMENT AND CONDITIONING

DEVELOPMENT OF A SPECIFIC HYDRAULIC BINDER FOR MAGNESIUM WASTE

Magnesium waste stored at the Marcoule site is in the form of bulk, crushed or compacted metallic magnesium cladding. Development of a specific hydraulic binder (called a geopolymer) is currently being conducted to control the physical-chemical interactions between the encapsulation material and the waste.

The CEA is studying this conditioning solution in partnership with Andra. If feasibility can be demonstrated, and if the acceptability of disposal is issued, the CEA aims to deploy this process in the short term on the oldest and least active magnesium waste (short-lived low- and intermediate-level waste).

DEM&MELT: AN INNOVATIVE TOOL FOR IMMOBILISING AND CONTAINING NUCLEAR WASTE FROM CLEAN-UP AND DISMANTLING OPERATIONS

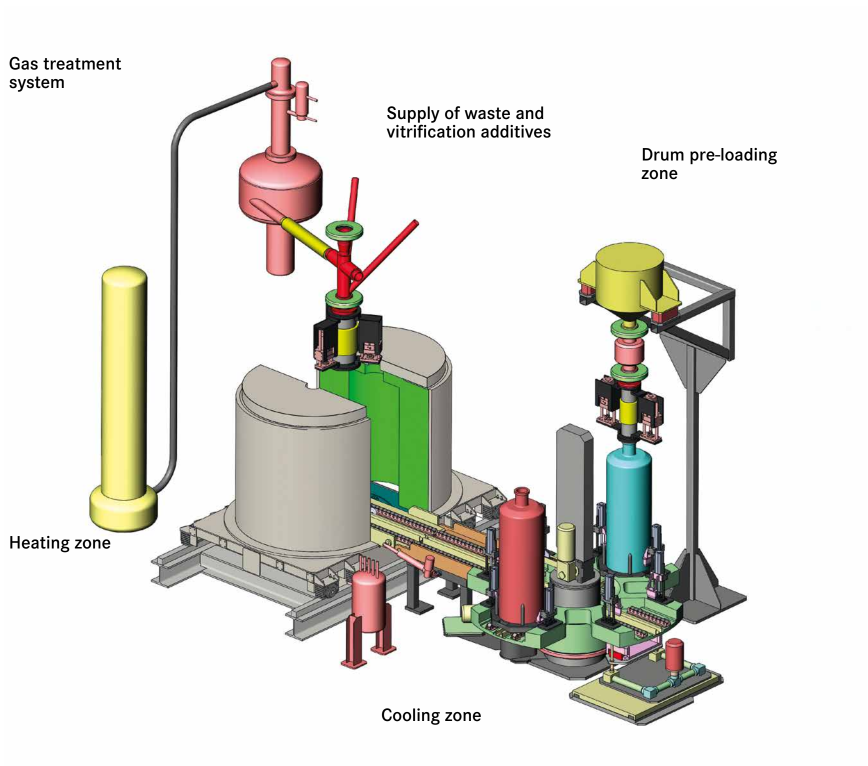
Orano, the CEA and ECM technologies, with the support of Andra, have developed a vitrification process, called DEM&MELT, which meets the requirements of a dismantling environment: it must be simple, robust, and quick and easy to deploy on site while limiting investment and operating costs. The objective is also to propose a process that is flexible enough to adapt to the uncertain composition of the waste to be treated, while simultaneously producing waste packages having a structure and containment performance level that are compatible with disposal.

DEM&MELT is a versatile "In-Can" thermal process for treating a wide variety of intermediate- to high-level waste types. The targeted waste may be solid (including powder waste), liquid, highly viscous, or sticky.

This process uses heating in a robust resistance furnace to ensure effective temperature control and homogeneity of the molten glass. Vitrification is carried out "In-Can", i.e. the container is directly used as a melting pot; it does not have an agitator or a pouring device.

Research on the treatment and conditioning of waste is supported by several funding mechanisms, which make it possible to accompany numerous projects:
- **the Investments for the Future programme, whose management has been entrusted to Andra and which includes several projects relating to this topic;**
- **the "innovative solutions for managing radioactive materials and waste" component of France 2030.**

3D VIEW OF THE DEM&MELT PROCESS



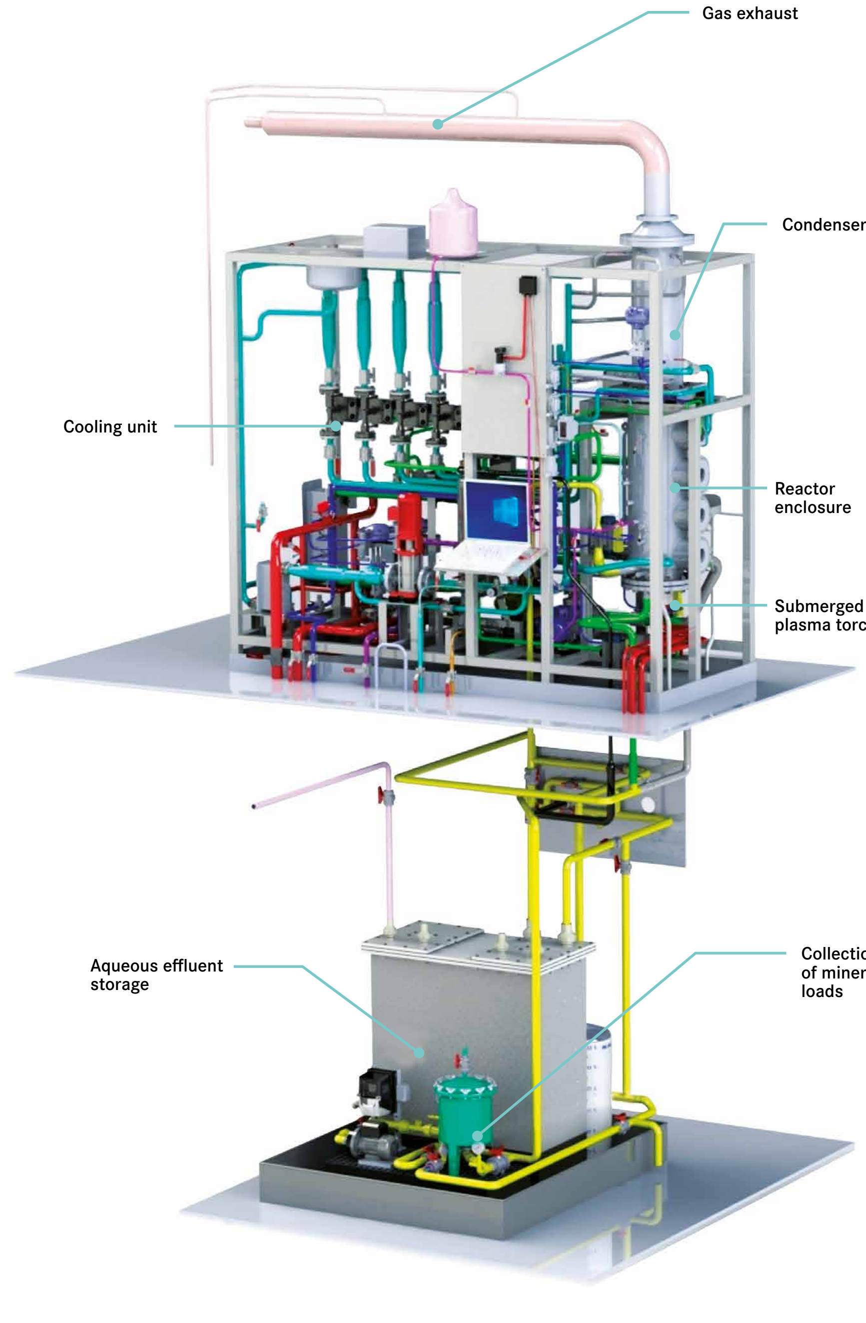
© Orano

ELIPSE: UNDERWATER PLASMA TECHNOLOGY FOR THE ELIMINATION OF ORGANIC LIQUID WASTE

Radioactive organic liquid waste, known as DLOR, must first be solidified in order to be disposed of. In the majority of cases, these liquids are incinerated in the Cyclife France Centraco facility, and the ashes resulting from the incineration can then be cemented. However, the composition of some types of DLOR does not allow them to be processed in this incinerator (in particular, highly chlorinated, phosphorus and fluorinated DLOR, as well as organic liquid waste overloaded with ^{14}C and ^{3}H). There is currently no treatment solution for these types of liquid waste.

The ELIPSE process, currently under development at the CEA, uses a high-powered oxygen plasma immersed in a water column to mineralize DLOR waste. This is an innovative technology for treating a wide variety of organic solvents in flow ranges around 3 L/h and with high chemical concentrations of chlorine, phosphorus and fluorine. The secondary waste produced are aqueous effluents containing minerals and it should be possible to filter and manage this waste using existing treatment solutions. The technological developments carried out have made it possible to develop a full-scale prototype to carry out treatment tests on DLOR waste that does not currently have a treatment solution. Further development of the ELIPSE process would make it possible to propose an alternative and complementary treatment solution to the Cyclife France process for this waste.

3D VIEW OF THE ELIPSE PROCESS



Report 3

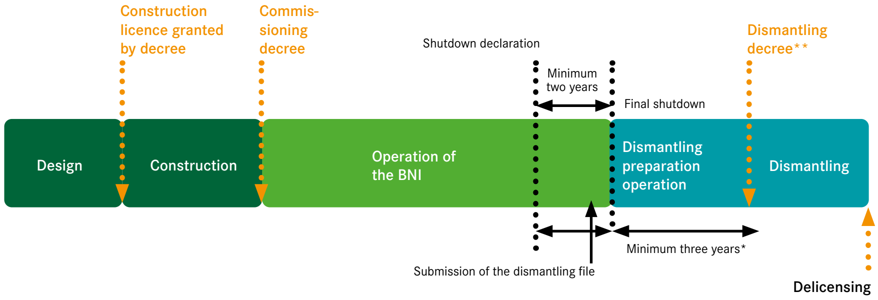
Dismantling and clean-up of basic nuclear installations

Like any industrial activity, the operation of a nuclear installation is limited in duration. When the nuclear operator, holder of the licence to operate the installation, decides to definitively stop operating, it initiates a process of operations that will bring the facility to a state where the impact and residual risk to the public, workers, and the environment will be as low as reasonably possible (ALARA principle) so that it can be delicensed from the list of nuclear installations.

This final phase of life corresponds to the dismantling of the nuclear installation.

There are four major phases in the life of a basic nuclear installation: its design, construction, operation and dismantling.

LIFE PHASES OF A BASIC NUCLEAR INSTALLATION



* May be extended by two years in some cases.

** The dismantling decree takes effect on the date on which ASN approves this revision of the general operating rules and, at the latest, one year after publication of the decree.

REGULATORY PROCESS

Dismantling of nuclear installations in France is a process initiated before the final end of operation date planned by the nuclear operator, and it continues up to delicensing of the installation is obtained from the supervisory authority of the nuclear installation.

This process, which is governed by the French Environmental Code, requires the operator to submit:

- a declaration of definitive shutdown to the Minister responsible for nuclear safety and to ASN, at least two years before the planned shutdown date;
- the dismantling file no later than two years after the declaration of final decommissioning.

Dismantling of the BNI at final shutdown is prescribed by decree issued after ASN opinion and after completion of a public inquiry, within three years after submission of the dismantling file. The decree sets the characteristics of dismantling and the completion time.

For application of the decree, ASN defines the requirements relating to dismantling necessary for the protection of the interests mentioned in the French Environmental Code.

Within three months after publication of the decree, the operator sends the revision of the safety report and the general operating rules for the installation to be dismantled.

The dismantling decree takes effect on the date on which the authority approves this revision of the general operating rules and, at the latest, one year after publication of the decree.

Entry into force of the decree authorises the start of dismantling operations at the facility.

The operator ofa BNI that has been dismantled in its entirety and no longer requires the planned control measures then sends a delicensing request to ASN.

FOCUS — DISTINCTION BETWEEN "DISMANTLING" AND "DELICENSING"

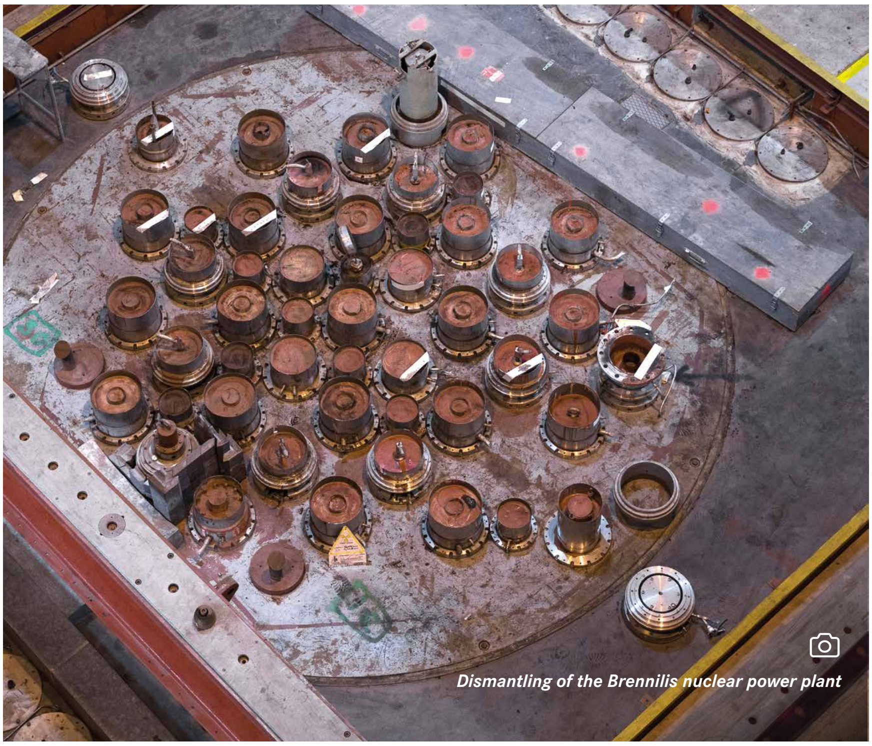
"Dismantling" is the set of technical operations after final shutdown of a nuclear installation that aim to reach a targeted final state to allow for delicensing. Clean-up consists in operations to reduce or eliminate the remaining radioactivity or any other hazardous substance remaining in both structures and soils. These operations are carried out with a view to reaching a final state that has already been defined, in particular according to future use: dismantling of equipment, clean-up of the premises, soil clean-up or remediation, possible destruction of civil works, conditioning, evacuation and elimination of the waste generated (radioactive or not).

"Delicensing", however, is a strictly administrative operation consisting in removing the installation from the list of classified installations. The installation is therefore no longer subject to the same legal and administrative regime.

Delicensing results in the lifting of regulatory inspections to which a classified installation is subject. Delicensing may be accompanied by restrictions on the use of the land around or adjacent to the delicensed facility.

The reference approach recommended by ASN for the dismantling of an installation in view of its delicensing is to implement complete clean-up. This approach provides, *"where technically possible, for the complete clean-up of radiocontaminated sites, even if the exposure of people caused by radioactive pollution appears to be limited"*, i.e. to return to the initial state before activation or contamination of the structures.

In situations where the baseline approach would pose implementation difficulties, the clean-up process is carried out as far as reasonably possible, under acceptable technical-economic conditions.



Dismantling of the Brennilis nuclear power plant

DISMANTLING STRATEGY

Two strategies are possible for the dismantling of nuclear facilities:

- dismantling following final shutdown of the facility. This strategy makes it possible to avoid burdening future generations with the responsibility of dismantling, both technically and financially. It also allows the knowledge and skills of the teams present during operation of the facility to be integrated, assets which are essential during the first dismantling operations. It avoids significant expenses of monitoring, maintaining in a satisfactory safe state, and possibly of regeneration;
- delayed dismantling, several decades after shutdown of the facility, mainly justified by the radioactive decay of the elements to be dismantled to allow for less complex dismantling operations and optimise exposure to ionizing radiation for the people carrying out the dismantling operations. It also makes it possible to spread expenses over time in order to ensure sound financial management.

The choice depends on national regulations, socio-economic factors, the capacity and method of financing operations and the availability of dismantling techniques, qualified personnel, and waste disposal solutions.

The strategy adopted in France, codified in Article L. 593-25 of the Environmental Code, is that of dismantling within as short a time as possible, after the final shutdown of the installation, under economically acceptable conditions and in compliance with the principles of prevention of health risks related to the environment and work.

DISMANTLING WORKS

PREPARING DISMANTLING WORKS

As soon as the final shutdown date of a nuclear installation or a part of the installation is reached, a phase of preparation for dismantling begins. This transition stage allows the teams responsible for operating the nuclear facility, as part of the operating licence, to carry out the operations in preparation of dismantling. This involves conditioning and evacuating as many radioactive and hazardous substances as possible from the installation, shutting down the processes and preparing for dismantling operations: site preparation, radiological and chemical research and investigations of the various areas, adaptation or renovation work if necessary of the facility or equipment, 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 reprocessing plant or waste treatment facility, the process equipment is emptied and rinsed.

During this stage, all safety and security functions required during the operating phase continue to be operational.

FOCUS — FINAL SHUTDOWN DECLARATION

In accordance with Article L. 593-26 of the French Environmental Code, the operator of a basic nuclear installation who plans to definitively shut down operation of its installation or part of its installation, declares this to the Minister responsible for nuclear safety and to ASN. It indicates in its declaration the date on which this shutdown is to take place and specifies, with justification, the operations it intends to carry out, considering this shutdown and pending the start of dismantling, to reduce the risks or disadvantages for the protected interests mentioned in Article L. 593-1.

This declaration is made at least two years before the planned shutdown date or as soon as possible if this shutdown is carried out with shorter notice for reasons that the operator justifies. This declaration must be accompanied by an update of the dismantling plan which presents and justifies the dismantling strategy adopted, the principles and provisions taken by the nuclear operator for the dismantling of its installation, the progress of dismantling and the intended final state.

EXECUTING DISMANTLING WORKS

At the end of the preparation phase for final shutdown, and after entry into force of the dismantling decree of the basic nuclear installation, the operator commences the dismantling phase, which may take several years.

Dismantling work is carried out in accordance with the facility's reference baseline and the regulatory requirements set out in the dismantling decree, possibly supplemented by requirements from the supervisory authority.

The procedures are adapted to each installation according to their history, the characterisations and investigations available, the accessibility of the areas, etc. The scenarios are studied according to the specificities of the installations or equipment, in particular relating to the nature of the materials and their type of contamination to define the means of containment, the tools, the protocols, the treatment, conditioning, and disposal solutions for waste generated, etc.


Dismantling of the EDF Chooz A nuclear power plant

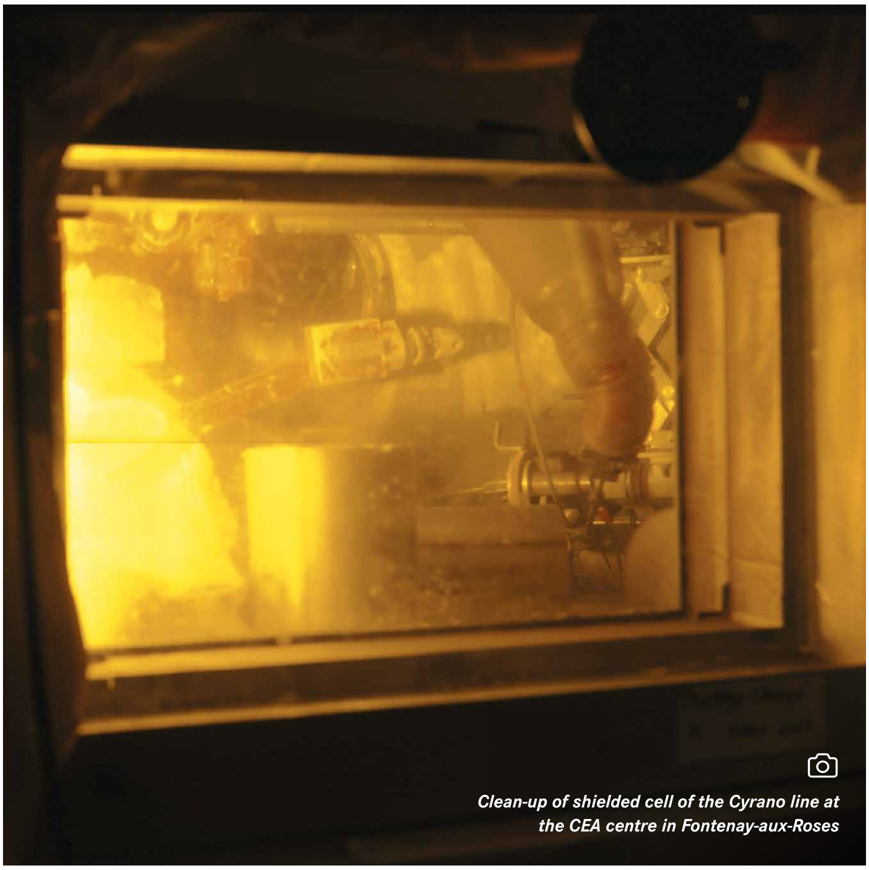
FINALISING DISMANTLING WORKS

In France, the final state at the end of dismantling a basic nuclear installation must make it possible to prevent the risks or disadvantages that the site may present for safety, health and public health, or the protection of nature and the environment. In particular, this includes taking into account the reuse of the site or buildings and the best clean-up and dismantling methods and techniques available under acceptable economic conditions.

The demolition of the buildings of the nuclear installation is not always necessary to reach this final state. The operator may seek to reuse buildings or surfaces that have been remediated and then delicensed.

ASN recommends that operators implement clean-up and dismantling practices that aim to reach an end state where all hazardous substances and radioactive substances have been evacuated from the installation.

In the event that, depending on the characteristics of the pollution, this approach would pose implementation difficulties, the operator must still go as far as reasonably possible in the clean-up process, by providing the elements, of a technical or economic nature, which justify that the reference approach cannot be implemented and that the clean-up operations cannot be taken any further with the best clean-up and dismantling methods and techniques available under acceptable economic conditions. In its justification, the operator includes the volume of waste generated by each of these scenarios as well as their respective costs.



Clean-up of shielded cell of the Cyrano line at the CEA centre in Fontenay-aux-Roses

When the total absence of risks to health, public health, and the protection of nature and the environment cannot be demonstrated, public utility easements are instituted. In this case, the delicensing application file is part of the documents submitted to the public inquiry for the implementation of these limitations. Administrative limitations of public interest may be instituted at the request of the operator or the administration (ASN, prefecture, municipality). These may contain a certain number of restrictions on use (limitation to industrial use, for example) or precautionary measures (preservation of memory, radiological measurements in the event of excavation, etc.). ASN may make the delicensing of a basic nuclear installation subject to the institution of such limitations.

In addition, in the event of a threat to the interests mentioned in Article L. 593-1 of the Environmental Code, ASN may, at any time, even after delicensing of the installation, require assessments and the implementation of any necessary provisions.

Dismantling of a prototype installation for pulsed column solvent extraction (BNI57) at the CEA in Fontenay-aux-Roses

FOCUS

R&D FOR DISMANTLING

Nuclear dismantling operations are complex projects that require a wide range of know-how and specific technologies. Although most operations use common techniques adapted to the nuclear environment, the development of specific methods, processes, and tools is necessary in certain areas.

France has therefore acquired recognised skill and is still developing R&D in the fields of:

- measuring radioactivity in support of initial characterisation and characterisation of waste;
- decontamination of structures and soils (lasers, foams, gels, etc.);
- cutting (laser processes in particular);
- 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 of specific effluents generated by these operations.

Storage of very low level waste (VLLW) from the dismantling of the Triton research reactor

WASTE FROM DISMANTLING

There are two types of waste generated by dismantling and clean-up operations: conventional or radioactive. To identify which of these two categories the waste belongs to, installations are divided into zones based on the history of the facility and the operations conducted there:

- waste from Conventional Waste Zones (ZDC) is non-radioactive waste, which is therefore eliminated after inspection through approved conventional waste management solutions;
- waste from Potential Nuclear Waste Production Zones (ZppDN) is all managed as if it were radioactive, even when the measuring devices do not detect radioactivity, and is conditioned and characterised for handover to Andra for long-term management.

Waste zoning can be reviewed between operation and dismantling to take into account the specificities of the different phases of operation and allow optimised waste management.

PRINCIPLES FOR MANAGING WASTE FROM DISMANTLING

As for other waste, the management policy for radioactive waste from dismantling is based on:

- ensuring the traceability of waste from nuclear installations (waste zoning, characterisation, inspection);
- minimising the volume of waste produced;
- optimising its categorisation;
- shipment of waste to existing disposal facilities immediately following production. If the waste does not have an outlet, it is stored in dedicated facilities.

Radioactive waste is sorted, potentially treated, and then conditioned and characterised (*see chapter 6 - special report 2*), before being transported to existing disposal facilities suitable for its level of radioactivity (respectively Cires for VLLW and CSA for LILW-SL waste) or stored while waiting for the appropriate disposal solution to open.

Metal containers of very low-level radioactive waste (VLLW)

TYPE OF WASTE FROM DISMANTLING

Dismantling waste is largely conventional waste, notably rubble and metals. For example, in the case of the dismantling of the Chooz A nuclear power plant, 60% of the 50,000 tonnes of dismantling and clean-up waste is conventional and 40% is radioactive.

Most radioactive waste from dismantling (> 99%) is very low level (VLLW) or short-lived low- and intermediate-level waste (LILW-SL). This waste comprises:

- materials related to the demolition of installations (concrete, rubble, scrap metal, glove box walls, piping, etc.);
- process equipment (e.g. metal parts);
- tools and work clothes (gloves, vinyl suits, etc.);
- effluents that have been used to rinse equipment.

In addition, there may be long-lived low-level waste (LLW-LL), in particular graphite waste from the first French reactors known as "gas-cooled graphite-moderated" reactors (GCR) and long-lived intermediate-level waste (ILW-LL) in small quantities (this is mainly activated waste, including metal parts located in the core of the reactors).

ESTIMATED QUANTITIES OF WASTE FROM DISMANTLING

Starting at commissioning of a basic nuclear installation, the quantity and nature of the waste that will be produced by the dismantling operations are assessed and updated periodically until the preparation of dismantling operations, where the estimates are refined and the treatment and conditioning means to be implemented are assessed . These assessments take into account all the waste produced by the operation, including secondary waste generated, for example the volumes of effluents generated by decontamination.

To do this, a rigorous inventory of the facilities to be cleaned, the equipment they contain and their level of contamination is carried out and then updated during operation of the installation.

The quantities of waste that will be produced are then assessed on the basis of this operating history, the experience feedback acquired from previous dismantling operations, and investigations carried out to consolidate this initial state prior to dismantling operations.

Dismantling of the Brennilis nuclear power plant

DISMANTLING OPERATIONS IN FRANCE

Since the early 1980s, dismantling operations of R&D facilities, research reactors or installations related to the fuel cycle have been carried out at various sites. More than thirty nuclear installations have been dismantled and delicensed.

In total, about seventy facilities are currently being dismantled or delicensed. Some of these dismantling operations in progress include:
- nuclear reactors, the majority of which are of a different technology and design from those currently operating in France;
- CEA installations (research reactors or prototypes, research facilities and laboratories), EDF installations (irradiated materials workshop) and Orano installations (fuel cycle).

The examples below illustrate the diversity of nuclear installations to be dismantled, the difficulties encountered, the delays between the shutdown of the installation and the re-industrialisation of the site, as well as 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.

EXAMPLE 1: SICN SITES

SICN (Société industrielle de combustible nucléaire) is a French 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 converting to the manufacture of uranium metal parts.

SICN had facilities (production workshops, laboratory, etc.) in Annecy starting in 1954 and Veurey-Voroize starting in November 1960.

ANNECY SITE

In 2002, the decision was made to stop nuclear activities falling under the Classified Environmental Protection Facility (ICPE) regulation, and then to launch the clean-up and dismantling project in 2005.

at the end of the site restoration work which lasted into 2013, the site was completely re-industrialised by the establishment of a biomass boiler in 2015, operated by Idex, rental of buildings to HTIM, and rental of land to Pfeiffer.

VEUREY-VOROIZE SITE

In 2006, the two basic nuclear installations (BNI) located at the Veurey-Voroize site were permanently shut down:
- nuclear fuel production plant, BNI No. 65 licensed in 1967;
- pelletising workshop, BNI No. 90 licensed in 1977.

Between 2006 and 2012, nuclear dismantling operations of equipment and clean-up of buildings were carried out to initiate delicensing procedures with the authorities.

Pronounced in 2019, the delicensing of the two BNIs located on the site made it possible to consider the re-industrialisation of the buildings and land that were sold in 2022 to Lynred, a joint venture of the Safran and Thales groups specialising in the manufacture of infrared sensors, as part of their plan to expand activities on this industrial site.

Dismantling of the Siloé reactor at the CEA centre in Grenoble

EXAMPLE 2: CEA SITE IN GRENOBLE

Created in 1956 to contribute to the development of the French nuclear power sector, the CEA Grenoble centre experienced a decrease in its nuclear research activities at the end of the 1990s. From 2001, CEA Grenoble undertook the clean-up and dismantling of the six basic nuclear installations located on the site:
- BNI 19 (Mélusine), a nuclear reactor that was shut down in 1988;
- BNI 20 (Siloé), a nuclear reactor that was shut down in 1997;
- BNI 21 (Siloëtte), a nuclear reactor that was shut down in 2002;
- BNI 61 Laboratory for the Analysis and Testing of Radioactive Materials (Lama);
- BNIs 36 and 79 Effluent and Waste Treatment Plant (Sted), former decay storage facilities.

These nuclear installations underwent major clean-up and deconstruction work, allowing four of them to be delicensed (BNI 19, BNI 20, BNI 21, and BNI 61) and the reuse of space for R&D activities in micro-nanoelectronics, health technologies, and renewable energies.


Dismantling of the Lama at the CEA centre in Grenoble

EXAMPLE 3: CHOOZ A NUCLEAR POWER PLANT

Located in the Ardennes département, on the banks of the Meuse river, the Chooz nuclear power plant has two reactors in operation (Chooz B1 and B2) and one reactor in the dismantling phase (Chooz A). Chooz A was commissioned in 1967 and operated until 1991. It is one of the eleven reactors currently being deconstructed by EDF in France.

Chooz A was the first power plant built in France's pressurised water reactor (PWR) fleet. It was a Franco-Belgian project led by the Société d'énergie nucléaire des Ardennes (SENA), formed by EDF and a group of Belgian electricity producers. It is unique in that the reactor and its nuclear auxiliaries (pumps, exchangers, cooling circuits, etc.) are installed in two rock caverns, dug into the hillside in a bend of the Meuse river valley.

From 2001 to 2004, the main operations consisted in removing the fuel, emptying the circuits, dismantling, cleaning, and demolishing the machine room, the pumping station and the nuclear buildings located outside the hill. As a result of these operations, 99.9% of the plant's radioactivity had been removed from the site.

After the public inquiry organised in August and September 2006, the decree authorising complete dismantling was signed on September 27, 2007. From this milestone, the operations took place in accordance with the baseline scenario:

- from 2008 to 2010, preparation for dismantling operations (creation of waste storage areas and changing rooms, repair of ventilation and lifting equipment, etc.);
- from 2010 to 2014, clean-up and dismantling of the auxiliary systems and the reactor coolant system (excluding the vessel) and evacuation to the appropriate disposal facilities;
- from 2015 to 2016, arrangement of the workshops necessary for dismantling of the reactor vessel, creation of a circuit allowing the pool to be filled with water and filtered, and start of dismantling of the remaining premises of the auxiliary cavern by remotely operated means;
- in 2017, the reactor pool was filled with water and the vessel cover removed in preparation for its evacuation in 2018.

The last dismantling operations, such as the cutting, conditioning, and evacuation of the reactor vessel, are scheduled into 2025.

FOCUS — DISMANTLING ABROAD

Globally, in the next 20 years, dozens of nuclear power reactors, research facilities (experimental reactors, laboratories, etc.), fuel fabrication and reprocessing plants will have to be dismantled.

The largest international projects are in the Americas, and especially in the United States, but also in Europe.

The expertise acquired by French companies in all the fields concerned, in an integrated manner, through dismantling operations carried out on research or production facilities for more than 30 years, clearly positions them as likely to respond effectively to the challenges presented by these major international projects.


Disposal of a steam generator from the Chooz A nuclear power plant at Cires


Deconstruction worksite of the Chooz A nuclear power plant: deconstruction of the cavern

THE IMPORTANCE OF EXPERIENCE FEEDBACK FOR FUTURE DISMANTLING WORKSITES

As dismantling worksites progress in France and abroad, experience feedback grows and provides a resource for future dismantling projects.

The main lessons learned are:

- the importance of taking into account the difficulties inherent to dismantling operations such as working in irradiating environments, the obsolescence of certain installations, changes to regulations, and the availability of outlets for the waste produced;
- a precise definition of the initial state (type and quantity of the waste to be produced, characterisation of the radiological status, etc.) and of the final state, allowing for a better assessment of the means necessary to achieve the objectives.

Report 4

Sites polluted by radioactivity

Sites polluted by radioactive substances represent only a very small proportion of all polluted sites in France.

This pollution may result from industrial, medical, or research activities involving radioactive substances. Pollution may concern the places where these activities are carried out as well as their immediate or more distant surroundings. Most sites polluted by radioactive substances are due to former industrial or trade activities, at a time when the perception of risks related to radioactivity and radiation protection measures were not at the same level as they are today.

Sites polluted by radioactive substances require preventive or remedial action by public authorities.

> *"Site polluted by radioactive substances: a site which, due to former deposits of radioactive substances or waste, use or infiltration of radioactive substances, or radiological activation of materials, presents radioactive pollution likely to cause harm or a lasting risk for people or the environment[1] ".*
>
> **The pollution observed must be attributable to one or more radioactive substances, as defined by Article L. 542-1-1 of the French Environmental Code, namely any *"substance that contains natural or artificial radionuclides, the activity or concentration of which justifies a radiation protection inspection".***

ORIGIN OF RADIOACTIVE POLLUTION

The sites polluted by radioactivity are mostly legacy sites which accommodated these activities, unrelated to the nuclear power industry. The substances which may have contributed to site pollution were:

- radium: its extraction, storage, handling, and sale for a range of applications including medicine, health and beauty products, and the manufacture of paint for night vision are responsible for a large proportion of radioactive pollution in France;
- tritium: used for night vision in the production of paint as a replacement for radium;
- monazite, a naturally radioactive mineral used, among other things, for the manufacture of cigarette lighter flints (former Orflam-Plast factory in Pargny-sur-Saulx);
- natural sands rich in zircons, naturally occurring and weakly radioactive minerals used in the manufacture of zirconium oxide;
- the manufacture of molecules for the chemical industry.

ROARING TWENTIES ADVERTISEMENT FOR RADIUM

1 Annex 13-7 of the French Public Health Code.

FOCUS RADIUM

Radium is present in very small quantities on Earth, in the form of several isotopes, the most abundant 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 plants were therefore created in France and may have been the source of pollution of these industrial sites.

At the beginning of the 20th century, the therapeutic use of radium came to the forefront for its ability to destroy diseased tissues. In view of the spectacular results obtained, a real enthusiasm for radium grew among the general public in the 1920s and 30s.

At that time, a large quantity of health and beauty products, manufactured products and more (powders, cosmetics, wool, livestock feed, car sparkplugs, fountains, luminescent paints for watchmaking and aviation, etc.) were marketed in France.

In the late 1950s, their manufacture, production, and marketing were banned due to the dangers related to their radioactivity.

Radium, also used at the time for its radioluminescent properties, was replaced by artificial radionuclides, such as tritium.

This craze ended when the dangers of radioactivity were recognised and the use of radium was prohibited. The memory of many of the industrial sites that developed during the "Roaring Twenties" of radium has been lost. Some sites, usually located in urban areas, have been redeveloped despite their radioactive pollution or have remained undeveloped.

Nevertheless, the pollution still present on these sites may require clean-up in order to reduce the risks to health and the environment.

Worker at the Bayard watchmaking factory

IDENTIFICATION OF SITES POLLUTED BY RADIOACTIVITY

The identification of polluted sites is a complex task because the memory of these sites has not always been preserved. There are a variety of information sources for identifying these sites. Inventory and identification is ongoing work, updated as new sites are identified.

The historical study conducted in 1996 by the Andra Observatory in close collaboration with the Institut Curie made it possible to find these sites, resulting in radioactivity inspection operations on several dozen of them, which could be followed by direct safety and/or clean-up actions.

It also made it possible to trigger a national operation for collection of objects containing radium for medical use.

FOCUS INFORMING THE PUBLIC

The management policy for sites and soils that are polluted or likely to be polluted was first based on large-scale survey of sites. Following the progress of other countries in this area, the policy of remediation and treatment of sites changed at the end of the 1990s, moving toward a policy of risk management according to use. Based on the examination and management of risk, more than on the level of intrinsic pollution, this policy requires the memory of pollution and of remediation actions to be preserved, but also for the assignment of land uses that are compatible with residual pollution after treatment of the site.

In order to improve public information on sites polluted by radioactivity and to supervise construction on such sites to ensure the absence of health risks (*see Article L. 556-1 of the Environmental Code*), the French legislature created the Soil Information Sectors (SIS).

For construction or housing subdivision projects, the SIS requires a soil study, the contents of which are detailed in Article R. 556-2 of the Environmental Code.

Two databases, accessible from the government's *Géorisques* portal, list the sites polluted by radioactivity:

- **the Map of former industrial sites and service activities** (Casias) (https://www.georisques.gouv.fr/donnees/bases-de-donnees/inventaire-historique-de-sites-industriels-et-activites-de-service), which lists all abandoned or non-abandoned industrial sites that may generate environmental pollution, in order to preserve the memory of these sites and provide useful information for urban planning, land use, and environmental protection stakeholders;
- **a space that lists polluted or potentially polluted sites** (https://www.georisques.gouv.fr/donnees/bases-de-donnees/sites-et-sols-pollues-ou-potentiellement-pollues) requiring preventive or remedial action by public authorities.

Finally, as part of monitoring population exposure and informing the public, the average individual doses received by the population as a result of authorised nuclear activities were made public. Estimated at least every five years by the French Institute for Radiation Protection and Nuclear Safety (IRSN), this information is the subject of a public report published on the Institute's website (*Article R. 1333-27 of the French Public Health Code*).

Although there was never a regulatory obligation, the *National Inventory* made it possible to identify and preserve the memory of sites polluted by radioactivity on French territory until 2015.
Every year, Andra identified all sites polluted by radioactivity, in collaboration with the French Nuclear Safety Authority (ASN) and the General Risk Prevention Directorate (DGPR). From now on, in agreement with the ministry in charge of the environment, information on polluted sites is no longer reported in the *National Inventory*, but is grouped together on the *Géorisques* information portal.

The *National* Inventory focuses only on radioactive materials and waste. Therefore, the waste from clean-up of polluted sites is always listed.

MANAGING SITES POLLUTED BY RADIOACTIVITY

The management of sites polluted by radioactive substances is part of the general framework of the national policy for the management of polluted sites and soils (*Articles L. 556-1 to L. 556-3 and R. 556-1 to R. 556-5 of the Environmental Code*), the implementation of which is detailed at the end of the note dated 19 April 2017 on polluted sites and soils.

The “polluter pays” principle defined by the Environmental Code provides the general principle for managing polluted sites. When the party responsible for a polluted site is identified, it takes the measures necessary to ensure clean-up. Andra can also intervene on these sites in the role of project owner assistance. If the polluter is solvent, they must finance clean-up of the polluted site clean-up and redevelopment operations until the waste is disposed of.

When the polluter defaults (the site is then "orphaned"), the public authorities take over clean-up and remediation of these sites by involving IRSN and Andra. Most polluted legacy sites are sites where the responsible party has defaulted.

FOCUS — ANDRA'S PUBLIC SERVICE MISSION

The Programme Act of 28 June 2006 defines Andra's missions, including that it must ensure *"(...) the collection, transport and handling of radioactive waste, and the remediation and, if necessary, management of sites polluted by radioactive substances, on request and at the expense of those responsible for the sites"* (*Article L. 542-12 of the French Environmental Code*).

The role of the “polluted sites” task force created within the Agency is to lead and coordinate the collection and handover of radioactive objects for domestic use and the clean-up of sites polluted by radioactivity where the responsible party has defaulted. Acting on behalf of the project owner, the polluted site taskforce builds the remediation scenarios, obtains the necessary funding and authorisations, and then specifies the field operations and ensures they are carried out with support from a network of specialised contractors.

Several stakeholders interact and collaborate to manage the polluted sites:

- IRSN carries out initial diagnostics of the polluted sites and evaluates the risks to the public and the environment;
- ASN (French Nuclear Safety Authority) defines the technical rules governing radioactive waste disposal and ensures that the sites identified as contaminated are made safe for the public and the environment. It also monitors the application of the radiation protection rules for those working on the clean-up jobsites;
- the CNAR (National Advisory Committee for Public Funding in the Field of Radioactivity), created in 2007 by Andra’s Governing Board, gives an opinion on the use of public funding solely for “orphaned” sites, whether or not site clean-up is needed, the priorities for allocating the funds, the strategies for managing the polluted sites, and the waste handling issues. The CNAR is chaired by an expert in the clean-up of polluted sites and includes, among others:
  - representatives of the Safety Authority (ASN) and the ministries responsible for Andra;
  - representatives of public technical institutions (ADEME, IRSN);
  - representatives of the non-profit world (two organisations for the defence of the environment: Robin des Bois and France Nature Environnement);
  - a representative for elected officials;
  - and two qualified persons (a representative of a public land institution and a clean-up specialist).

Andra can provide project owner or project owner assistance, and completes the detailed characterisation of the site if necessary, in particular with regard to deeper pollution, then establishes the clean-up project and presents it to the stakeholders (validation by the CNAR depending on the circumstances). It also handles the resulting radioactive waste. The prefecture orders and regulates the clean-up work by prefectural decree and ensures its monitoring with support from DREALs (Regional Directorates for the Environment, Planning, and Housing).

Diagnostics are carried out on a site when there is a suspicion of contamination. This knowledge-gathering phase must be carried out in detail, including a historical and vulnerability literature review.

The purpose of the field characterisation is first to confirm or deny the presence of the suspected radioactive pollution and then, if necessary, to determine its location, type, and level in order to define the purpose of clean-up.

Once exposure is identified, it is necessary to determine whether or not the pollution observed is compatible with the established or planned use of the site and to find exposure reduction actions that are appropriate and proportionate to the situation encountered.

Demolition site for a contaminated house in Gif-sur-Yvette

The definition of the management objectives must be established in accordance with the optimisation principle applicable in radiation protection, taking into account the characteristics of the pollution, the type of existing or planned uses and the redevelopment plan.

In accordance with the principles of radiation protection specified in Article L. 1333-2 of the French Public Health Code, the cost/benefit balance, which must be established as soon as it is part of a management plan, must first aim to reduce, as much as reasonably possible, the exposure of people to ionising radiation resulting from the use of the site and from remediation operations.
Therefore, depending on the specificities of each polluted site and the future use of the site, it is possible either to completely clean up the site to make it suitable for all uses and without constraint, or to maintain residual pollution and control its impact by limiting the possible uses, putting in place barriers. The continued existence of these precautions is ensured by the integration of easements in urban planning documents. For example, construction or planting may be prohibited.

After remediation of a site, the memory of past pollution and remediation is preserved, in particular using the Basias and Basol databases and the SIS (*see Focus on page 141).*

In practice, once pollution is identified, the site is secured by the installation of fences, barriers, and adequate signage. When Andra is in charge of cleaning up a site, it does so in several steps:

1. **preparation**: protections are in place (e.g. vinyl sheets, airlocks, dust extraction, etc.) to prevent any dispersal of contaminated substances into the environment;

2. **remediation work:** the contaminated materials are removed and packaged by qualified and specialised personnel;

3. **handover:** the radioactive waste generated by clean-up (soil, rubble, objects, etc.) is directed to the suitable waste management solution (disposal or storage facility);

4. **Renovation and redevelopment:** work is carried out if necessary.


Clean-up work at Institut Curie

MANAGING RADIOACTIVE WASTE

The clean-up of polluted sites produces radioactive waste.

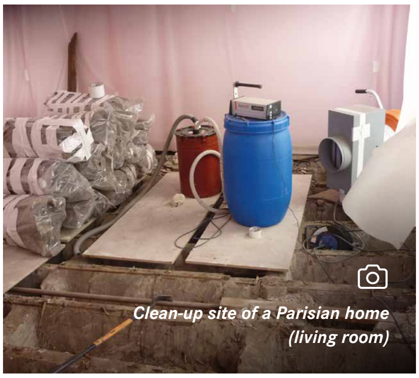
The volumes and characteristics of the radioactive waste which may be produced during clean-up of the polluted site are evaluated as soon as the clean-up scenarios are defined. Given the type of polluted sites, the waste produced consists mainly of rubble, soil, wood, and technological waste (work suits, tools, etc.).

The waste sorting operations are devised and carried out with the aim of reducing the quantity of radioactive waste generated and observing the acceptance criteria and conditioning modes of the disposal or storage facilities. The waste must therefore be characterised before shipment to ensure that it is handed over to the appropriate waste management solution.

The waste generated during clean-up of a polluted site is mostly very low-level waste (VLLW), which is dispatched, as is, to Cires (Andra's Industrial Facility for Grouping, Storage and Disposal) or disposed of *in situ* if the waste quantities are too large. More rarely, LLW-LL waste may also be produced. In this case, it will be dispatched to Cires for storage, pending the opening of a suitable disposal facility.

Chemical pollutants subject to particular acceptance conditions at the disposal facilities must be given specific attention.

The waste is conditioned in big bags or injectable metal containers, sometimes after being temporarily placed in smaller drums. Because the sites are located in urban areas (most sites are in Paris or Île-de-France département), it is sometimes necessary to use 120-litre drums first, which are easy to handle. These drums are transported to an industrial buffer facility where they are emptied, and the waste is reconditioned in its final packaging.


Clean-up site of a Parisian home (living room)

EXAMPLES OF CLEAN-UP WORKSITES CARRIED OUT BY ANDRA

PROPERTY OF THE FORMER SOCIÉTÉ NOUVELLE DU RADIUM IN GIF-SUR-YVETTE

In the early 1900s, the Société nouvelle du radium was created in the municipality of Gif-sur-Yvette.

It included:

- a Radioactive Substances Testing Laboratory (LESR) located in the Coudraies neighbourhood;
- a radium extraction plant located in the nearby Clos-Rose neighbourhood.

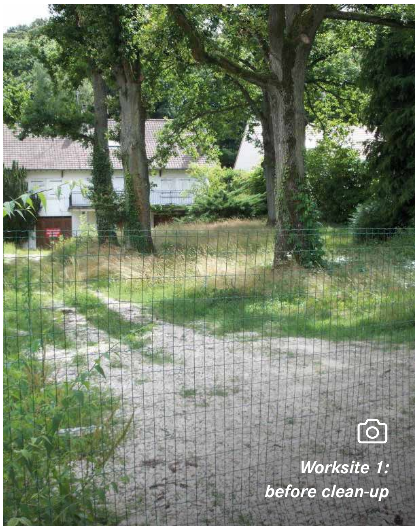
The plant operated between 1913 and 1935 and the laboratory until the late 1950s. When it closed, the buildings were demolished to make way for a housing subdivision, and the soil presented several areas of pollution.

It is in this context that Andra intervened on two residential plots in this neighbourhood to carry out clean-up work. Each of these plots contained a house built in the 1960s, on already polluted soil, with a radon content in the homes that was higher than the health recommendations.

Prior technical and economic studies showed that it was not possible to remove the polluted land under the houses without demolishing them. For this reason, the State decided to buy back the two plots from their owners and allocate them to "green space" use.

The remediation project, which began in September 2013, lasted one year. After demolition of the houses, the most polluted soil was extracted and eliminated, and the low residual pollution present at the bottom of the excavation was contained under a layer of clean earth between 50 cm and several meters thick. Restrictions on use are in force in the neighbourhood to prevent digging beyond the clean soil layer (urban planning documents and land register).

In total, the waste produced was 339 m^3 of VLLW waste which was sent to Cires for disposal, and 0.2 m^3 of LLW-LL waste sent to Cires for storage.



Worksite 1: before clean-up

Worksite 1: after clean-up

FORMER ORFLAM-PLAST FACTORY IN PARGNY-SUR-SAULX

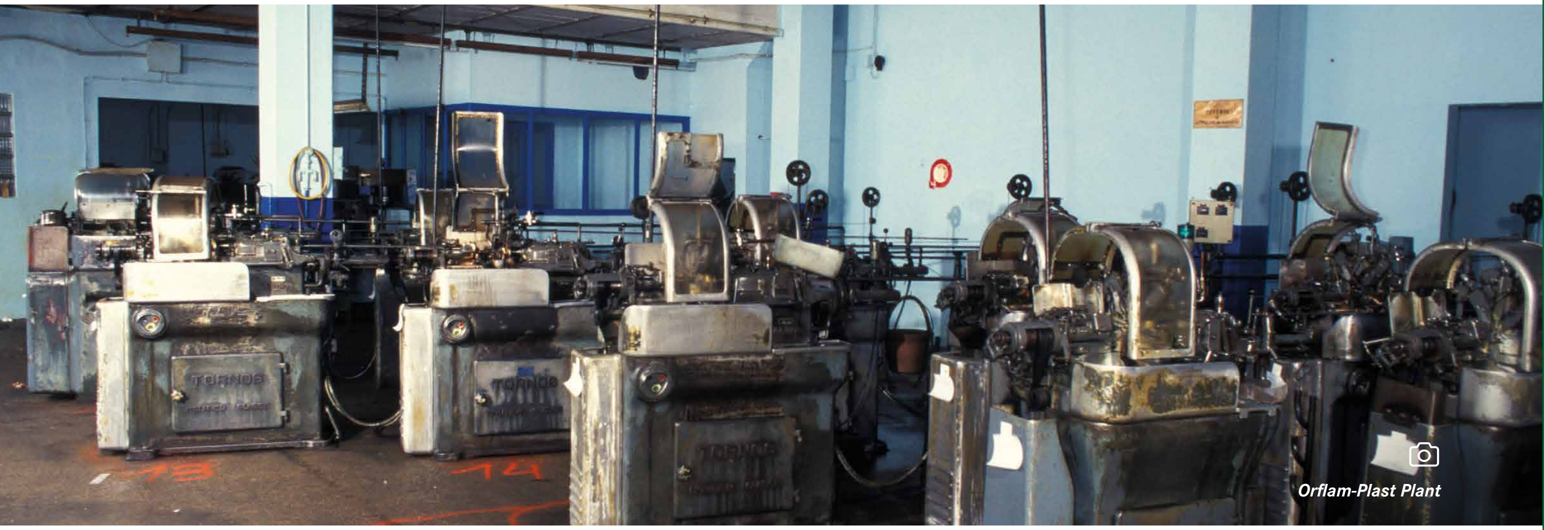
Orflam-Plast manufactured cigarette lighters until February 1997, when it ceased operations following a compulsory liquidation.

These activities concerned, in particular, between 1932 and 1967, the processing of a thorium-rich ore, monazite, from which cerium was extracted. Cerium was necessary for the manufacture of lighter flints. This extraction led to the production of thorium 232 residue, a long-lived low-level radioactive material, concentrating the radioactivity initially present in the monazite. These residues contaminated the site of the plant, but also the banks of the Saulx, a river that borders the site. The State became the owner of the site in 2009 to compensate for the absence of an owner. As early as 1997, the most urgent safety work was carried out. This work consisted in covering the contaminated banks with an impermeable screen, in order to protect the public likely to spend time in the area. In 2008 and 2009, two polluted areas outside the site were identified a few hundred metres from the plant: La Peupleraie.

According to the testimony of a former employee, treatment waste rich in thorium 232 was buried in this area and near the Gravière pond. These areas were immediately subjected to safety measures: marking and fencing off. To complete the search, an extensive radiation survey was carried out in June 2009. This survey did not reveal any other contaminated areas. In December 2009, the CNAR gave its approval for remediation of the Gravière pond, safety works on the Peupleraie site, demolition of the factory buildings, and containment of the demolition rubble *in situ* with a permanent containment solution.

The contaminated land around the pond was partially extracted and evacuated. This treated area is now open to the public and fishing is authorised. The trees in the Peupleraie were cut down, milled on site and covered with a layer of clay. Finally, all the buildings of the old factory were demolished. The very low-level radioactive rubble from the demolition was collected on site, under thousands of tonnes of clay and soil, ensuring sustainable and safe containment for the residents. The hydraulic structures were rebuilt and the banks of the Saulx were consolidated locally.

Aerial view of the former Orflam-Plast contaminated site in Pargny-sur-Saulx after remediation



Orflam-Plast Plant

Report 5

Radioactive waste from the medical sector

A BRIEF HISTORY

RADIOTHERAPY

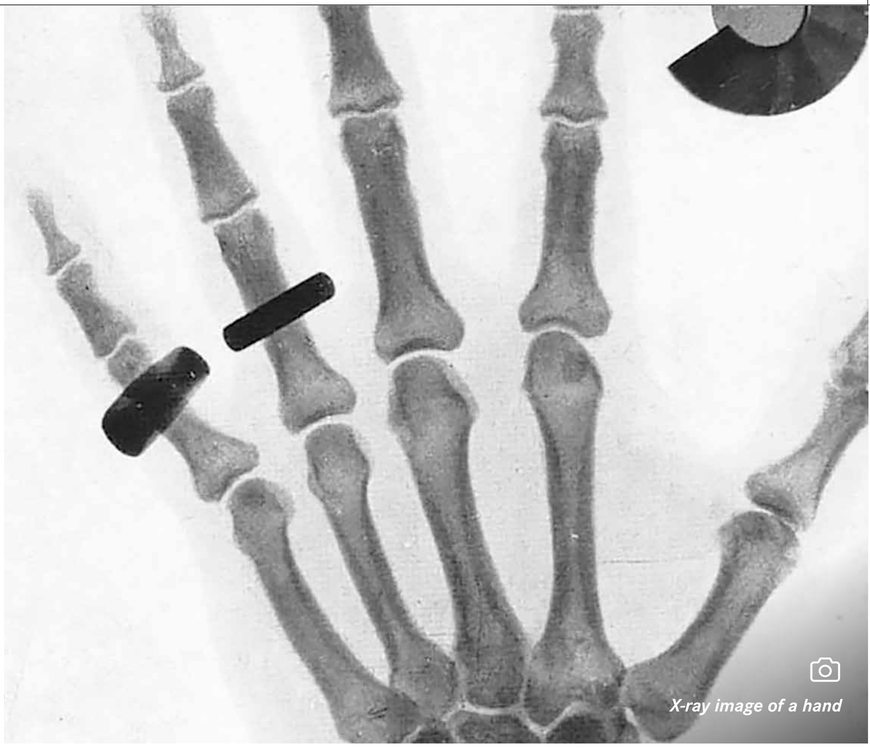
The discovery of X-rays by Röntgen in 1895 marked the beginning of radiotherapy, because one year later, doctors used these rays for the first time to treat a tumour. Following the discovery of the phenomenon of radioactivity in 1896 and radium in 1898, Pierre Curie and Henri Becquerel published a paper[1] in 1901 which testified to the energetic effect of radium rays on the skin, causing skin lesions. This note was the starting point for the use of radium in medicine to cure dermatological infections and cancers. X-ray and radium treatments quickly underwent their first developments.

Doctors first used devices consisting of a cathode and an anode emitting X-rays to treat tumours. However, X-rays from these tubes have only low energy and do not penetrate deep under the skin. They were therefore mainly used to treat skin cancers. Sometime later, with the use of radium (an extremely rare element), treatments for other types of cancer began to be developed. Radium emits higher-energy radiation that can reach deeper tumours.

Small plastic bags containing radium powder placed in contact with the skin were first used by doctors to treat tumours and skin lesions. Then, in 1920, radium was conditioned in small tubes and needles.

This was the beginning of brachytherapy, a technique consisting in the treatment of cancers with radioactive sources placed in contact with tumours, or implanted directly into these tumours.

With the development of man-made radioactivity in 1934, the use of radium gradually declined in favour of artificial radioelements which were more suitable for treatments and less expensive. Thus, new radioactive sources were made available to radiotherapists, who replaced radium with caesium-137, iridium-192, and iodine-125.

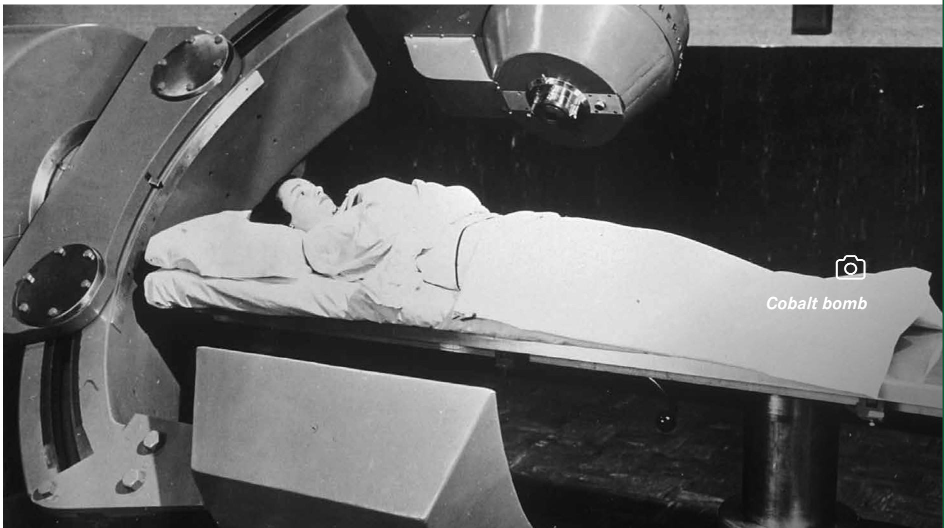

X-ray image of a hand


Radium needles

Starting in 1955, cobalt sources producing more penetrating high-energy radiation were used in "cobalt bombs" allowing better irradiation of tumours while limiting the damage to healthy tissues. In the late 1960s, "cobalt bombs" were replaced by particle accelerators, which performed better and are still used today.

DIAGNOSTICS IN NUCLEAR MEDICINE

In 1913, Georg von Hevsey used the radioactive tracer method for the first time: he watered plants with water containing a radioelement, lead-210, and followed its movement in plants by measuring radioactivity in the roots, stems and leaves. Eleven years later, in 1924, two doctors injected patients with bismuth-214, used as a tracer to determine the speed of blood circulation by measuring the radioactivity in the patient's body: this was the beginning of nuclear medicine. Diagnostic radiology only really developed with the discovery of artificial radioelements in 1934 and the discovery of technetium-99m in 1937, still today the most widely used radionuclide in nuclear medicine because of its short half-life (six hours), cost, availability, and ability to be associated with many molecules.


Cobalt bomb

1 Physiology – Physiological action of radium rays. Note by Henri Becquerel and Pierre Curie.

THE USE OF IONISING RADIATION

THERAPEUTIC USES (RADIOTHERAPY)

Radiotherapy is a method of treating cancers using ionising radiation from radioactive sources. Along with surgery and chemotherapy, it is one of the major 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: irradiation of cancer cells leads to their destruction and blocks their ability to multiply while preserving healthy tissues and nearby organs as well as possible. Radiation directed towards cancer cells creates lesions on these cells and induces alterations in their DNA. Thus, the cells can no longer multiply, which leads to cell death.

The different radiotherapy techniques are described below.

EXTERNAL RADIOTHERAPY

External radiotherapy consists in irradiating the cancer cells with radiation emitted by a source located at a distance from the patient. The radiation passes through 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 can also be used, which is called proton therapy.

External radiotherapy is used to treat a large number of cancers such as cancers of the breast, lung, blood, etc.

There are several external radiotherapy techniques, detailed below, which are constantly being modernised to improve treatments and reduce side effects, mainly due to irradiation of healthy cells near cancer cells:

- the most used today is **3D conformational radiotherapy** which matches as precisely as possible the volume in which the rays are directed to the volume of the tumour, sparing the neighbouring healthy tissues as much as possible;
- **intensity-modulated conformational** radiotherapy is based on the same principle as 3D conformational radiotherapy but by modulating the dose rate delivered;
- **respiratory gating for radiotherapy** takes into account the movements of the patient, and therefore of their organs, due to breathing. This radiotherapy technique delivers radiation according to the movement of the organs and therefore improves the accuracy of the treatments;
- **stereotactic radiotherapy** is a high-precision technique that uses microbeams of photons or protons, making it possible to irradiate small volumes at high doses. In particular, it is used to treat brain tumours;
- **tomotherapy** provides radiation adapted to the tumour, sparing neighbouring organs as much as possible. The particle accelerator rotates around the patient as the patient moves longitudinally;
- ***cyberknife*** is a technique where many beams converge with great precision on the tumour, thus minimising the impact on healthy tissues.

The last two techniques are intended to treat tumours whose location does not allow other radiotherapy techniques to be used.

Tomotherapy device


Cyberknife device

BRACHYTHERAPY

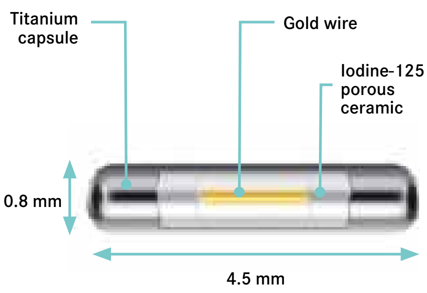
Brachytherapy is an irradiation technique consisting in introducing radioactive sources directly in contact with or inside the tumour.

There are three types of brachytherapy:

- **low-flow brachytherapy**: this requires the patient to be hospitalised for several days. It delivers dose rates ranging from 0.4 to 2 Gy/h. Iridium-192 sources are in the form of wires (0.3 to 0.5 mm in diameter and 14 cm in length, maximum). They are placed on the patient in a protected chamber and left for the duration of the hospitalisation. Low-flow brachytherapy can be used to treat eye, ENT, breast, or gynaecological cancers. It is also used for the treatment of prostate cancers: sealed sources of iodine-125 a few millimetres long are permanently implanted in the patient's prostate due to the rapid decay of their radioactivity. The radioactive sources emit rays that destroy cancer cells;
- **medium-flow pulsed brachytherapy:** this treatment delivers doses identical to low-flow brachytherapy but over shorter periods of time with a small source of iridium. Unlike low-flow brachytherapy, the patient does not continuously wear the sources. This technique is expected to replace low-flow brachytherapy because it reinforces the radiation protection of personnel who can intervene without being exposed, but also improves the level of comfort of the patient. It can be used to treat ENT, breast, or gynaecological cancers;
- **high-flow brachytherapy:** the dose rate is high, around 12 Gy/h and the treatment time is very short. The source used is a small source of iridium. This technique is mainly used to treat cancers of the oesophagus, bronchial tubes, breast, etc.

The radionuclides used in brachytherapy are different from those used in nuclear medicine. They have a higher energy and emit beta and gamma radiation. The doses given to patients are higher and they vary depending on the type of cancer, the stage of the cancer, the organ to be treated, the age of the patient, etc.

IODINE-125 SEEDS FOR PROSTATE BRACHYTHERAPY



X-ray of the prostate with visualisation of iodine-125 seeds

METABOLIC RADIOTHERAPY

Metabolic radiotherapy is a radiotherapy technique implemented in nuclear medicine (use of non-sealed sources) during which the radionuclides are directly injected into the patients. This technique consists in locally irradiating small tumours or tumours spread throughout the body with a radiopharmaceutical.

The radiopharmaceutical is a molecule carrying a radioactive beta-minus emitting atom that selectively binds to the cells to be treated. It is injected into the patient. This is the same principle as for scintigraphy, but with much higher quantities (the dose delivered is greater than 50 Gy). The radiopharmaceutical is injected orally or intravenously. It selectively binds to the cells to be treated and the beta electron emitted during its disintegration deposits its energy inside the cell by ionisation, which leads to its destruction.
Due to the limited path of beta emitters in matter, the radiation remains confined to the tissues to be treated.

Iodine-131 is used for the treatment of hyperthyroidism and thyroid cancers.
The dose administered is very high and requires hospitalisation in a room with shielded walls and windows to protect personnel from ionising radiation. Iodine-131 is preferentially captured by the thyroid and thus destroys the thyroid cells while limiting the irradiation of nearby cells.

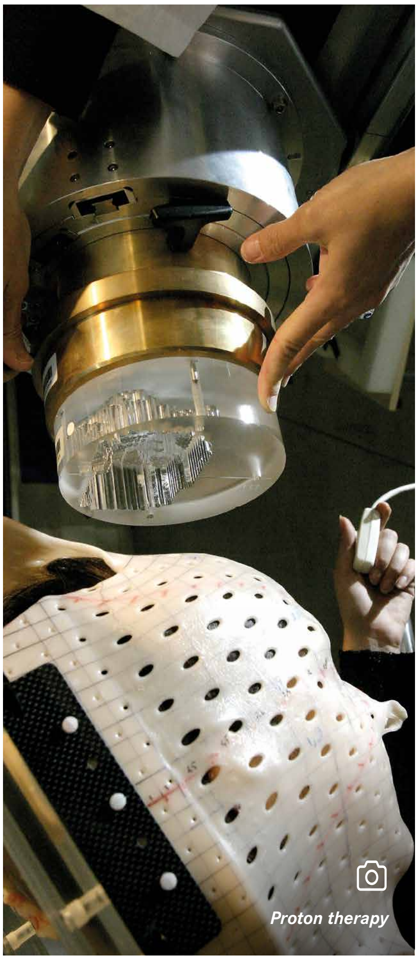
Today, the use of alpha-emitting radiopharmaceuticals is on the rise. They have the advantage, compared to beta emitters, of delivering a large amount of energy over a short distance and thus irradiating the tumour while limiting the exposure of healthy cells. As an example, radium-223 dichloride (also called Xofigo®), intended for the treatment of bone metastases of prostate cancer, binds to newly formed bone (like calcium) and destroys the cancer cells while limiting the irradiation of healthy tissues.

PROTON THERAPY

This technique consists in treating tumours with accelerated protons, unlike conventional radiotherapy, which exclusively uses photon or electron beams. It is a precise technique that spares healthy tissues, which is why it is used for tumours located near critical and radiation-sensitive organs such as the eye or the brain. It is also used in paediatrics.

The principle of proton therapy is to direct the beam of accelerated protons from the particle accelerator towards the patient's tumour. The protons are adjusted to reach the tumour and release as much of their energy as possible into the tumour. Beyond the tumour, healthy tissues are not affected.

This technique is very expensive because it requires complex and sophisticated technologies. In France, there are currently only two proton therapy facilities.



Proton therapy

DIAGNOSTIC USES

Diagnostic techniques in nuclear medicine are functional imaging techniques: they show the biology at work in the cells (and not the anatomy, such as an X-ray or a scanner).

SCINTIGRAPHY (*IN VIVO* DIAGNOSIS)

Scintigraphy is a so-called "functional" medical imaging technique that makes it possible to observe the structure and functioning of an organ and thus to detect many different disorders of the organs and pathological processes such as inflammation, tumour, or infection, etc. It is complementary to so-called morphological imaging such as MRI or CT scan, which take a photograph of the body without providing information on how it is functioning.

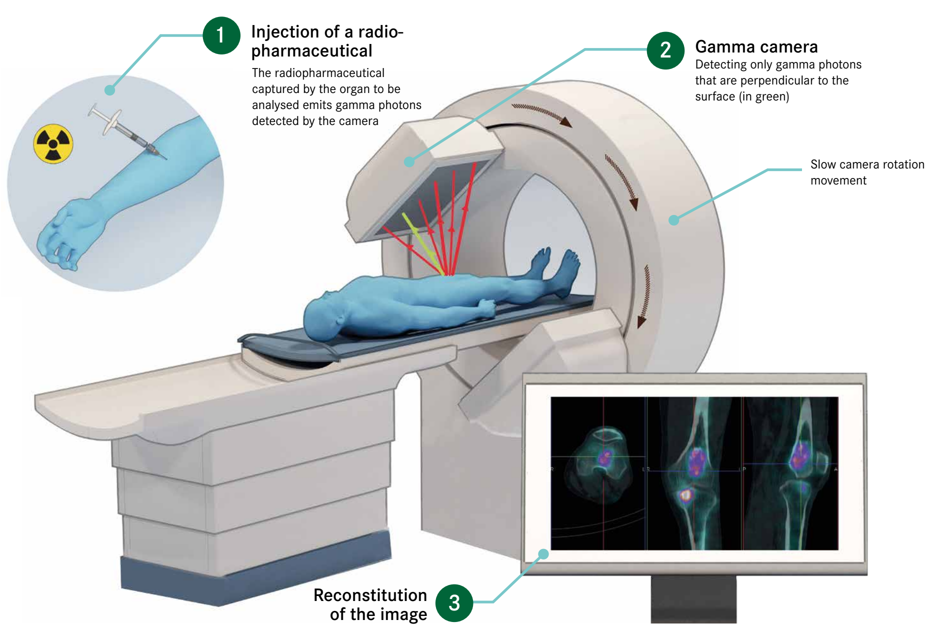
The principle of scintigraphy is to administer a radioactive substance, called a radiopharmaceutical, to the patient intravenously, by inhalation or by ingestion in small quantities. The radiopharmaceutical selectively binds to the organ or tissue to be explored. The injected radiopharmaceutical is a gamma radiation emitter chosen according to the organ or pathology to be observed. It may be a radionuclide alone or bound to a molecule or a cell (hormone, antibody). The radioelements used most often have a very short half-life and are quickly evacuated from the body.
By way of example, the half-life of technetium-99 m, widely used in scintigraphy, is six hours and it is rapidly excreted from the body in urine. The activity injected into the patient varies depending on the examination.

Gamma radiation emitted by the radiopharmaceutical bound to the organ or tissue to be analysed is detected using a special gamma camera. The recording of a succession of images makes it possible to visualise the functioning of the organ or tissue analysed. Photographs can be taken immediately after injection, after a few hours, or a few days and lasts between 5 and 30 minutes.

The gamma camera consists of a collimator which is a thick plate of lead or tungsten pierced with thin parallel channels, a crystal, and a photomultiplier in the form of an electron tube that detects light signals. The collimator selects the gamma photons emitted by the radiopharmaceutical that are perpendicular to the surface of the crystal. The thallium-doped sodium iodide crystal stops the gamma photons and converts some of the deposited energy into light scintillation detected by the photomultipliers that convert the light signal into an electrical signal. The energy and position of the gamma ray that has interacted in the crystal are then determined.

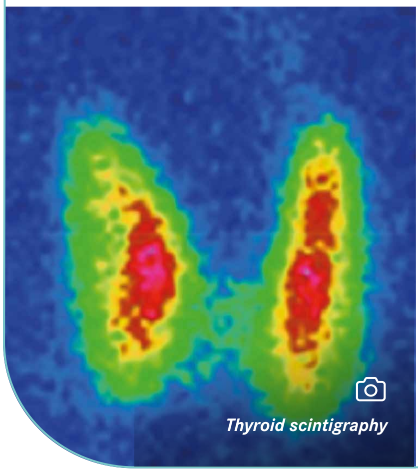
The injection of a radiopharmaceutical has no effect on the body because of the small amount administered.

EXAMPLE OF HOW SCINTIGRAPHY WORKS



FOCUS — EXAMPLES OF SCINTIGRAPHIC EXAMINATIONS

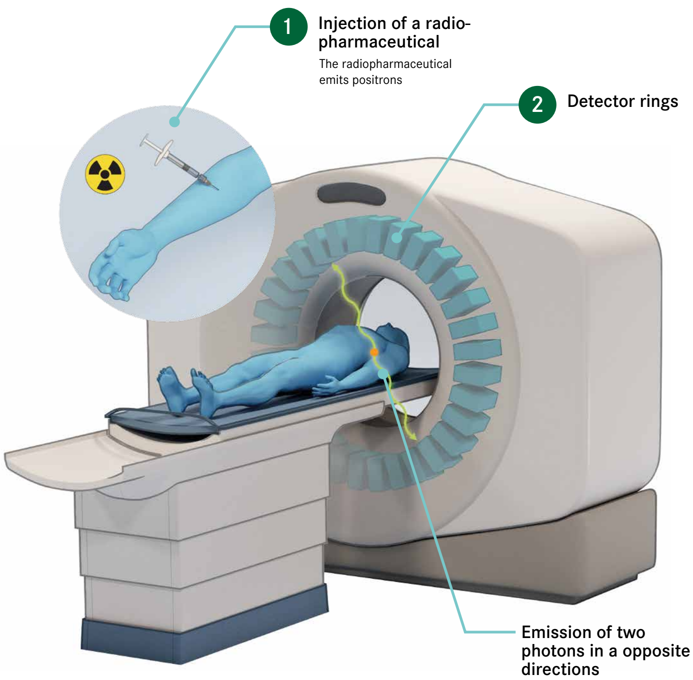
Thyroid scintigraphy makes it possible to observe the metabolism of iodine in the thyroid gland. Iodine-123 or technetium-99m are injected into the patient and will selectively bind to the thyroid. The scintigraphy thus makes it possible to visualise the regions of the thyroid that capture the least radiopharmaceuticals (cold nodules) or that capture the most radiopharmaceuticals.



Thyroid scintigraphy

Lung scintigraphy makes it possible to study the functioning of the lungs: ventilation of the lungs (circulation of air) and perfusion (circulation of blood). Ventilation scintigraphy consists in administering, by inhalation, an aerosol containing a known amount of radioactive product (xenon-133, krypton-81m, technetium-99m) to the patient. The images taken using the gamma camera make it possible to highlight a defect in the binding of the inhaled radiopharmaceutical, which results in a lung area that does not receive air. Perfusion scintigraphy consists in injecting the radiopharmaceutical intravenously, which then diffuses into the body. When the lung is normally perfused, radiopharmaceuticals are distributed homogeneously in both lungs. When an artery is blocked by a clot, the particles do not penetrate and are not detected by the gamma camera: this is the case with pulmonary embolism.

EXAMPLE OF HOW POSITRON EMISSION TOMOGRAPHY WORKS



POSITRON EMISSION TOMOGRAPHY (PET) (*IN VIVO* DIAGNOSIS)

Positron emission tomography (PET) is scintigraphy using positron-emitting radioelements such as fluorine-18, bromine-76, or oxygen-15. Unlike the photon-emitting radioelements used in conventional scintigraphy, positron emitters are light, abundant, and easier to use. After a short journey through the body, the positrons disappear by emitting two gamma rays, emitted back to back. The simultaneous detection of the two gamma rays makes it possible to locate the emission zone and to draw up a map of the binding of radioactive atoms in the cells. The PET scan requires a suitable scintillation camera. This imaging technique makes it possible to detect cancers early, monitor treatment or monitor cancers. It is also used to diagnose degenerative brain diseases such as Alzheimer's disease, inflammatory or infectious diseases.

To diagnose cancers, the radiopharmaceutical most often used is fluorine-18 in the form of sugar comparable to glucose, 18F-FDG (Fluorine-18 Fluorodeoxyglucose). It is injected into the patient intravenously, and will bind to cancer cells. Cancer cells are constantly multiplying, so they need a lot of energy and therefore a lot of glucose. They will consume an abnormally high amount of glucose compared to healthy cells.
The radiopharmaceutical binds in large quantities to cancer cells, which can then be detected with the PET camera.

PET scan

RADIO-IMMUNOLOGY (*IN VITRO* DIAGNOSIS)

Radio-immunology is a bio-medical analysis technique. Unlike in *vivo* diagnosis, the radio-element is not injected into the patient. This technique makes it possible to measure the amount of compounds (hormones, drugs, enzymes, etc.) in the biological fluids previously collected from the patient (blood, urine, saliva, etc.). However, today, the use of radio-immunology is increasingly challenged by analysis techniques that do not use radionuclides, which are simpler to implement. Radio-immunology is an assay technique that is generally based on immunological reactions (specific antibody-antigen reactions). To determine the amount of antigens in the patient sample, a known amount of antigens marked with a radionuclide and a small amount of specific antibodies are added to the medium. The marked antigen is used to determine the amount of antigen in the sample.

Antigens, whether marked or not, bind to antibodies. Since there is an excess of antigens in the sample compared to antibodies, some of the antigens will be bound to the antibodies and the others will remain free. The free antigens are separated from the bound antigens and the amounts of free and bound marked antigens are measured to determine the amount of unmarked antigens present in the sample taken from the patient.

RADIOISOTOPE PRODUCTION

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 diagnosis and 10% for therapy. The radioelements used in medicine are produced with particle accelerators (cyclotron and linear accelerator) or by reactors.

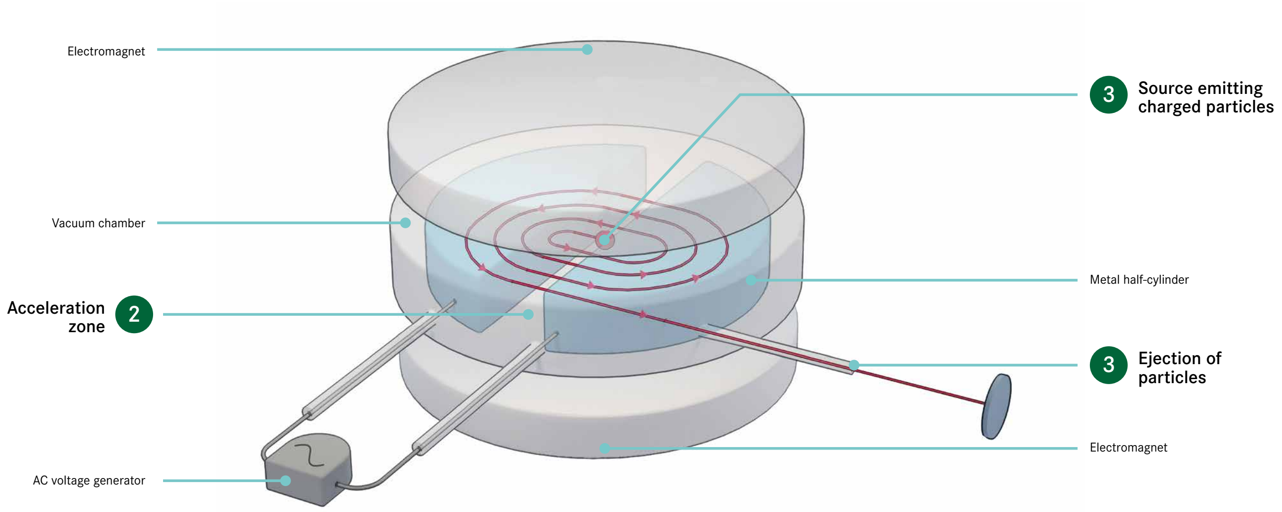
Technetium-99m, used in 75% of scintigraphic examinations, is obtained by beta decay of molybdenum-99, itself produced by irradiation in a nuclear reactor of uranium enriched to nearly 20%. After irradiation, the molybdenum is extracted from the reactor and then placed in a generator that allows for extraction of technetium-99m. Due to its higher radioactive half-life (66 hours for molybdenum-99, compared to six hours for technetium-99m), molybdenum can be stored longer than technetium. Generators are distributed in hospitals once or twice a week. The technetium can then be extracted from this generator and mixed with injectable molecules. Fission molybdenum-99 is mainly produced by six research reactors around the world.

Some radioisotopes are produced in particle accelerators called cyclotrons. They are composed of two metal half-cylinders facing each other, separated by a space, all in a high vacuum. A magnetic field perpendicular to the plane of the half-cylinders is applied, as well as an electric field in the space between the half-cylinders. A source, placed near the centre of the cyclotron, emits charged particles. These particles are subjected to the magnetic field that curves their trajectory and to the electric field that accelerates them. The particles therefore have an accelerated trajectory in the form of a spiral until they are expelled from the cyclotron to be propelled onto their target.

As an example, the source used in proton therapy is a system that ionises a hydrogen gas by heating it. Since the hydrogen nucleus consists of a single proton, it is separated

Osiris experimental reactor

EXAMPLE OF HOW THE CYCLOTRON WORKS



EQUIPMENT STERILISATION USING RADIATION

Radiation is also used in the medical sector to sterilise equipment used in operating theatres and for care: syringes, needles, surgical gloves, compresses, implants, bags for intravenous solution, etc. Radiation causes lesions in DNA molecules and thus leads to the destruction of various organisms (fungi, insects, parasites, moulds, microbes, and bacteria). Sterilisation is carried out in a sterilisation plant, generally using sources of cobalt-60 or caesium-137, high-intensity gamma emitters, and lasts a few seconds.
This method of sterilisation is ideal for sterilising heat-sensitive materials. Therefore, the material can be directly sterilised in its packaging.

Before a blood transfusion, the blood bags are irradiated in hospitals using irradiators to eliminate the cells that may lead to death of the patient.

Whether for the sterilisation of medical equipment or the treatment of blood bags, radiation has no effect on the product itself.

Blood irradiator

FOCUS — PLUTONIUM-238 PACEMAKERS

The first pacemakers operated with a battery that had a limited lifespan and required regular replacement (approximately every 10 years). To improve on this flaw, plutonium-238 pacemakers were developed in the 1970s. Their lifespan is much longer than the pacemakers of the time (about 40 years), so they can function until the death of the patient. These pacemakers use the thermal energy from alpha decay of the plutonium, transformed into electricity to power the pacemaker. Plutonium-238 is enclosed in a multi-layer metal housing to protect the patient from radiation. Plutonium-238 pacemakers have been abandoned in favour of iodine/lithium battery pacemakers because of the risk of irradiation in the event of failure of the hermetically sealed housing. Today, these pacemakers are still functioning in some patients. When the patient dies, it is removed and returned to the supplier, as it is considered a sealed source.

Plutonium pacemaker

ASN inspection in the medical sector

Nuclear activities relating to the manufacture, possession and use of radionuclides and products or devices containing them, as well as possession and use of a particle accelerator are subject to authorisation.
Authorisation requests are submitted to the French Nuclear Safety Authority (ASN). ASN is responsible for monitoring radiation protection in the medical field. Every two years, it carries out inspections at radiotherapy centres (compliance with rules relating to the radiation protection of workers and patients, the layout of premises, equipment and source management, quality assurance). ASN also carries out inspections in nuclear medical services. The summaries of inspections can be consulted on the ASN website (asn.fr).

A person competent in radiation protection is appointed at each establishment to ensure the radiation protection of workers, which consists of: assessing risks, communicating on good practices, setting up zoning, training workers, and monitoring dosimetry. Radiation protection patients is also ensured.

RADIOACTIVE WASTE FROM THE MEDICAL SECTOR

WASTE TYPE

Radioactive waste from the medical sector produced following *in vitro, in vivo* analyses or radiotherapy may be liquid or gaseous effluents or contaminated solid or liquid waste.

Liquid radioactive effluents mainly come from:

- rinsing in sinks reserved for radioactive effluents, called "hot sinks", non-disposable instruments used for preparations and injections (shielded syringe carriers, trays, etc.);
- sanitary facilities for patients who have received radionuclide injections (scintigraphy, PET scans) or sanitary facilities in protected rooms in the case of iodine-131 treatments.

Gaseous radioactive effluents come from radioelements potentially volatilised during the preparation and handling phases of unsealed sources or pulmonary ventilation examinations.

Contaminated waste is of two types: sharp or cutting waste (blades, needles, etc.) and other waste (gloves, compresses, cotton pads, tubing, reagent tubes, pipette tips, etc.). The particularity of this waste is that, in addition to the radioactive risk, it can present other risks: infectious risk, chemical or toxic risk.

Other waste: some waste may be generated. This includes, for example, lead jars carrying radiopharmaceuticals which, after checking for non-contamination, are evacuated to a specific waste management solution.

Medical waste in the National Inventory

Establishments that use radionuclides for diagnostic or therapeutic purposes in the field of medicine are required to send Andra an annual inventory of the radioactive waste they hold as of 31 December of the previous year, indicating the management solution used.

At the end of 2021, the volume of waste produced by medical activities was around 10,800 m³, of which 2,170 m³ are managed by decay at their production sites and 8,400 m³ are disposed of at Andra disposal centres.

Syringe carrier

Use of radioactive products in the medical sector

WASTE MANAGEMENT

Management of waste from the medical sector is governed by French law. The decree of 23 July 2008 approved ASN decision No. 2008-DC-0095, taken in application of the provisions of Article R.1333-12 of the French Public Health Code, which *"lays down the technical rules governing the disposal of effluents and waste contaminated by radionuclides, or likely to be so as a result of nuclear activity"*.

In healthcare facilities, "waste zoning" is implemented to distinguish areas where the waste and effluents that have been produced are contaminated or likely to be contaminated, from areas where the waste or effluents are conventional. It may be a simple lab bench (hot sink, for example), part of a room, or a room in its entirety.

The management procedures for contaminated waste and effluents are described for each establishment in a document, the management plan for contaminated waste and effluents.

This plan includes:

- the methods of production and management of radioactive effluents and waste (sorting, conditioning, and disposal methods);
- the provisions ensuring the disposal of waste and effluents and the associated inspection procedures;
- identification of the areas where effluents and waste are produced and stored;
- identification and location of effluent discharge points;
- monitoring of the effluent recovery network and the environment.

Contaminated waste and radioactive effluents are managed independently.

FOCUS — ARTICLE R.1333-16 OF THE FRENCH PUBLIC HEALTH CODE

"Effluents and waste contaminated by radionuclides or likely to be so, or activated as a result of nuclear activity are collected and managed, accounting for the characteristics and quantities of these radionuclides, the risk of exposure incurred, as well as the outlets selected.

The procedures for collecting, managing, and disposing of effluents and waste are documented by the person in charge of a nuclear activity in an effluent and waste management plan that is made available to the competent authority".

MANAGING CONTAMINATED WASTE

Waste contaminated by radionuclides poses a risk of exposure and contamination to personnel, patients, and the environment. It is therefore necessary to eliminate this waste using dedicated management solutions while ensuring control of the exposure and contamination risks.

Healthcare facilities that hold or produce contaminated waste are responsible for this waste up to its final disposal. Disposal of waste involves sorting, conditioning, characterisation, storage, collection, transport, and possible treatment.

Contaminated waste is separated from uncontaminated waste and then sorted according to its type, the radionuclides it contains, and the specific risks (infectious, carcinogenic, reprotoxic, etc.). It is conditioned in suitable packaging that protects against radiological risk (lead bin) and other risks (infectious, chemical, or toxic). The lead bins may therefore contain DASRI packaging (waste from healthcare activities with infectious and similar risks)[1]. Contaminated waste is managed according to the radioactive half-life of the radionuclides it contains.

Contaminated waste can 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, resulting from the successive decays of the radionuclides, are not themselves radionuclides with a half-life greater than 100 days. If the daughter products are radionuclides with a half-life greater than 100 days, the waste may be managed by radioactive decay if the ratio of the parent radionuclide half-life to that of the daughter radionuclide is less than the coefficient 10-7.

Sorting bins used in hospitals

DASRI packaging

1 DASRIs contain viable microorganisms or their toxins, which are known or reasonably believed to cause disease in humans or other living organisms due to their nature, quantity, or metabolism. Even in the absence of infectious risk, the following are also considered as DASRI: sharp or cutting materials and blood products.

Most radionuclides used for *in vivo* applications have a half-life of less than 100 days: technetium-99m, iodine-123, iodine-131, fluorine-18. The waste is stored in an enclosed place reserved for this type of waste. After a storage time at least 10 times greater than the half-life of the radionuclide with the longest half-life, the waste may be disposed of as non-radioactive waste after checking it for contamination. After decay, this waste is directed to:

- non-hazardous waste management solutions, in the absence of infectious and chemical risks;
- the waste management solution for healthcare activities with an infectious risk (DASRI), in the presence of an infectious risk;
- the appropriate management solution for waste with chemical or toxic risks, in the presence of chemical or toxic risks.

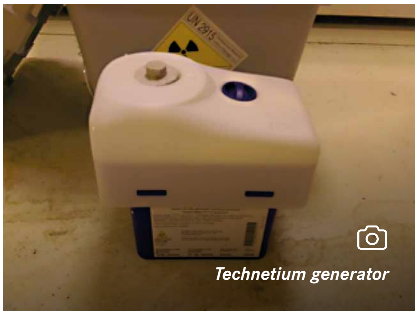
To ensure there is no contamination of waste destined for non-radioactive waste management solutions, detection systems (beacons, scanners) are installed in establishments with a nuclear medicine facility.

Radioactive waste storage room

Generators producing technetium used in nuclear medicine and delivered regularly to healthcare facilities can be used for a limited time. Due to radioactive decay, after about a week, the generator no longer produces enough technetium. It is then stored to decay for three weeks. When the level of radioactivity is low enough, it is returned to the supplier.

Waste that cannot be managed by decay, with a radioactive half-life of more than 100 days, is managed by solutions authorised for the management of radioactive waste. It is sent to Andra waste disposal facilities.

Technetium generator transport container



Technetium generator

MANAGING RADIOACTIVE LIQUID EFFLUENTS

Liquid effluents can be managed by radioactive decay if they meet the same criteria as those specified for contaminated waste.

Liquid effluents are directed to and stored in tanks before discharge to avoid direct release into the sewer system. At least two tanks collect effluents: when one is in the filling phase, the other is in the decay storage phase. Liquid effluents contained in the storage tanks are discharged into the sewer system if the activity is less than 10 Bq/L, except for rooms of patients treated with iodine-131, where the limit is 100 Bq/L. It should be noted that the voluntary dilution of radioactive liquid effluents before discharge is strictly prohibited.

After decay of a duration equivalent to at least 10 times the half-life of the radionuclide with the longest half-life, and after inspection, the effluents may be discharged into the environment. However, it should be noted that *"any discharge of wastewater other than domestic wastewater into the public network must be authorised in advance by the network operator"*.

The discharge of liquid effluents containing radionuclides with a half-life greater than 100 days is subject to the approval of ASN.

The establishment must carry out a technical-economic study, an impact study presenting the effects of discharges on the population, the environment, and workers and must define the procedures put in place to inspect the discharges and suspend them if necessary. On the basis of these elements, ASN may either authorise the discharge of effluents by setting conditions for discharge into the environment, or require their disposal at Andra disposal facilities if the impact on the environment, the population or workers is too great.

Decay tanks

MANAGING RADIOACTIVE GASEOUS EFFLUENTS

The discharge of gaseous effluents must be as low as reasonably possible. Filters, such as activated carbon filters, are installed. These filters are disposed of with the contaminated waste. When the gaseous effluents contain a radionuclide with a half-life greater than 100 days, ASN sets the conditions for discharge into the environment (monitoring of the activity discharged, monitoring plan, etc.), as for radioactive liquid effluents.

THE PARTICULAR CASE OF LINEAR PARTICLE ACCELERATORS

The dismantling of linear particle accelerators also induces waste. This is because some parts of the accelerator may become activated under the flow of particles. These parts must be identified, characterised, and their activity evaluated with a view to defining their management solution and their potential handover to Andra. However, since characterisation of long-lived pure beta emitters is difficult and costly, waste is generally stored *in situ* pending characterisation. Studies are under way to help characterise these metal parts.

Report 6

Sealed sources

PRESENTATION OF SEALED SOURCES

DEFINITION

A sealed radioactive source is a radioactive source where the radioactive substances are either permanently enclosed in a non-radioactive envelope or incorporated in solid form for the purpose of preventing any dispersal of radioactive substances, under normal conditions of use.

IRSN MANAGEMENT OF SEALED SOURCES

Sealed sources concentrate radioactivity and may pose a hazard in the event of prolonged contact or ingestion.

To ensure the safety of users, the public, and the environment, regulations require inspection of the conditions for holding, using, and disposing of sources from the time of their manufacture to their disposal or recycling.

In France, compliance with these regulations is monitored by IRSN (French Institute for Radiation Protection and Nuclear Safety - irsn.fr).

Requests relating to the possession and use of ionising radiation are examined and issued by the various competent authorities on radioactive sources (ASN, prefectures, DSND, etc.). The examination of authorisation applications concerning the manufacture and distribution of sources is centralised at a national level. IRSN centralises these authorisations as well as the movements of sources on French territory (acquisition, transfer, export, import, recovery, replacement, etc.).
From these computerised data, IRSN forms the *National Inventory* of Sources of Ionising Radiation.

IRSN is therefore the correspondent for the practical arrangements for any movement of sources: obtaining forms for the purchase of sources, recovery of sources, annual inventory, etc.

ROLE OF SEALED SOURCES IN THE NATIONAL INVENTORY OF RADIOACTIVE MATERIALS AND WASTE

Not all sealed sources present on French territory are listed in *the National Inventory of Radioactive Materials and Waste* prepared by Andra. Only sources that are disused (*see page 163*) or for which the holder no longer has a use are considered waste and may, as such, be inventoried by Andra.

For historical reasons, sources that have benefited from a special exemption regime in the past are not inventoried by IRSN but by Andra because they are out of use and considered as waste.

This is the case of:
- radioactive lightning conductors;
- ionic fire detectors (current detectors do not contain a radioactive source);
- radioluminescent sources;
- surge protectors (old electronic components used in particular for the electrical protection of the telephone network).

All these objects could have been made with radium, a radionuclide whose use was not regulated for a long time; subsequently, other radionuclides may have been used.

FOCUS — SPENT SEALED SOURCES IN THE NATIONAL INVENTORY

Spent sealed sources fall under several streams in the *National Inventory*:
- CEA "source assembly" packages (ILW-LL stream F2-9-01), which include packages made up of spent sealed sources (solids, liquids or gases), collected from small waste producers (hospitals, agri-food industries, paper mills, petrochemical industries, etc.);
- packages of sealed radioactive sources, with a half-life less than or equal to cobalt-60 from the CEA (LILW-SL stream F3-9-02). These sources were used in the past for medical, research, or industrial purposes;
- spent sealed sources (stream S01). The majority of these sources correspond to sources from ionic smoke detectors. These sources also include primary and secondary source rods from EDF's pressurized water reactors. The rest correspond to sealed sources without use, recovered and stored by the major source suppliers or manufacturers;
- radioluminescent objects (stream S02). This stream mainly concerns condemned material from the military that groups together radioluminescent objects containing radium and tritium (compasses, dials, sighting devices, etc.);
- contaminated spent sealed sources (stream S03) and radioactive surge protectors (stream S04).

FOCUS OLD RADIOLUMINESCENT OBJECTS

When old models of watches, alarm clocks, compasses, aircraft dials, night sight systems have hands and dials that remain luminescent after a two-day stay in complete darkness, they are radioactive and considered to be sealed sources. This luminescent effect was achieved by adding radium, then tritium, to the paint. The quantities of radioactive substances involved are extremely small and are contained by the glass housing. A problem arises if the glass or housing is no longer waterproof. These old models are often owned by collectors, especially collectors of military objects, by watchmakers, or heirs of watchmakers. They cannot be sold or donated, they must be treated as radioactive waste by Andra.

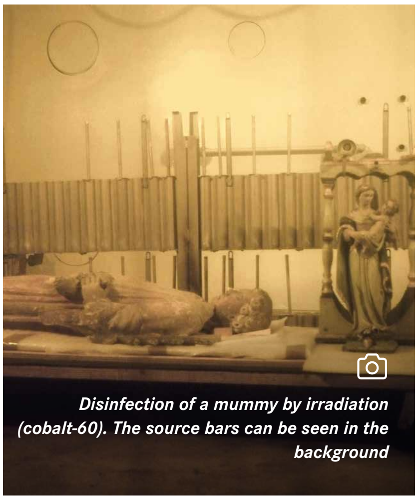
Radioluminescent alarm clocks

APPLICATIONS OF SEALED SOURCES

The principle of justification (*see insert below*) only allows for the use of radionuclides if there is no alternative solution.
The sealed sources currently in use, whether in the industrial or medical field, respect this principle.

Principle of justification (article L. 1333-2 of the French Public Health Code)

Any activity likely to subject people to exposure to ionising radiation may only be undertaken or carried out if it is justified by its health, social, economic, or scientific benefits, among others, in relation to the risks inherent to this exposure. Any unjustified activity is prohibited. When several techniques make it possible to obtain the same result, the choice will be made to select the technique with the lowest dose in terms of ionising radiation, and whose risk balance is the most favourable.



Disinfection of a mummy by irradiation (cobalt-60). The source bars can be seen in the background

INDUSTRIAL USE

The radioactive properties of sealed sources are used in various industrial processes detailed below.

STERILISATION BY IRRADIATION

Sterilisation consists in exposing the items to ionising radiation, which leads to the destruction of all organisms without altering the composition of organic matter. This process is used for several applications:

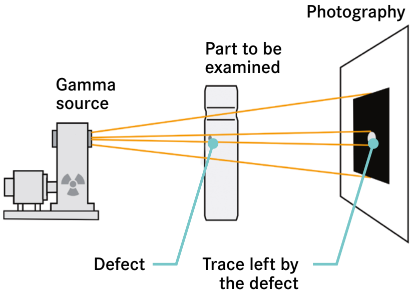
- **treatment of food:** irradiation can prevent germination, exterminate insects, delay ripening (fruits and vegetables), prevent disease (poultry) or reduce the amount of microorganisms (aromatic herbs). At the end of treatment, these products do not contain any residual radioactivity. For these operations, several food irradiation plants exist in France. They can use either a radioactive sealed source (cobalt-60) or an electron accelerator;
- **eradication of harmful insects:** for example, male tsetse flies are raised in the laboratory and sterilized by being briefly exposed to gamma rays from a radioactive sealed source of cobalt-60. These sterile flies are then released into the targeted area to replace the local males in mating with the females;
- **protection of heritage items** from fungi or to eliminate any risk of contamination of the public and researchers. The mummy of Ramses II was exposed to ionising radiation for this reason;
- **sterilisation of medical devices,** pharmaceuticals, and cosmetics. Treatment with gamma radiation allows quick turnaround times for products already in sealed packaging.

INSPECTIONS AND ANALYSES OF MATERIALS

Sealed sources are used in several types of devices for the physical or chemical analysis of materials:

- **non-destructive tests by gammagraphy:** these tests are carried out without damaging the objects tested. This is a "radiograph" used to identify internal defects. These techniques and methods provide information on the soundness of a part or structure, without resulting in alterations detrimental to their subsequent use;
- **lead inspection:** portable devices containing a sealed source are used to detect lead present in paints. These inspections are widely used for diagnostic surveys of property in view of sale, etc. These detectors use X-ray fluorescence: when the material is bombarded with radiation (emitted by a source of cadmium-109 or cobalt-57), the material re-emits energy according to the composition of the sample.

DIAGRAM OF NON-DESTRUCTIVE TESTING BY GAMMAGRAPHY



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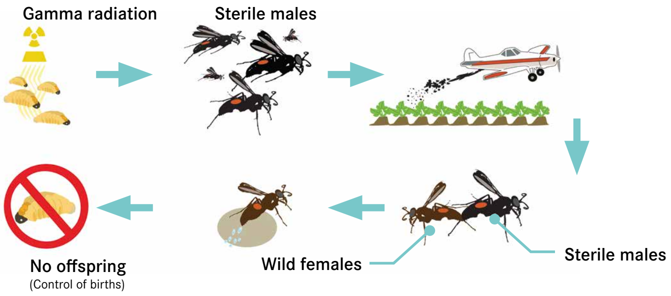
CONTROL OF HARMFUL INSECTS BY THE STERILE INSECT TECHNIQUE (TIS)



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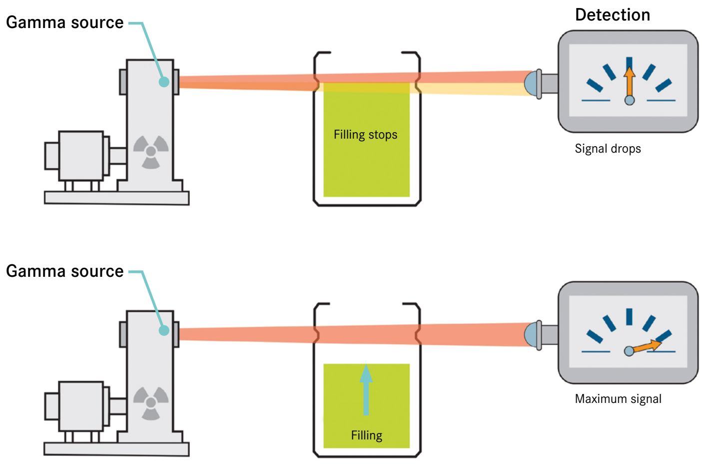
PARAMETER CONTROL

Sealed sources are used in various industrial sensors:

- to control the weight or thickness of paper, fabric, plastic, and metal. The attenuation of the radiation produced by the radioactive source depends on the thickness of the materials through which it passes;
- to carry out level checks on tanks: a beam of gamma radiation passes through the container to be filled before being received by a detector located across from it. When the liquid intercepts the beam of gamma rays as it rises, the signal seen by the detector drops abruptly. This drop automatically triggers stoppage of filling. The radionuclides used depend on the characteristics of the container and the contents.

DIAGRAM OF TANK FILLING CONTROL



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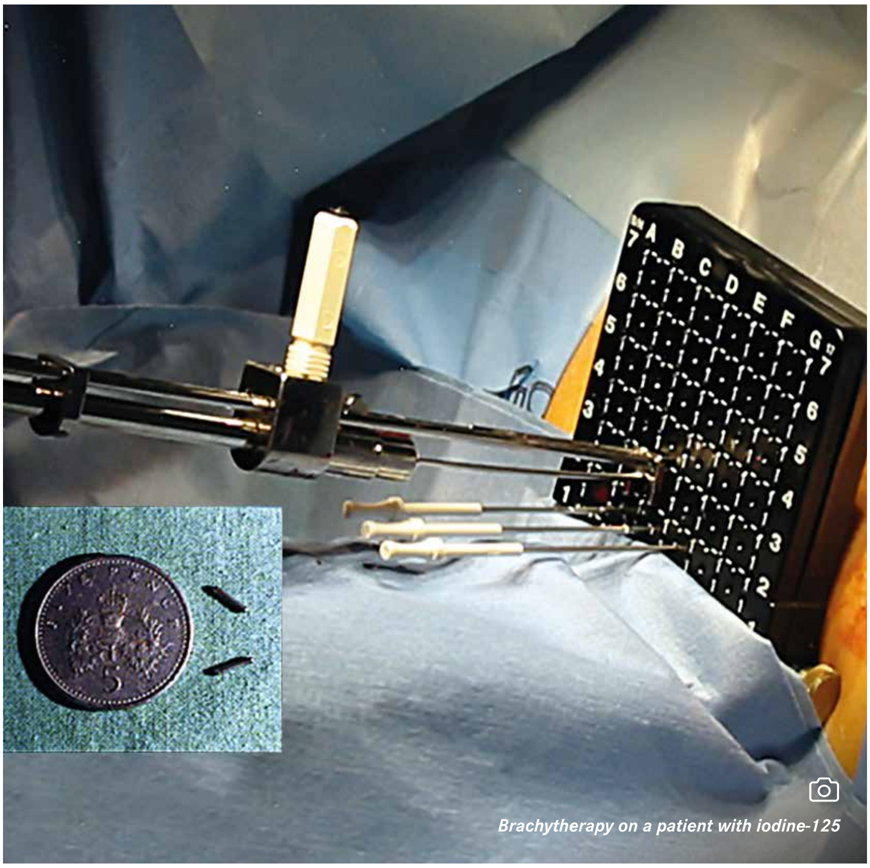
MEDICAL USE

Sealed sources are used in medicine for:

- **brachytherapy**, which involves implanting radioactive sources inside the body, directly on the lesion to be treated. This makes it possible to concentrate the doses on a small volume without attacking the surrounding tissues. Gamma rays are delivered by a sealed source, implanted in the body, often in a natural cavity. The radium used in the past has been abandoned in favour of man-made radioelements (e.g. caesium-137 and iridium-192);
- **inspection and calibration of devices** used in nuclear medicine: standard sources make it possible to check the proper functioning of the measuring devices used in the diagnostic or therapeutic process;
- **sterilisation:** in addition to the examples already mentioned above, this method is commonly used to sterilise human blood before a transfusion. The irradiators consist of a shielded tank that contains a high-activity source of cobalt-60 or caesium-137.



Brachytherapy on a patient with iodine-125

MANAGING SPENT SEALED SOURCES

FOCUS

LEGISLATION RELATING TO SOURCES

The legislation relating to sources is grouped together in the French Public Health Code, in Articles L. 1333-1 and following as well as in Articles R. 1333-152 and following.

Article R. 1333-161 of the French Public Health Code states in particular that:

I. A sealed radioactive source is considered disused no later than 10 years after the date of the first registration on the supply form or, failing that, 10 years after the date of its first commercialisation, unless extended by the competent authority.

II. Any holder of disused or end-of-use sealed radioactive sources is required to return them, regardless of their condition, to a supplier who is authorised to take them back by the authorisation provided for in Article L. 1333-8. Sealed radioactive sources that are not recyclable under current technical and economic conditions may be taken back as a last resort by the National Radioactive Waste Management Agency. The costs relating to the recovery of these sources are the responsibility of the holder.

If the holder returns their sealed radioactive sources to a supplier other than the original supplier or if they are taken back by the French National Radioactive Waste Management Agency, within one month of receiving the recovery certificate issued by the recovery entity, the holder shall send a copy of this certificate to the original supplier and to the French Institute for Radiation Protection and Nuclear Safety.

III. The provisions of I and II are not applicable to sealed radioactive sources whose activity, at the time of their manufacture or, if this time is not known, at the time of their first commercialisation, does not exceed the exemption limit values set out in Table 1 and in the second and third columns of Table 2 of Annex 13-8.

IV. The supplier of sealed radioactive sources, products, or devices containing them is obliged to recover (take back) any sealed radioactive source that it has distributed, when this source is disused or when its holder no longer has use of it or has defaulted. The conditions of this recovery, including the related costs, are defined between the supplier and the purchaser at the time of transfer of the source, and are maintained by the holder and the supplier of the source for as long as the source has not been recovered. These terms and conditions may be updated according to technical or economic developments and are taken into account when implementing the financial guarantee referred to in Article R. 1333-162. When the source has been supplied in a device or product, the supplier is also required to take it back in full if the holder so requests. In the event of defaulting of the holder and if the holder is not itself the beneficiary of a guarantee covering the recovery costs mentioned in Article R. 1333-163, the supplier is required by the French Nuclear Safety Authority to take back the sources unconditionally.

This recovery requirement ceases when the supplier stops all distribution activity of sealed radioactive sources. This obligation is, however, maintained for a period of three years following the date of disuse of distributed sealed radioactive sources whose activity, at the time of their manufacture or, if this time is not known, at the time of their first commercialisation, exceeds the exemption limit values set out in Table 1 and in the second and third columns of Table 2 of Annex 13-8. The aforementioned date of disuse takes into account the extensions granted pursuant to I for which the supplier has confirmed upholding of the financial guarantee.

V. The supplier shall dispose of or ensure disposal of recovered sealed radioactive sources in a facility authorised for this purpose or return them to their supplier or to the manufacturer. The supplier justifies sufficient storage capacities to receive the sources taken back during the period before their disposal or recycling.

RECOVERY REQUIREMENT

French law requires suppliers to take back, at the request of the holder, all sealed sources that it has supplied on French territory (recovery requirement that ceases when the supplier stops all distribution activity of these sources).

In order to allow the effective recovery of sources, even in the event of financial failure of its manufacturer, the suppliers have grouped together within the Ressources organisation to pool financial guarantees and allow Andra or any other authorised body to be reimbursed for the costs of recovering sources.

This organisation, with around sixty members, represents nearly 95% of the market for this activity.

Source management

RECYCLING SEALED SOURCES

The radioelements present in some sources have a very high radioactive half-life (for example, americium-241 has a half-life of 432 years), the activity at the end of its life has decayed very little and is therefore very close to its initial activity level. After recovery, some sources may be recycled: depending on the type of source (geometry, matrix, etc.), it would be possible to recover the radioactive isotopes to include them in new packaging and thus produce a new source. The used packaging would then be treated as waste. However, today, sources are hardly ever recycled, due in particular to significant technical constraints (radionuclides trapped in matrices that are difficult to recycle, etc.) and the significant cost of recycling.

HANDOVER TO ANDRA

The Andra disposal facilities in operation or planned for the future may be able to accommodate spent sealed sources, provided that they meet the acceptability criteria.

Most spent sealed sources are currently in storage pending a final disposal solution.

CIRES

The purpose of Cires is to receive very low-level waste for final disposal.

Since 2015, the acceptance specifications of this facility allow the disposal of spent sealed sources in compliance with the safety demonstration of the facility.

The activity of each source packaged at the time of its declaration for management at Cires must be such that the resulting activity following a decay of 30 years is less than or equal to 1 Bq.

These sources contain radionuclides with short half-lives, such as cobalt-57 (272 days), iron-55 (2.7 years) or zinc-65 (244 days), so they are not recyclable.

CSA

Since 2006, an acceptance specification provides the procedures for handover of packages from spent sealed sources. Before 2006, sources could be accepted at the CSA, but only on exemption from ASN.

Among other things, the sources contained in the same package must have only one and the same radionuclide with a half-life of less than 30 years. Sources containing cobalt-60 (5.3-year half-life) and radioelements of shorter half-lives are currently stored at the CSA.
The limitation of the acceptability of sealed sources in surface disposal facilities for radioactive waste is due to their concentrated activity and their potentially attractive nature (sources are small manufactured objects that can be put in a pocket or kept as trinkets, destroyed or ingested). It is therefore important that the residual activity does not induce an unacceptable effect at a date when the memory of the site is assumed to have been lost (300 years) and when human intrusion (roadworks, construction, etc.) is possible.

LLW-LL

To date, the design of a disposal facility for long-lived low-level waste (LLW-LL) has not been defined. The characteristics of the sources acceptable in this type of disposal facility will depend on the design. The sources that will be destined for this disposal facility will be those that are not acceptable at Cires or CSA, and for which disposal in Cigéo is not justified from a safety point of view.

These sources will be conditioned in packages so as to comply with the acceptance specifications to be set by Andra.

CIGÉO

The Cigéo planned disposal facility is designed for disposal of high-level radioactive waste as well as long-lived intermediate-level radioactive waste (HLW and ILW-LL waste) in a deep geological layer.

In accordance with the provisions of Article L. 542-1-2 of the Environmental Code, sealed sources that cannot be disposed of on the surface or near surface will be stored in a deep geological layer at Cigéo.

These sources will be conditioned in packages so as to comply with the acceptance specifications to be set by Andra.

FOCUS – DEVELOPMENTS IN THE USE OF SEALED SOURCES FOR CERTAIN ACTIVITIES

In order to comply with the principle of justification and the use of sealed sources imposing many constraints, alternative solutions without radioactivity are preferred. For example:

- the sealed sources used for external radiotherapy have been replaced by particle accelerators that only emit radiation if they are electrically powered;
- surge protectors that contained radioactivity have been replaced with surge protectors containing various electronic components without radioactivity;
- the radium present in radioluminescent objects has been gradually replaced by tritium (which is less toxic), itself replaced by photoluminescent paint where possible;
- pacemakers powered by a plutonium-238 electric generator have been replaced by pacemakers powered by an "iodine/lithium" battery;
- ionic smoke detectors (americium source) have been replaced with optical detectors containing an LED and a photoelectric cell.

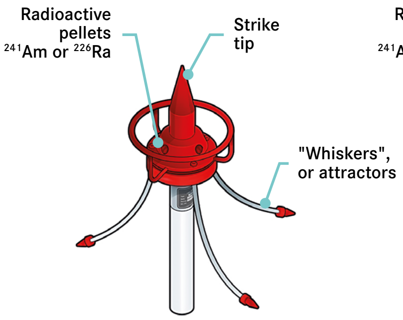
Depending on the type of sources, regulations may require the disposal of these radioactive devices even if they are still functional or, on the contrary, allow their use until their end of life.

Ionic smoke detector

FOCUS – LIGHTNING CONDUCTORS

At the beginning of the 20th century, radioactive sources were added to lightning conductors to reinforce the natural ionisation of the air and thus the effectiveness of the lightning conductor. They were manufactured in France from 1932 to 1986 by the companies Helita and then Duval Messien, Franklin France, and Indelec. As their additional effectiveness was never demonstrated, their manufacture was prohibited by the order of 11 October 1983, applicable on 1 January 1987.

DIAGRAM 1: OVERALL TREATMENT OF A LIGHTNING CONDUCTOR HEAD

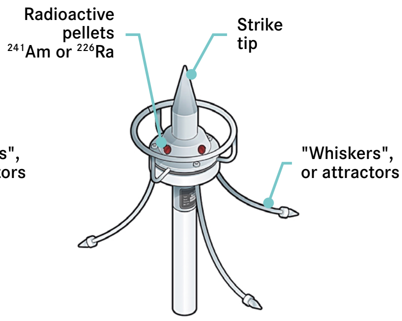


© Andra

No text requires their removal, but each time one of them is dismantled, it must be removed as radioactive waste to Andra.

The total number of lightning conductors installed in France is estimated at about 50,000, including 30,000 equipped with radium-226 sources (or both radium-226 and americium-241 source mixed lightning conductors) and 20,000 equipped with americium-241 sources.

DIAGRAM 2: LOCALISED TREATMENT OF A LIGHTNING CONDUCTOR HEAD



© Andra

The average activity of a radium-226 lightning conductor head is about 50 megabecquerels, and that of a americium-241 lightning conductor head is about 20 megabecquerels.

The radioactive substances are in the form of sintered pellets, plates, sheets, or painted porcelain beads, usually of small dimensions.

Initially, the radioactive head of a lightning conductor was treated in its entirety. The removed head was considered LLW-LL waste (*see diagram 1*).

In order to optimise disposal space, Andra plans to simply remove the pellets that concentrate all the radioactivity (*see diagram 2*). The pellets would be grouped in 870-litre drums and then stored pending disposal at Cigéo. As a precaution, the rest of the lightning conductor head would be considered VLLW waste. Pending the completion of this project, these lightning conductors are directed to the Andra storage platform at Cires.

Report 7

Foreign inventories of radioactive waste

The establishment of a radioactive waste inventory for a country has several purposes, including:

- providing support for the definition of the radioactive waste management programme by establishing an inventory of the stores of radioactive waste present on the territory, and therefore plan the necessary facilities and R&D programmes intended to provide responses for waste with no available solution;
- ensuring that information associated with the long-term storage and disposal of waste is preserved, in accordance with quality management requirements, and appropriate to the needs of future generations;
- establishing *"an inventory of all spent fuel and radioactive waste and estimates for future quantities, including those from dismantling, 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;
- presenting the impact of different strategies or potential changes to national energy policy over the long term on the quantities of radioactive materials and waste, without anticipating the industrial and strategic decisions that may be made. This forecasting exercise is based on the definition of contrasting scenarios.

Through their inventories, countries report on the volumes of radioactive waste produced and their situations (for example, the existence of disposal solutions). They also transmit information on waste location, radioactivity, conditioning, origins, destinations, etc.

FOCUS – INTERNATIONAL BODIES

International agencies play an important role in the sharing of experience between countries, the establishment of safety standards and the dissemination of good practices in the management of radioactive waste. Several bodies, European or global, are active and invested in inventories of radioactive materials and waste.

IAEA[1]

Established in 1957 by the United Nations as an independent body, the mission of the International Atomic Energy Agency (IAEA) is to promote the safe use of nuclear technologies for peaceful purposes. It has 175 Member States. One of the main missions of the IAEA is to prevent the proliferation of nuclear weapons and to promote the safe, secure and peaceful use of nuclear science and technology.

EUROPEANUNION – EURATOM[2]

Signed in 1957, the Euratom Treaty aims to allow the development of nuclear energy in the countries of the European Union while ensuring the protection of the public and workers against the harmful effects of ionising radiation. As such, the European Commission develops directives that Member States have an obligation to translate into their national law. Hence Council Directive 2011/70/EURATOM of 19 July 2011 establishing a European Community framework for responsible and safe management of spent fuel and radioactive waste[3].

NEA[4]

The Nuclear Energy Agency (NEA), established in 1958, 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."* To date, 34 countries are members of the NEA.

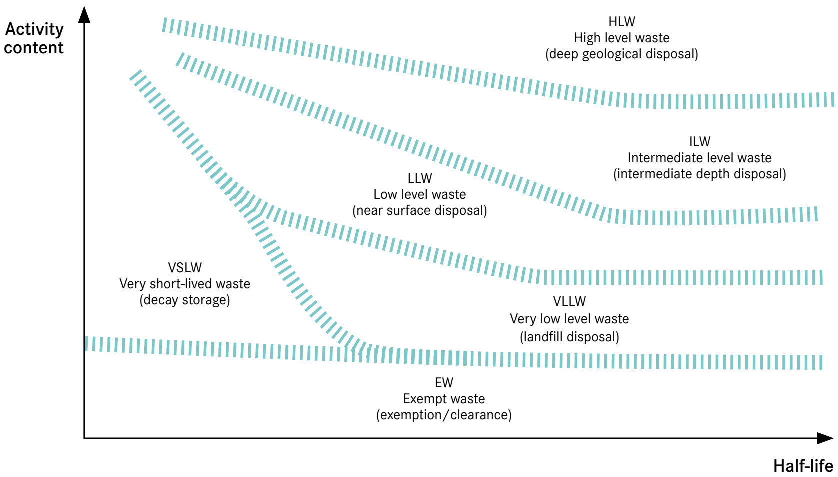
1 https://www.iaea.org/
2 https://www.europarl.europa.eu/about-parliament/fr/in-the-past/the-parliament-and-the-treaties/euratom-treaty
3 https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000024479846
4 https://www.oecd-nea.org/jcms/j_6/home

CLASSIFICATION OF RADIOACTIVE WASTE ABROAD

The first step in establishing a radioactive waste inventory is to define a classification of radioactive waste. However, this generally differs from one country to another. Under the impetus of international bodies such as the IAEA, the OECD/NEA, and as far as Europe is concerned, Directive 2011/70/Euratom, a convergence towards a common classification at an international level is progressing.

For example, the International Atomic Energy Agency (IAEA) proposes the classification of radioactive waste in General Safety Guide No. GSG-1 published in 2009[1]. It is based on two parameters, activity and half-life.

IAEA CLASSIFICATION OF RADIOACTIVE WASTE



FOCUS EQUIVALENCE BETWEEN FRENCH AND INTERNATIONAL CLASSIFICATIONS

The following table presents the equivalence as it is generally accepted between the French classification and the international classification.

In reports in English, the "*Exempted Waste*" (EW) category is also mentioned, which does not exist in France. This is due to the fact that the French regulatory framework does not include the concept of a clearance level, i.e. the level of radioactivity below which nuclear waste can be considered non-radioactive and recycled in conventional industry. Work is nevertheless underway, in particular within the framework of the PNGMDR 2022-2026, to study all management methods that can be considered for different types of VLLW (TFA) waste.

In France, there is an additional class, Low Activity – Long Life (LLW-LL or FA-VL in French) which is included in the "*Intermediate Level Waste*" (ILW) class of the IAEA.

French classification of radioactive waste	Equivalence with IAEA classification (GSG)
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 Waste Short Lived (LILW-SL)***	*Low Level Waste (LLW)*
Déchets de faible activité à vie longue (FA-VL) ***Low Level Waste Long Lived (LLW-LL)***	*Intermediate Level Waste (ILW)*
Déchets de moyenne activité à vie longue (MA-VL) ***Intermediate Level Waste Long Lived (ILW-LL)***	*Intermediate Level Waste (ILW)*
Déchets de haute activité (HA) ***High Level Waste (HLW)***	*High Level Waste (HLW)*

1 General Safety Guides – IAEA safety standards No. GSG-1 (2009) https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1419_web.pdf

EUROPEAN DIRECTIVE ON SAFE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE (2011/70/EURATOM)

BACKGROUND

In 2011, the Council of the European Union adopted Directive 2011/70/Euratom establishing a European Community framework for the management of spent fuel and radioactive waste, from its production to its disposal. It therefore complements the Euratom legislative instruments which did not yet cover this subject. It makes EU Member States and producers responsible for the responsible and safe management of spent fuel and radioactive waste and for protecting people and the environment from the dangers of ionising radiation.

It requires Member States to adopt a legal framework for nuclear safety with:

- a competent safety and control authority, independent of the waste producers;
- licensees able to demonstrate and maintain the safety of their facilities in the management of spent fuel and radioactive waste, over their entire lifetime.

It also requires Member States to establish a national programme for developing and implementing spent fuel and radioactive waste management policy with:

- the general objectives that the national policies of Member States of the European Union will have to achieve with regard to the management of spent fuel and radioactive waste;
- important deadlines taking into account the objectives to be achieved for the national programmes;
- an inventory of all spent fuel and radioactive waste and estimates for future quantities, including those from dismantling,
  This inventory must clearly indicate the location and amount of radioactive waste and spent fuel in accordance with appropriate classification of the radioactive waste.

In addition, Member States of the European Union must:

- ensure the solution resources necessary for the management of spent fuel and radioactive waste;
- maintain adequate human resources;
- ensure transparency of information and participation of the public;
- review and regularly update their national programme to incorporate developments and progress, and undergo peer reviews;
- dispose of the radioactive waste in the Member State where it was produced. However, the Directive opens the possibility for Member States of the European Union to dispose of their radioactive waste in another country (Member State or, under certain conditions, an outside country).

This directive entered into force on 23 August 2011 and Member States of the European Union had a period of two years to transpose it into national law.

In the expectations expressed, the directive mentions that geological disposal is the safest and most sustainable solution as a final step in the management of long-lived high-level and intermediate-level waste. Indeed, in most countries, geological disposal has emerged as a long-term solution after extensive research on different options.

The Member States of the European Union submitted a report to the Commission on the implementation of the Directive by 23 August 2015 and every three years thereafter, drawing on the assessments and reports drawn up under the Joint Convention.

Finally, the European Commission must submit the following to the European Parliament and the Council every three years:

- a report on the progress made in the implementation of the Directive;
- an inventory of spent fuel and radioactive waste present on the territory of the European Community and forecasts for the future.

IMPLEMENTING THE DIRECTIVE

All Member States of the European Union have now completed transposing of the Directive and have fulfilled their obligations: reports, national programmes, or draft programmes. It was on the basis of the information available in these documents that, in 2019, the European Commission's report on the application of the directive was submitted to the European Parliament and the Council.

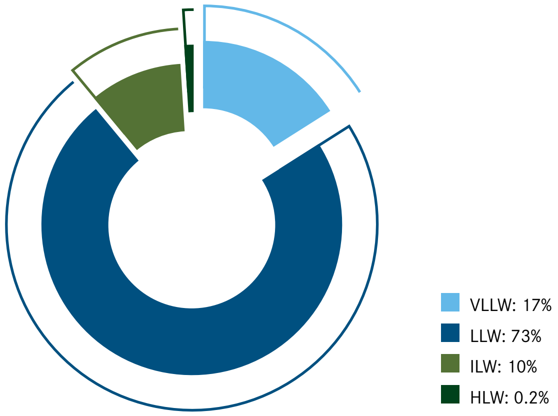
This report, as indicated in the previous paragraph, presents an inventory of radioactive waste and spent fuel in the European Union, national policies and programmes on the management of radioactive waste and spent fuel. National frameworks and the regulatory context in all countries are also mentioned. The following figure shows the consolidation, at the European level, of the volumes of radioactive waste.

The report concludes by focusing on the support that the Commission will provide to the Member States of the European Union for the various aspects contained in the directive, and in particular on the work that the Commission intends to carry out to have an overview of the costs and funding of radioactive waste management. The Commission also undertakes to carry out an in-depth analysis of the inventories in each country.

TRENDS IN TOTAL QUANTITIES OF RADIOACTIVE WASTE DURING THE PERIOD 2004-2016 FOR EUROPE

Category of waste					Total volume (m^3)
	2004	2007	2010	2013	2016
VLLW	210,000	280,000	414,000	516,000	603,000
LLW	2,228,000	2,435,000	2,356,000	2,453,000	2,519,000
ILW	206,000	280,000	321,000	338,000	338,000
HLW	5,000	4,000	5,000	6,000	6,000

DISTRIBUTION AMONG THE CATEGORIES OF RADIOACTIVE WASTE (AT END OF 2016)[1]



MONITORING CARRIED OUT BY THE INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)

The IAEA, an agency of the United Nations (UN), makes available to the public a database, called SRIS *(Spent Fuel and Radioactive Waste Information System)* which is a database of radioactive waste from different member countries. Data are updated regularly and their presentation tends to be harmonised between countries.

Each country, which generally has its own classification of radioactive waste, can translate it to the IAEA classification, specified in the GSG-11 general safety guide. In SRIS, the quantities of waste are entered according to the national classification and the international classification to allow these quantities to be added together or compared.

In addition, radioactive waste inventory volumes in each country can be established in different ways: volumes of raw, treated, conditioned, stored waste, or waste ready for disposal. However, the trend is towards a harmonisation of the reported volumes, which are increasingly volumes of waste that can be disposed of (conditioned equivalent volume).

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management is organised by the IAEA every 3 years. Each country that is a signatory to the Convention undertakes to produce a report on the national situation and to present it at a review meeting at the IAEA's headquarters in Vienna, Austria. To date, 88 contracting parties have ratified the Joint Convention on the Safety of Spent Fuel and Radioactive Waste Management. This convention was approved by France on 22 February 2000 and entered into force on 18 June 2001. Part of the reports is devoted to inventories of existing radioactive waste and spent fuel updated on the occasion of their publication.

The 7th review meeting was held in June 2022 at the IAEA's headquarters in Vienna (Austria). About sixty national reports have been published on the IAEA website[2].

1 Taken from the European inventory of radioactive waste and spent fuel. Source: COM(2019) 632 final.

2 https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste

FOCUS ON A FEW COUNTRIES

In the following paragraphs, you will find (non-exhaustive) information about several different countries: Germany, Belgium, Spain, Finland, Switzerland, the United Kingdom and the United States of America.

This information comes from the national reports submitted by each country during the 7th report for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management of the IAEA or the published national inventory reports or publications of each country on the basis of SRIS data.

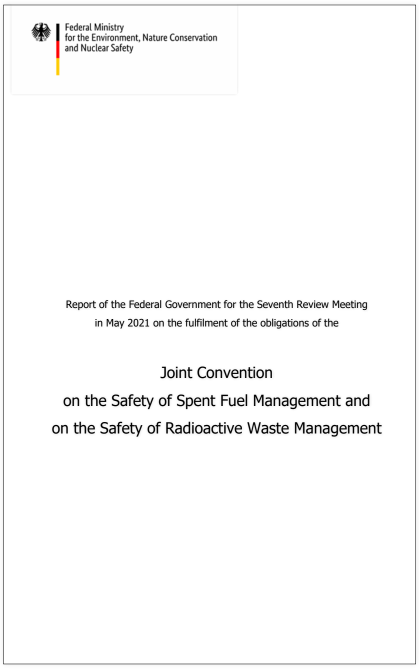
GERMANY[3]

The *Bundesgesellschaft für Endlagerung mbH* (BGE) was established in July 2016 as a state-owned enterprise under the supervision of the German Ministry of the Environment to manage radioactive waste.

This waste comes from theoperation of nuclear power plants and research reactors, as well as their dismantling, the medical sector, industry and the military sector.

In Germany, radioactive materials are distinguished into reusable or recyclable materials and radioactive waste. A release threshold exists and allows certain low- and very low-level radioactive materials to be recycled (metals, rubble) or treated as waste in a conventional waste management circuit.

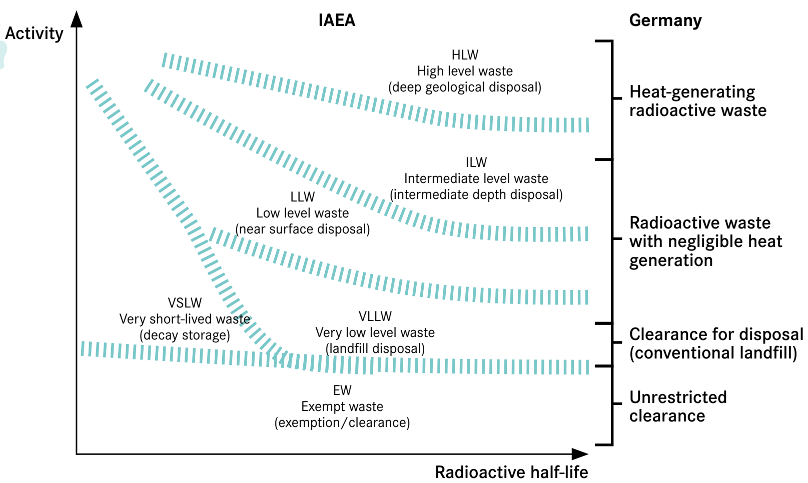
The classification of radioactive waste is based on exothermic characteristics and presents two groups according to this parameter. The figure below shows a comparison between the IAEA waste classification and the German classification. The inventory of radioactive waste is carried out with the German classification. According to the German national report for the 2021 Joint Convention, as of December 31, 2019, approximately 125,000 m³ of radioactive waste with negligible heat production is identified, and 575 m³ of radioactive waste generating heat in addition to spent fuel.


Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

Report of the Federal Government for the Seventh Review Meeting in May 2021 on the fulfilment of the obligations of the

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

COMPARISON OF IAEA AND GERMAN CLASSIFICATIONS OF RADIOACTIVE WASTE



3 https://www.iaea.org/sites/default/files/germany-7rm.pdf
https://sris.iaea.org/country-overview/introduction/DE/Germany

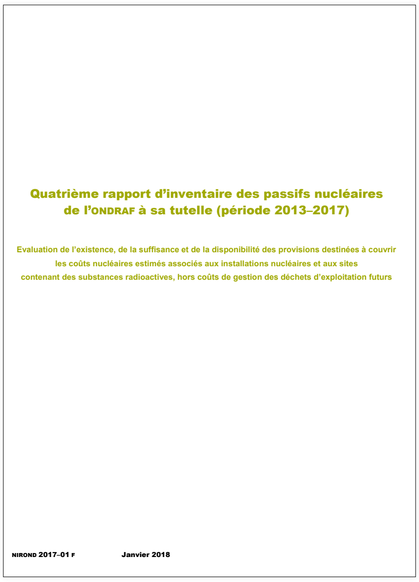
BELGIUM[4]

Ondraf, the national body for radioactive waste in Belgium, has been responsible for carrying out the inventory every five years since 1997. This inventory has two components: the radioactive substances present on Belgian territory and the "nuclear liabilities" that inventory the various sites and producers of radioactive waste. In addition, one of the objectives of this exercise is to estimate the costs and provisions associated with radioactive waste management.

The last inventory published in 2018 covered the period 2013-2017. The next publication is scheduled for 2023. Belgian radioactive waste comes from nuclear reactors as well as the industrial, medical, and military sectors.

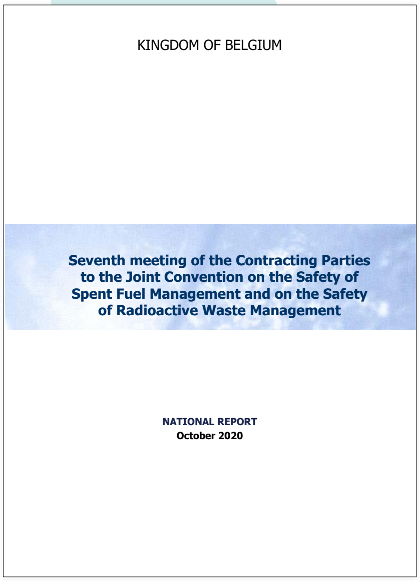
For the long-term management of radioactive waste, Belgium has adopted a classification consisting of three categories (A-B-C) according to the characteristics of the waste, defined in accordance with the classification proposed by the IAEA and the classification recommended by the European Commission: according to waste activity and half-life:

- Category A waste is short-lived, low- and intermediate-level conditioned waste. The volume of this waste is 54,900 m³;
- Category B waste is low- and intermediate-level conditioned waste contaminated with quantities of long-lived radionuclides. The volume of this waste is 11,000 m³;
- Category C waste is high-level conditioned waste containing large quantities of long-lived radionuclides. The volume of this waste is 2,600 m³.


Quatrième rapport d'inventaire des passifs nucléaires de l'ONDRAF à sa tutelle (période 2013–2017)

Evaluation de l'existence, de la suffisance et de la disponibilité des provisions destinées à couvrir les coûts nucléaires estimés associés aux installations nucléaires et aux sites contenant des substances radioactives, hors coûts de gestion des déchets d'exploitation futurs

NIROND 2017–01 F Janvier 2018


KINGDOM OF BELGIUM

Seventh meeting of the Contracting Parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

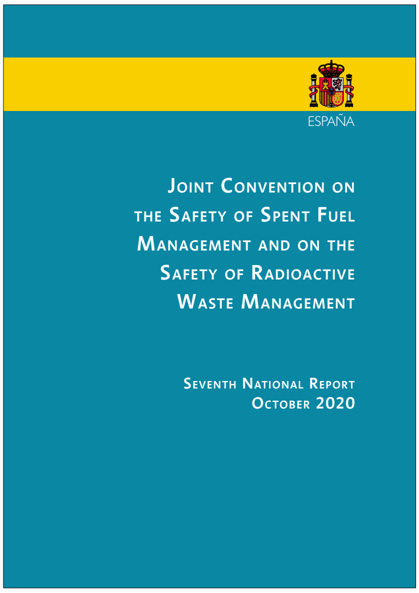
NATIONAL REPORT
October 2020

4 https://www.ondraf.be/search?keys=inventaire
https://www.iaea.org/sites/default/files/belgium-jc-rapport-be-2020-public.pdf

SPAIN[5]

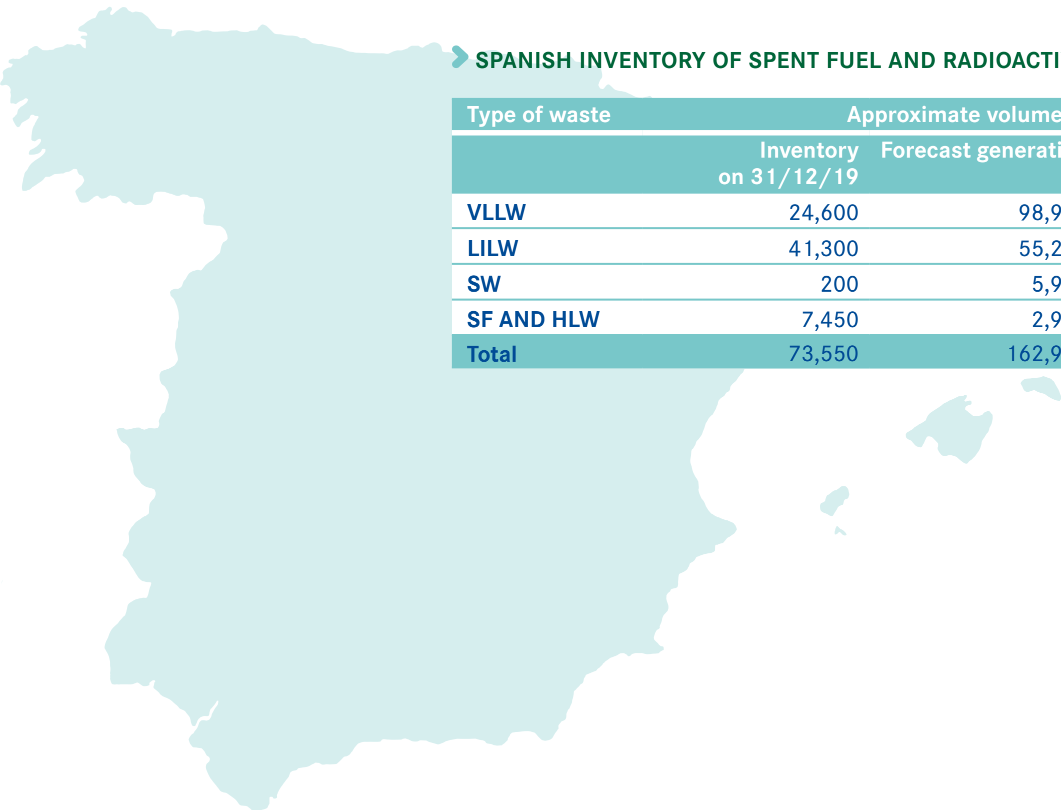
In Spain, ENRESA (*Empresa Nacional de Residuos Radiactivos SA*) was created in 1984 as a public company responsible for the management of radioactive waste and the delicensing of nuclear power plants. The waste comes from the operation of nuclear plants, the operations of nuclear installations for industrial, medical, agricultural, and research activities. The categories of waste correspond to the classification criteria adopted by theIAEA and the European Commission: activity and half-life of radionuclides.

As of December 31, 2019, the total volume of radioactive waste present in Spain was 73,550 m³, including 24,600 m³ of very low-level waste (VLLW), 41,300 m³ of low- and intermediate-level waste (LILW) and 7,450 m³ of spent fuel and high-level waste (HLW).


ESPAÑA

JOINT CONVENTION ON THE SAFETY OF SPENT FUEL MANAGEMENT AND ON THE SAFETY OF RADIOACTIVE WASTE MANAGEMENT

SEVENTH NATIONAL REPORT
OCTOBER 2020



SPANISH INVENTORY OF SPENT FUEL AND RADIOACTIVE WASTE

Type of waste	Approximate volume (m³)		
	Inventory on 31/12/19	Forecast generation	Total inventory
VLLW	24,600	98,900	123,500
LILW	41,300	55,200	96,500
SW	200	5,900	6,100
SF AND HLW	7,450	2,950	10,400
Total	73,550	162,950	236,500

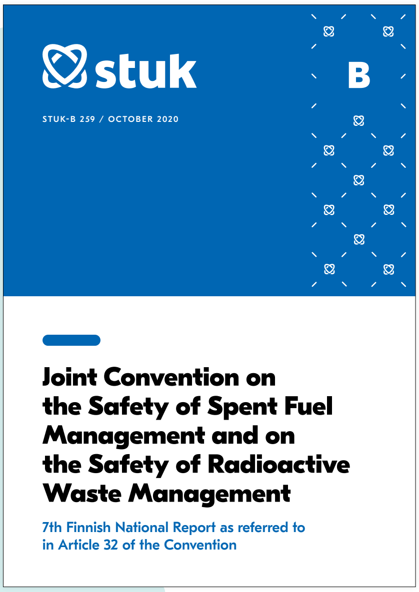
5 https://www.iaea.org/sites/default/files/spain-7rm_english.pdf
https://sris.iaea.org/country-overview/introduction/ES/Spain

FINLAND[6]

The activities of 5 nuclear reactors are the source of the volumes that TVO and Fortum, the operators, are responsible for managing. In 1995, Posiva Oy was created (TVO-Fortum joint venture) to manage spent fuel. Other radioactive waste comes from industrial, research, or medical activities.

Finland bases its inventory on the IAEA classification and follows Euratom Directive 2011/70, and so the classification is based on activity and half-life. Radioactive waste is classified as very low-, low- or intermediate-level waste. Spent fuel is classified as high-level waste.

As of December 31, 2019, the total volume of radioactive waste present in Finland was 12,500 m³. Finland also contributes to the IAEA's SRIS database. To date, inventories from the end of 2020 and 2021 are available.


stuk

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STUK-B 259 / OCTOBER 2020

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

7th Finnish National Report as referred to in Article 32 of the Convention

FINNISH INVENTORY OF RADIOACTIVE WASTE AT END OF 2019

Waste Class	Total Stored Amount m³	Total Disposed Amount m³
VLLW	204	-[a]
LLW	1,691	6,541
ILW	1,970	2,117
HLW	0	0

a *Currently VLLW is disposed of in LILW repository and is included in the total inventory of disposed LLW.*

Spent fuel	Total Stored Amount	Total Disposed Amount
Spent fuel from NPP's	2,261 tHM	0
Spent fuel from research reactor	21.3 kgHM	1[b]

b *The first option is to send the fuel back to USA according existing returning agreement.*

6 https://www.iaea.org/sites/default/files/finland-7rm.pdf
https://sris.iaea.org/country-overview/introduction/FI/Finland

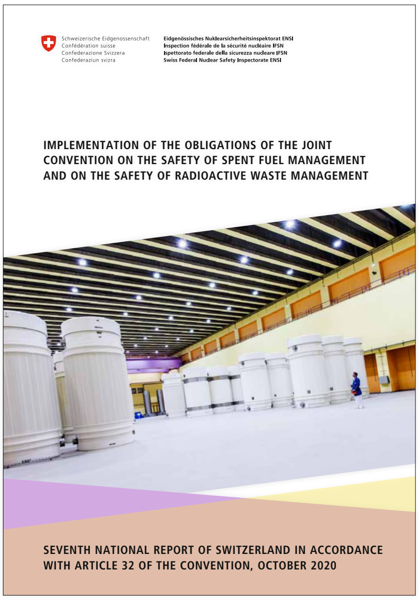
SWITZERLAND[7]

Established in 1972, La Nagra (National Cooperative for the Disposal of Radioactive Waste) maintains a centralised inventory: the ISRAM *(Information System for Radioactive Material)*, where it lists the quantities of existing waste as well as their chemical and physical properties. Radioactive waste comes from nuclear power plants as well as from research, medical, and industrial activities.

The Swiss classification of radioactive waste is as follows:

- High-activity waste (HA): vitrified fission product waste from the reprocessing of spent fuel, or spent fuel if it is declared as waste;
- Alpha-toxic waste (ATA): waste with a concentration of alpha emitters greater than 20,000 Bq/g of conditioned waste;
- Low- and intermediate-level waste (LILW): all other radioactive waste.

The volumes of radioactive waste according to these categories and their location (site) at the end of 2019 are indicated in the table opposite.



SWISS INVENTORY OF RADIOACTIVE WASTE BY STORAGE SITE AT END OF 2019

Site name	Waste class	Waste volume (m^3)
Beznau NPP	L / ILW, cond.[a]	1,199
(incl. ZWIBEZ)	/ ILW, uncond.[b]	28
Mühleberg NPP	L / ILW, cond.	797
	L / ILW, uncond.	62
Gösgen NPP	L / ILW, cond.	109
	L / ILW, uncond.	18
Leibstadt NPP	L / ILW, cond.	1,401
	L / ILW, uncond.	5
ZZL	HLW, cond.	115
	ATA[c], cond.	99
	L / ILW, cond.	2,253
	L / ILW, uncond.	391
PSI	ATA, cond.	68
	ATA, uncond.	15
	L / ILW, cond.	1,555
	L / ILW, uncond.	549

a *conditioned waste (cond.)*
b *unconditioned and partly conditioned waste (uncond.)*
c *Alpha-toxic waste (ATA)*

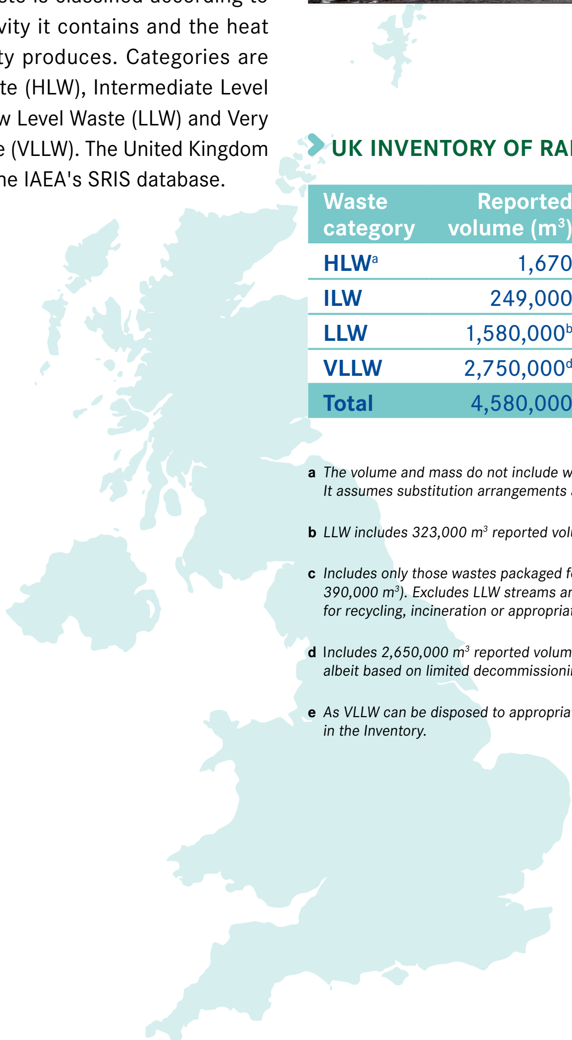
7 https://www.iaea.org/sites/default/files/switzerland-7rm.pdf https://sris.iaea.org/country-overview/introduction/CH/Switzerland

UNITED KINGDOM[8]

In 2022, *Nuclear Waste Services NWS* brought together the UK's leading nuclear waste management entities by integrating the expertise of Low Level Waste Repository (LLWR) and Radioactive Waste Management (RWM). NWS is a division of the *Nuclear Decommissioning Authority* (NDA).

The NDA establishes an inventory of radioactive waste and material in the United Kingdom every three years with the *Department for Business, Energy & Industrial Strategy* (BEIS). The civil nuclear energy sector is the source of most radioactive waste. It comes from the preparation of nuclear fuel, the operations and delicensing of nuclear power plants, the reprocessing of spent nuclear fuel as well as research, medical, and defence activities.

Radioactive waste is classified according to how much activity it contains and the heat that this activity produces. Categories are High Level Waste (HLW), Intermediate Level Waste (ILW), Low Level Waste (LLW) and Very Low Level Waste (VLLW). The United Kingdom contributes to the IAEA's SRIS database.



UK INVENTORY OF RADIOACTIVE WASTE AS OF 1 APRIL 2022

Waste category	Reported volume (m³)	Reported mass (tonnes)	Packaged volume (m³)	Number of packages
HLW[a]	1,670	3,500	1,470	7,520
ILW	249,000	310,000	496,000	282,000
LLW	1,580,000[b]	2,000,000	1,340,000	19,900[c]
VLLW	2,750,000[d]	2,800,000	2,610,000	See Note[e]
Total	4,580,000	5,100,000	4,450,000	310,000

a *The volume and mass do not include waste from reprocessing overseas spent fuel that will be exported to the country of origin. It assumes substitution arrangements are implemented (see section 14 for further information).*

b *LLW includes 323,000 m³ reported volume of mixed LLW/VLLW at Springfields.*

c *Includes only those wastes packaged for disposal at the LLWR, on-site and Dounreay LLW vaults (packaged volume 390,000 m³). Excludes LLW streams and component parts of LLW streams whose characteristics make them suitable for recycling, incineration or appropriately permitted landfill disposal.*

d *Includes 2,650,000 m³ reported volume from facility decommissioning at Sellafield. However the current best estimate, albeit based on limited decommissioning experience, is that 70% of this material may be 'out of scope' of regulatory control.*

e *As VLLW can be disposed to appropriately permitted landfill sites no package numbers are collated for this waste category in the Inventory.*

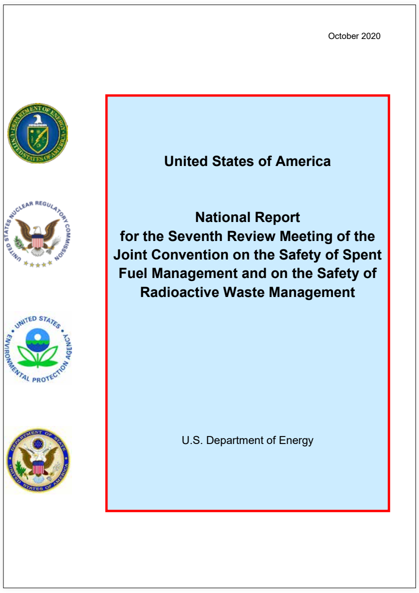
8 https://www.iaea.org/sites/default/files/uk-7rm.pdf
https://ukinventory.nda.gov.uk/wp-content/uploads/2020/01/2019-Waste-Report-Final.pdf
https://www.gov.uk/government/organisations/nuclear-waste-services/about
https://sris.iaea.org/country-overview/introduction/GB/United%20Kingdom

UNITED STATES[9]

The NRC (Nuclear Regulatory Commission), the EPA (Environmental Protection Agency) and the DOE (Department of Energy) participate in the regulation and/or organisation of radioactive waste management.

The waste comes from nuclear energy production activities as well as the military, medical, and industrial sectors.

The classification of radioactive waste from commercial activities in the United States includes high-level waste (HLW), resulting from the reprocessing of fuel in particular, and 4 classes of low-level waste (LLW): A, B, C and GTCC. Class B waste must meet more stringent requirements than Class A waste with regard to the form of the waste, in order to ensure its stability for long-term disposal. Same for class C compared to class B, and GTCC compared to class C. TRU waste is "material contaminated by elements with an atomic number greater than 92 (in particular neptunium, plutonium, americium, and curium)". The correspondence between these categories and those of the IAEA is presented in the table opposite.



October 2020

United States of America

National Report
for the Seventh Review Meeting of the
Joint Convention on the Safety of Spent
Fuel Management and on the Safety of
Radioactive Waste Management

U.S. Department of Energy

COMPARISON OF IAEA AND AMERICAN CLASSIFICATIONS OF RADIOACTIVE WASTE

Waste Class	Description
HLW	The highly radioactive material resulting from the reprocessing of spent fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations, and other highly radioactive material that NRC determines by rule requires permanent isolation.
Class A LLW	Class A waste is determined by characteristics listed in 10 CFR 61.55 and physical form requirements in 10 CFR 61.56. (U.S. does not have a minimum threshold for Class A waste.)
Class B LLW	In accordance with 10 CFR 61.55, Class B waste must meet more rigorous requirements on waste form than Class A waste to ensure stability after disposal. The physical form and characteristics of Class B waste must meet both the minimum and stability requirements set forth in 10 CFR 61.56.
Class C LLW	In accordance with 10 CFR 61.55, Class C waste not only must meet more rigorous requirements on waste form than Class B waste to ensure stability but also requires additional measures at the disposal facility to protect against inadvertent intrusion, such as engineered barriers or greater depth of burial. The physical form and characteristics of Class C waste must meet both the minimum and stability requirements set forth in 10 CFR 61.56.
GTCC LLW	LLW that exceeds Class C concentrations.
AEA Section 11e.(2) Byproduct Material	Tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by such solution extraction operations do not constitute "byproduct material" within this definition.

9 https://www.iaea.org/sites/default/files/usa-7rm.pdf
https://sris.iaea.org/country-overview/introduction/US/United%20States%20of%20America

Report 8

Radioactive waste dumped at sea

The use of radioactivity in many sectors is at the origin of the production of radioactive waste that has the particularity of emitting radiation that can pose a risk to humans and the environment. It cannot be managed like conventional waste and must be dealt with in a specific way. One of the first means used to manage this waste and isolate it from humans was dumping in the oceans.

Following the work of the *Grenelle de la Mer* policy debate held in 2009, a commitment was made to establish better monitoring and more effective control of the marine environment. With regard to dumped radioactive waste, this commitment translates into *"consolidating the inventory of underwater nuclear waste dumps, assessing its dangerousness and establishing priorities for carrying out analyses on sedentary fauna and flora as well as sediments"* (Blue Book of the *Grenelle de la Mer* commitments - 10 and 15 July 2009).

This special report summarises, in particular, the data presented in two reference reports: a 1999 IAEA report: "Inventory of Radioactive Waste Disposals at Sea" (TECDOC 1105), and a report by the DSND (Delegate for nuclear safety and radiation protection for activities and facilities involving defence) following the visit to the Mururoa site on 24 June 2010.

This special report presents information on the dumping of radioactive waste at the international level, including data specific to French radioactive waste.

INTERNATIONAL AND HISTORICAL CONTEXT

Dumping at sea has been a means of managing all types of waste. Radioactive waste was no exception to this rule.

The solution of dumping this waste, i.e. depositing it on the seabed, without burial, after conditioning for the most active wastes, was considered by the scientific community, at the time, to be safe because the dilution and assumed duration of isolation provided by the marine environment were sufficient.

This practice was implemented by many countries for more than four decades, starting in 1946.

REGULATORY CONTEXT

The first texts regulating the dumping of radioactive waste were formulated by the United Nations Conference on the Law of the Sea in 1958.

These texts called on all States to take measures to prevent pollution of the seas due to dumping radioactive waste and recommended that the International Atomic Energy Agency (IAEA) establish safety criteria and recommendations on this subject. States remained free to organise their dumping operations.

In 1961, the IAEA recommended that these dumping operations be carried out at sites specially designated by a competent authority, which would also ensure the control of the operations.

It was in this spirit that, from 1967, the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD), which at the time had only European countries as members, began to coordinate waste collections of the candidate European States, with a view to optimising dumping operations.

Then the London Convention of 1972, recognised as the main international mechanism for controlling the dumping of waste into the sea, prohibited, as soon as it entered into force in 1975, the dumping of highly radioactive waste and required a special authorisation for dumping low-level radioactive waste.

The London Convention also confirmed the role of the IAEA in defining specific rules for the dumping of radioactive waste at sea.

Despite the introduction of these regulatory provisions, a number of parties of the Convention have expressed concern about the possible risks to human health and the environment involved in the disposal of radioactive waste at sea. A voluntary moratorium on the dumping of this waste was adopted in 1983 pending a comprehensive review of the issue.

Following this review, to which the IAEA contributed significantly, the signatory parties of the Convention decided in 1993 to prohibit the dumping of any type of radioactive waste into the sea, specifying, however, that this decision was not based on scientific and technical considerations, but rather on moral, social and political criteria.

THE DIFFERENT TYPES OF WASTE DUMPED

Several forms of radioactive waste have been dumped at sea:

- **liquid waste**, directly discharged at sea on dedicated sites or placed in containers, but not solidified;
- non-conditioned **solid waste** or, for the most part, packaged solid waste, generally in metal drums, after incorporation into a concrete or bitumen matrix, in accordance with IAEA recommendations.

There are also nuclear reactor vessels, possibly containing fuel, from the United States or the former USSR.

HISTORY OF DUMPING AT SEA

The first dumping operation was carried out by the United States in 1946 in the North-East Pacific, some 80 kilometres off the coast of California; the last, excluding the former USSR, took place under the authority of the NEA in 1982 in the Atlantic, about 550 kilometres off the European continental shelf.

Between these two dates, 14 countries have dumped waste at more than 80 sites in the Pacific and Atlantic oceans (and their adjacent seas). The total activity of the dumped waste was approximately 85,000 terabecquerels at the time of dumping.

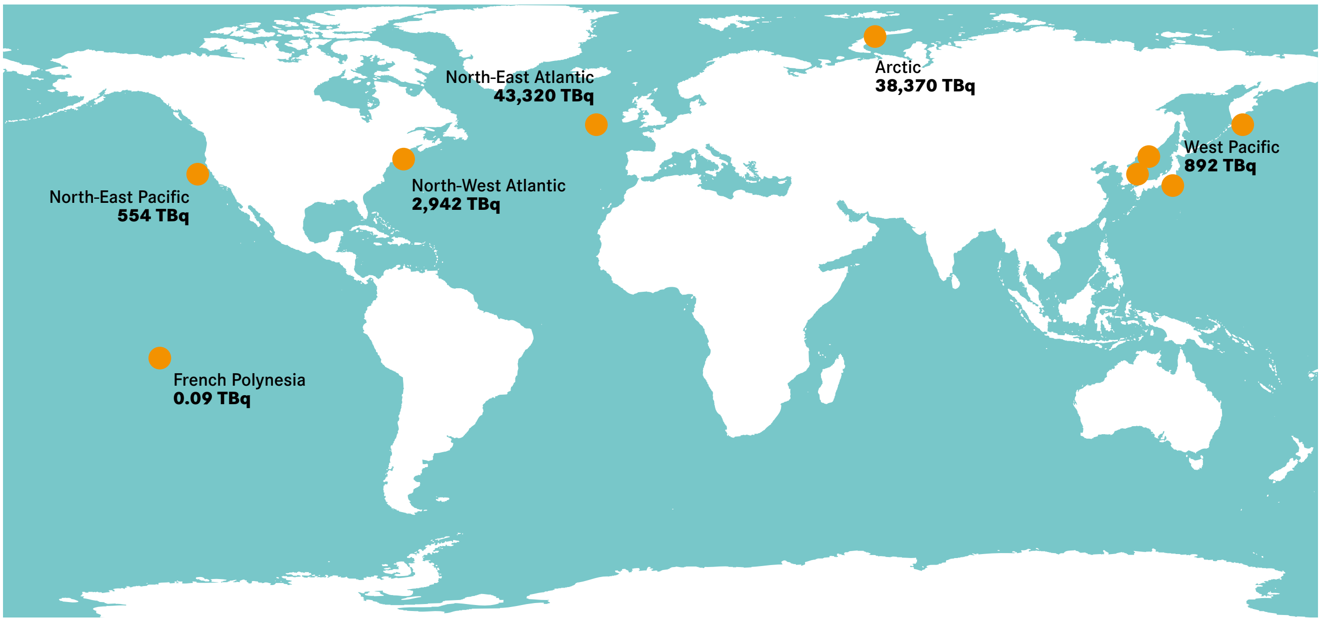
The map below lists the different sites used and the table shows the reports of activity dumped for each area concerned.

99% of the total radioactivity comes from waste containing beta/gamma emitters, including fission and activation products such as strontium-90, caesium-137, iron-55, cobalt-58, cobalt-60, iodine-125, carbon-14, and tritium.

DISTRIBUTION OF THE ACTIVITY OF THE DUMPED WASTE

Zone	α activity (TBq)	β/γ activity (TBq)	Total activity (TBq)	Percentage of total activity (TBq)
North-East Atlantic	675	41,645	42,320	49.7%
North-West Atlantic	-	2,942	2,942	3.5%
Arctic	-	38,370	38,370	45.1%
North-East Pacific	0.04	554	554	0.7%
West Pacific	-	892	892	1%
Pacific (French Polynesia)	0.07	0.02	0.09	-
Total	~ 675	~ 84,400	~ 85,100	100%

RADIOACTIVE WASTE DUMPING SITES WORLDWIDE



DUMPING IN THE NORTH-EAST ATLANTIC AND THE BALTIC SEA

The first dumping operation in the North-East Atlantic, in 1949, was carried out by the United Kingdom (which had already dumped liquid waste in its territorial waters east of Norwich in 1948) through an experimental operation carried out at a site located about 600 km west of Brittany, France.

This operation involved 9 tonnes of conditioned waste, representing an activity of around 0.04 terabecquerels.

From that date until 1966, the United Kingdom, but also Belgium to a lesser extent, regularly dumped at various sites in the Atlantic and the English Channel. In particular, these two countries dumped waste at Hurd's Deep, located 15 km north-west of Cap de La Hague *(site 2 of the table below)*.

Sweden, for its part, dumped 230 containers (about 44 m^3) in the Baltic Sea, about 30 km south-east of the island of Öja, during two operations in 1959 and 1961 for a total activity of about 15 gigabecquerels (0.015 TBq)

Dumping of radioactive waste at sea in the 1960s

DUMPING IN THE NORTH-EAST ATLANTIC FROM 1949 TO 1966

Site	Latitude	Longitude	Depth (m)	Date	Country	Tonnage (t)	Activity (TBq)
1	48°30' N	13°00' W	3,600-4,000	1949	United Kingdom	9	0.04
2	49°50' N	2°18' W	65-160	Every year from 1950 to 1963	Belgium, United Kingdom	17,274	60
3	55°20' N	11°20' W	2,700	1951	United Kingdom	33	0.2
4	55°80' N	12°10' W	2,800	1953	United Kingdom	57	0.15
5	32°37' N	14°50' W	4,000-4,200	1955	United Kingdom	1,453	1.7
6	32°42' N	19°30' W	3,600-4,100	1957, 1958	United Kingdom	7,098	131
7	32°38' N	20°50' W	2,100-4,800	1961	United Kingdom	4,360	81
8	46°27' N	6°10' W	4,200-4,600	1962	United Kingdom	253	6.7
9	45°27' N	6°16' W	4,100-4,800	1963, 1964	Belgium, United Kingdom	10,201	850
10	48°20' N	13°16' W	1,900-4,500	1965, 1966	United Kingdom	2,803	617
Total						~ 43,500	~ 1,800

The table above summarises the data collected by the IAEA on these different operations and marked in orange on the map on page 183.

From 1967 to 1983, when the moratorium on the disposal of low-level radioactive waste at sea was signed, the dumping operations were coordinated by the NEA. They concerned three sites, all located in oceanic trenches.

In 1967, Germany, Belgium, France, the United Kingdom, and the Netherlands dumped around 11,000 tonnes of waste (34,000 containers) at a site 400 km off the coast of Galicia (Spain) (*site marked in purple on the map on page 183),* more than 4,600 metres deep: this waste represented a radioactivity of around 300 terabecquerels.

DUMPING COORDINATED BY THE NEA AT THE 1967 SITE

Country	Number of containers	Mass (t)	Activity (TBq)
Germany	480	181	0.2
Belgium	1,945	600	7
France*	31,596	9,184	220
United Kingdom	-	722	66
Netherlands	-	207	0.07
Total	34,021	10,894	293.27

* These data for France are detailed on page 184.

In 1969, a new operation, this time involving Belgium, France, the United Kingdom, Italy, the Netherlands, Sweden, and Switzerland, resulted in the dumping of about 9,000 tonnes of waste corresponding to a radioactivity of around 900 terabecquerels at a site 900 km west of Brittany, at a depth between 4,000 and 4,600 m (*the so-called Porcupine site marked in yellow on the map on page 183).*

DUMPING COORDINATED BY THE NEA AT THE 1969 SITE

Country	Number of containers	Mass (t)	Activity (TBq)
Belgium	2,222	600	18
France*	14,800	5,015	134
Italy	100	45	0.2
Netherlands	-	303	1
United Kingdom	-	1,878	665
Sweden	2,895	1,081	3.2
Switzerland	100	224	13
Total	20,117	9,146	834.4

* These data for France are detailed on page 184.

From 1971 to 1982, a single site, with an area of 4,000 km^2, located off the Bay of Biscay, nearly 1,000 km from the French coast (sites marked in green on the map opposite) was recommended by the NEA and used by Belgium, the United Kingdom, the Netherlands, and Switzerland: 87,000 containers were dumped there, totalling about 36,000 terabecquerels in activity (*see table opposite*).

DUMPING AT THE NEA SITE BETWEEN 1971 AND 1982

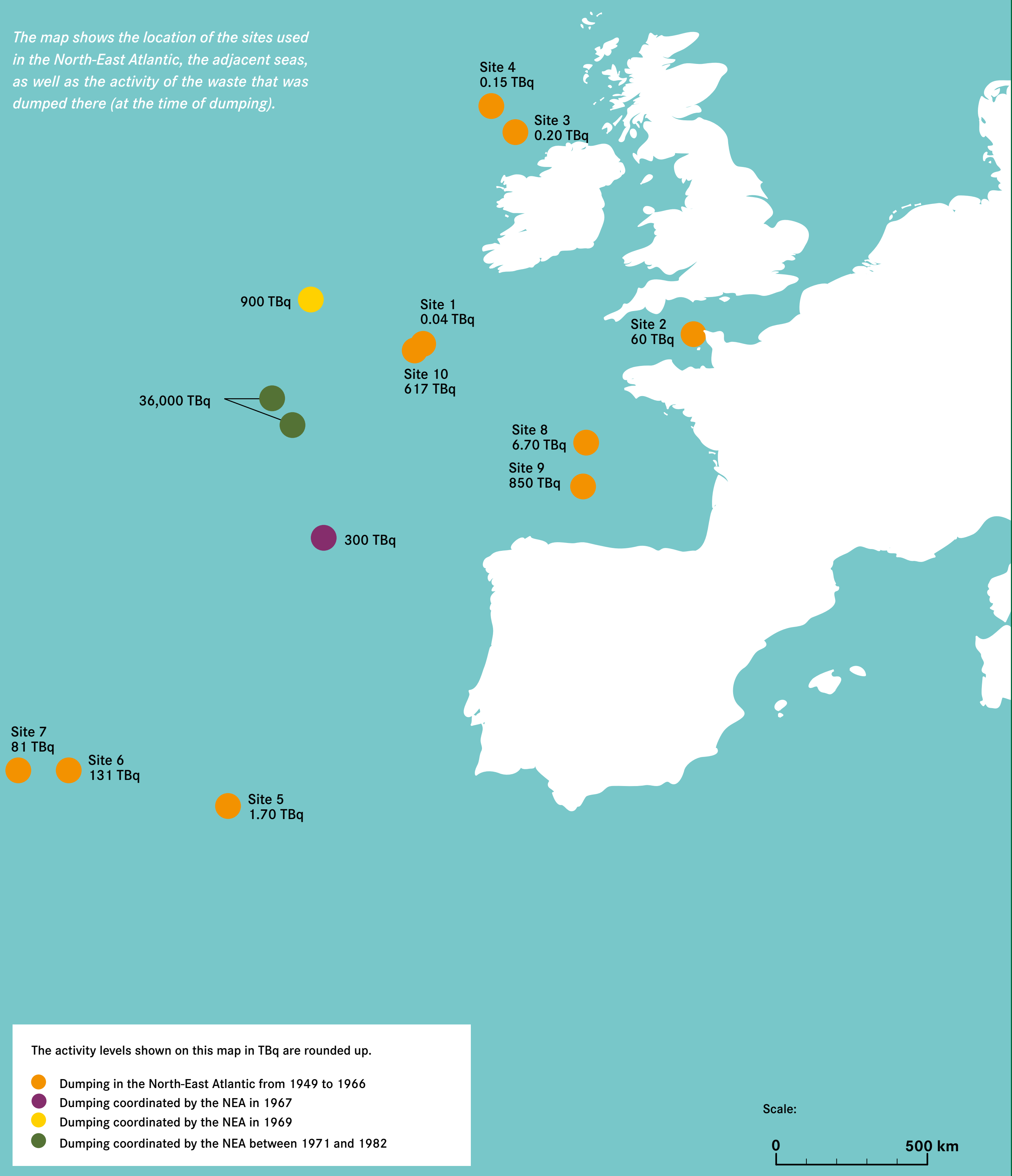
Country	Number of containers	Mass (t)	Activity (TBq)
Belgium	51,157	27,026	2,090
United Kingdom	-	23,788	29,050
Netherlands	> 28,428	18,652	335
Switzerland	7,370	5,097	4,407
Total	86,955	74,563	35,882

During the entire period from 1949 to 1982, the United Kingdom also carried out dumping operations at about twenty other sites within its territorial waters, particularly in the Irish Sea, totalling an activity of about 10 terabecquerels.

It also carried out two operations in 1968 and 1970 at a site *(site 10 of the table on page 181)* in the Atlantic that it had already used in 1965 and 1966, dumping 4,838 tonnes of waste for a total activity of 13,500 terabecquerels.

SITES USED IN THE NORTH-EAST ATLANTIC

The map shows the location of the sites used in the North-East Atlantic, the adjacent seas, as well as the activity of the waste that was dumped there (at the time of dumping).



The activity levels shown on this map in TBq are rounded up.

- Dumping in the North-East Atlantic from 1949 to 1966
- Dumping coordinated by the NEA in 1967
- Dumping coordinated by the NEA in 1969
- Dumping coordinated by the NEA between 1971 and 1982

DUMPING PRACTISED BY FRANCE

As previously reported, France took part in the two operations coordinated by the NEA in 1967 and 1969 in the North-East Atlantic.

It did not participate in the following campaigns coordinated by the NEA, the opening of the Manche disposal facility having been authorised in 1969.

In addition, France has carried out dumping in the Pacific in order to dispose of certain waste induced by activities related to nuclear tests carried out in Polynesia.

Three sites were used, all located in French territorial waters: two off Mururoa Atoll, one off Hao Atoll.

No French dumping was practised in the English Channel: only the United Kingdom and Belgium used Hurd's Deep north-west of Cap de La Hague.

With regard to the Mediterranean, the CEA announced in 1962 its intention to dump 6,500 drums of radioactive waste, at a depth of 2,500 m, 80 km off the coast between Toulon and Corsica, but this project was abandoned following various protests.

However, in order to verify the feasibility of such operations, inactive drums were dumped in this area.

DETAILS OF FRENCH DUMPING IN THE NORTH-EAST ATLANTIC

During the dumping campaign coordinated by the NEA in 1967, France dumped 896 metal containers (347 tonnes) containing waste encapsulated in concrete, corresponding to an activity of about 0.4 terabecquerels, and 30,700 galvanized steel drums (8,837 tonnes) containing thickened sludge from the treatment of liquid effluents for an activity of 220 terabecquerels.

During the dumping campaign coordinated by the NEA in 1969, 14,800 containers of metal drums containing either sludge from liquid effluent treatment, encapsulated or not in bitumen (2,201 tonnes), or concreted waste (2,814 tonnes), were dumped between 4,000 and 4,600 m deep at the so-called "Porcupine" site. The total activity of this waste was 134 terabecquerels.

DETAILS OF FRENCH DUMPING IN THE PACIFIC

Two sites were used near Mururoa:
- the ***Novembre*** site, located between 4 and 8 km from the atoll;
- the ***Oscar*** site at a distance of 5 to 10 km from the atoll (*see map opposite*).

These two sites allowed dumping from helicopters for ***Novembre*** and from boats for ***Oscar***, at a depth of more than 2,000 m.

A single site, ***Hôtel***, was used in Hao, about 8 km from the atoll, to carry out dumping by boat at a depth of 2,500 m.

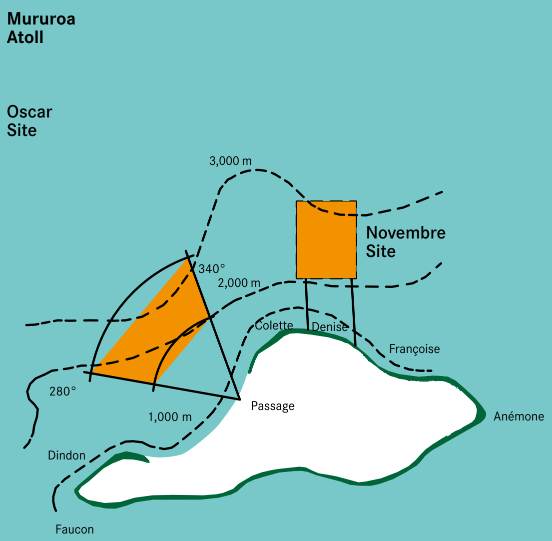
76 tonnes of non-conditioned radioactive waste were dumped between 1972 and 1975 at the Novembre site, for a total radioactivity of eight gigabecquerels (0.008 TBq).

On ***Oscar***, 2,580 tonnes of waste conditioned in concrete containers or in bulk were dumped between 1974 and 1982, for a total radioactivity of about 60 gigabecquerels (0.06 TBq).

The activity of this waste comes mainly from alpha emitters, in particular plutonium.

Finally, 310 tonnes of radioactive waste packaged in concrete drums and 222 tonnes of bulk radioactive waste were dumped at the *Hôtel* site between 1967 and 1975: the activity of this waste was due to beta-gamma emitters and was about 15 gigabecquerels (0.015 TBq).

SITES USED IN FRENCH POLYNESIA



Mururoa Site

Hao Site

SURVEILLANCE OF DUMP SITES

Until 1977, in accordance with the provisions adopted by the United Nations Conference on the Law of the Sea in 1958, States were free to organise and supervise radioactive waste dumping operations themselves, subject to compliance with the recommendations issued by the IAEA, in particular with regard to the choice of dumping site, the monitoring of operations and the evaluation of the radiological impact, and to keep the IAEA informed of the details of the operations carried out.

The monitoring of the sites was therefore under the sole control of the State concerned, as defined by the London Convention.

In 1977, most of the NEA member countries, particularly those that had participated in coordinated dumping operations but also those that opposed these practises, wished to increase their cooperation with a view to adding effective international surveillance to national control.

This desire was at the origin of the decision of the OECD Council to set up a *"multilateral consultation and surveillance mechanism for sea dumping of radioactive waste"* which replaced the *ad hoc* and voluntary arrangements in force up to that time. This decision obliged member countries to submit to the guidelines and the surveillance exercised by the NEA.

SURVEILLANCE OF SITES USED, IN PARTICULAR UNDER THE COORDINATION OF THE NEA

In 1977, only one site was still used by the NEA countries for dumping (sites marked in green on the map on page 183).

The decision of the OECD Council also obliged the NEA to assess, at least every five years, whether this site was still appropriate.

A research program called CRESP[1] was then set up in 1980 to provide a reliable and complete scientific basis for site assessments.

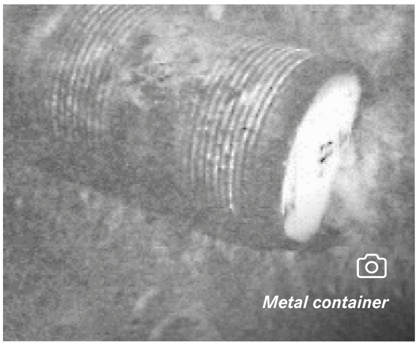
Primarily concerned with the radiological consequences of dumping and based on the study of the processes that control the transfer of radionuclides into the marine environment to establish safety assessments, this international programme incorporated a large amount of data on oceanography, water geochemistry, biology, etc., collected by all the research vessels that operated on or around the last dumping zone used from 1971 to 1982, but also on the two sites used by France in 1967 and 1969 (*sites marked in yellow and purple on the map on page 183*).

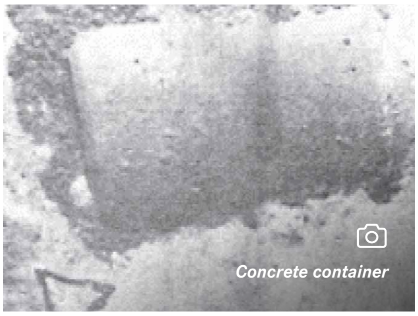
The results of the analyses of samples collected showed no significant increase in the concentrations of radionuclides representative of the dumped waste.

The radioactivity observed in the area of the submerged waste becomes mixed with the fluctuations in the natural radioactivity of these seabeds.

In view of the low levels of exposure and irradiation that could be demonstrated, the need for continuous monitoring of the NEA site after the total ban on dumping of radioactive waste in 1993 was not retained and the CRESP programme therefore ended in 1995.

In parallel with these surveillance programmes based on the interpretation of different measurements, a direct photographic site investigation of the NEA site was organised by Ifremer, in collaboration with the CEA, in June 1984[2].





Photographs taken in 1984 of containers dumped in 1979.

1 NEA 1996: *Co-ordinated Research and Environmental Surveillance Programme Related to Sea Disposal of Radioactive Waste.*

2 Minutes from the Academy of Sciences vol. 301, series III, No. 10, year 1985: "*Photographic reconnaissance of containers in place in the disposal zone of low-level radioactive waste in the North-East Atlantic*" by Myriam Sibuet, Dominique Calmet, and Gérard Auffret.

An unmanned submersible travelled 61 linear km at an average depth of about 3.6 m above the seabed, making it possible to take 15,890 photographs at the rate of one photograph every 5 seconds. Six containers were able to be photographed (compared to the 123,000 containers dumped in this area). Five had metal enclosures (like most packages dumped at this site), the sixth was made of concrete. In 1984, these six containers seemed to be intact, despite some deformation. The impact on the containers when they landed on the seabed was different according to these two types of packaging and seemed to be a function of the density of the containers. The five metal containers were very slightly embedded in the sediment; the concrete container was more deeply buried in the centre of a large crater.

The enclosures of some metal containers seemed to be corroded. Two of the containers could be identified as part of those dumped in 1979. Finally, in the early 2000s, Greenpeace explored the seabed of Hurd's Deep, used by the United Kingdom and Belgium, at a depth of up to a hundred metres. After locating the radioactive waste drums, a remotely controlled vehicle, equipped with cameras, was lowered to the bottom to allow a more precise inspection which made it possible to note the degradation of many drums.

Countries that have carried out dumping operations in the past, including as part of operations coordinated by the NEA, remain responsible for these operations. Any new measurement or photographic investigation campaign therefore remains at the initiative of each relevant country that may decide to perform such a campaign.

MONITORING OF THE MURUROA AND HAO ATOLLS

When the French nuclear tests in the Pacific were definitively halted in 1996, France asked the IAEA to carry out a radiological assessment of the Mururoa test sites and the areas surrounding these sites.

It is this assessment that constitutes the reference situation for activity levels in the environment of the two testing atolls. Although the IAEA experts concluded that there was no need to continue radiological monitoring of the atolls, it was decided to maintain a monitoring programme in order to detect, in particular, possible releases of radionuclides from the cavities and sediments of the lagoons.

This monitoring concerns the environment of the two atolls and has two parts:

- continuous monitoring of atmospheric aerosols and integrated dose;
- an annual sampling campaign, the Turbo mission, conducted each year from March to June.

Samples of the different species of flora and fauna, both terrestrial and marine, as well as underground circulating in the island, are taken to measure their radioactivity. All the samples are searched for gamma-emitting radionuclides and a selection of them is measured for tritium, strontium-90 and plutonium isotopes.

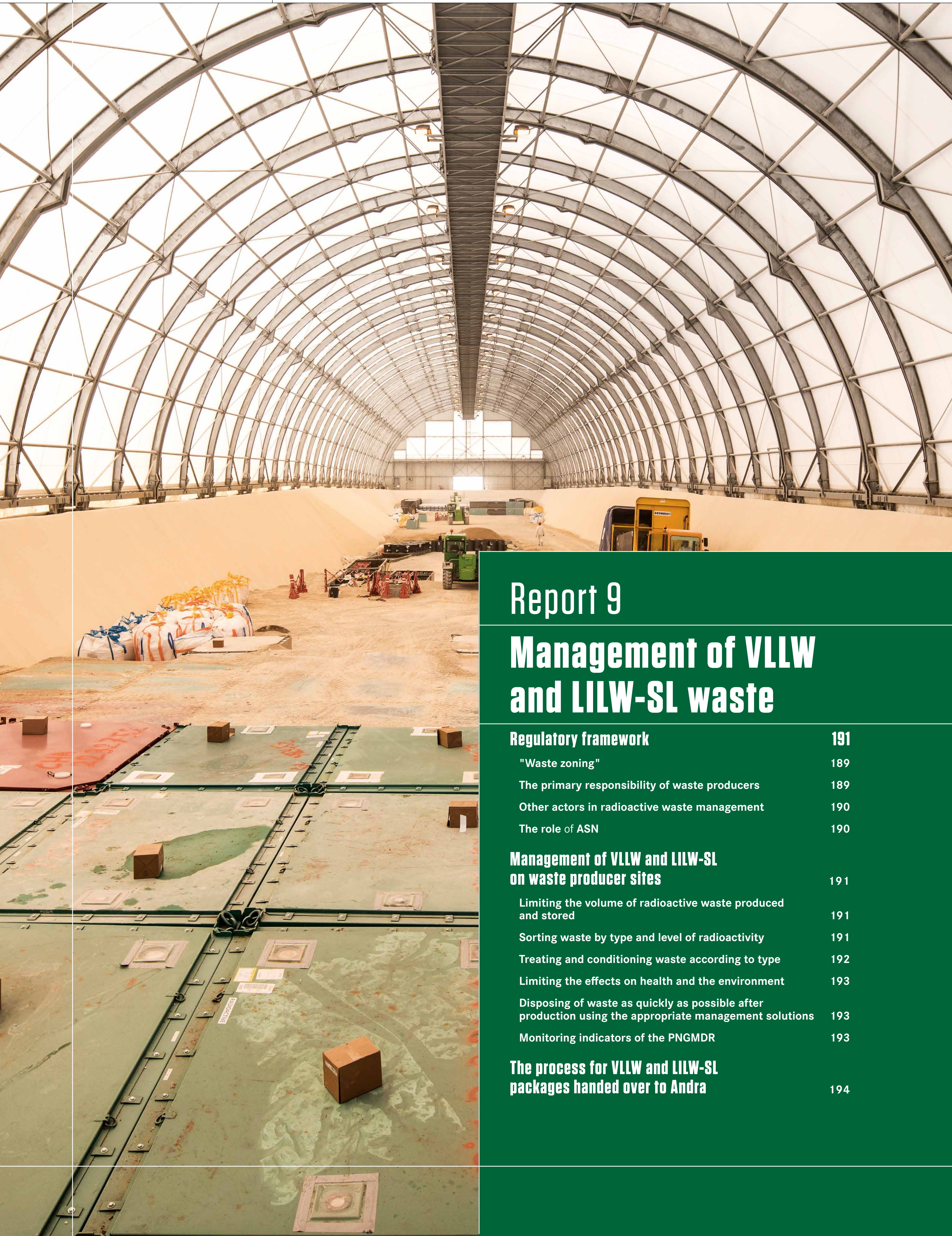
Radionuclides measured in and around Mururoa are present at very low levels and most often close to the detection limit of radioactivity measuring devices.

Particularly regarding the Hao dumping zone, radiological measurements were carried out at the disposal site in 2007 by taking water samples at various depths. There was no increase in radioactivity compared to the reference level of oceanic radioactivity.

FOCUS — SPECIFIC CASE OF FANGATAUFA ATOLL

South of Mururoa atoll is Fangataufa atoll where France carried out 4 nuclear experiments in the atmosphere between 1966 and 1970 and then, from 1975 to January 1996, 10 underground nuclear tests.
The facilities of the Pacific Experimentation Centre (CEP) were dismantled between February 1996 and July 1998.

Although no radioactive waste was dumped in Fangataufa Atoll, the sediments at the bottom of the lagoon and the atoll's subsoil are marked by deposits resulting from atmospheric and underground nuclear tests.
As for Mururoa atoll, a study on the radiological situation of Fangatufa atoll was carried out in 1996, concluding that radioactivity levels in the environment were similar.

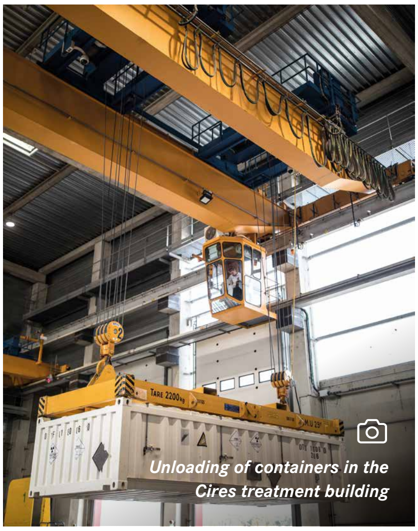


Report 9

Management of VLLW and LILW-SL waste

Very low-level (VLLW) and short-lived low- and intermediate-level (LILW-SL) waste categories are the categories that represent the largest volume of waste. These categories of waste are produced by nuclear and non-nuclear installations, whether they are in the operating or dismantling phase. Depending on the installations, the phase they are in, and the volume of waste produced, it may be "common" waste, for which industrial and standardised management is implemented by the waste producer, or "non-standard" waste due to its size or type, and for which management requires a suitable solution.

This special report proposes to cover the various steps relating to the management of VLLW and LILW-SL waste produced by the main operators of the French nuclear power sector (EDF, Orano, and the CEA), from its production site through to its disposal in Andra facilities.



Unloading of containers in the Cires treatment building

REGULATORY FRAMEWORK

The management of waste, whether radioactive or not, is governed by Articles L. 541-1 et seq. of the French Environmental Code, which incorporates, in particular, transpositions of Directive 2011/70/Euratom adopted in 2011. The French Public Health Code also provides for provisions relating to waste generated in the context of nuclear activities, which should be called to memory in order to shed light on the management arrangements for VLLW and LILW-SL waste.

"WASTE ZONING"

Waste management at nuclear installations is regulated. Industrial actors must establish "waste zoning" of their installation, making it possible to distinguish two types of zones:

- "potential nuclear waste production zones", where contaminated, activated or likely to be contaminated/activated waste is produced. The waste produced in these areas must be subject to specific and reinforced management, through dedicated solutions, authorised for this purpose;
- “conventional waste zones”. After checking there is no radioactivity, waste from these areas is directed to conventional waste solutions (hazardous, non-hazardous or inert waste).

These elements are specified in decision 2022-DC-0749 of 29/11/2022 amending decision 2015-DC-0508 of 21 April 2015.

THE PRIMARY RESPONSIBILITY OF WASTE PRODUCERS

The operator producing radioactive waste is responsible for its disposal in a facility authorised for this purpose. As producers of waste, operators of nuclear activities must pursue an objective of minimising the volume and activity of their waste throughout the duration of their installations: upstream during the design phase, then the operating phase, as well as downstream during the clean-up-dismantling phases. The quality of the conditioning must also be ensured.

The responsibility of the producer also includes monitoring of the way in which waste is produced and stored in its own installations, but also the verification that the waste is managed through authorised solutions (treatment, storage, and disposal solutions).

Decision No. 2017-DC-0587 of the French Nuclear Safety Authority of 23 March 2017 specifies the general requirements concerning radioactive waste packages, their manufacturing and inspection conditions, so that they can be accepted at basic nuclear disposal installations, whether existing or under consideration.

The operator is therefore responsible for sorting, conditioning, and transporting the waste products to the treatment or disposal centre and, above all, for characterising them (permeability, radiological inventory, etc.) before they are handed over to the selected disposal solution.

OTHER ACTORS IN RADIOACTIVE WASTE MANAGEMENT

ASN inspection at the Aube disposal facility

Actors other than waste producers are involved in waste management. This is the case of:

- transport companies (Orano Packages and Services, BNFL SA, etc.);
- treatment companies that can carry out compaction, incineration and melting operations (Cyclife, Orano, CEA, etc.);
- managers of storage facilities (CEA, Orano, EDF);
- managers of disposal facilities (Andra);
- Industrial actors and organisations in charge of research and development to optimise the management of radioactive waste (CEA, Andra, CNRS, Orano, Framatome, and EDF).

Each actor is responsible for the safety of their activities. Waste treatment providers or managers of storage or disposal facilities act on behalf of producers, who remain the owners of their waste.

THE ROLE OF ASN

ASN participates in the development of regulations relating to the management of radioactive waste, ensures the monitoring of regulatory compliance and provisions relating to safety, from design to dismantling, of basic nuclear installations at the origin of the waste or involved in its disposal and carries out inspections at the various waste producer premises, treatment provider premises and at Andra. It checks the general organisation set up by Andra for the acceptance of waste from producers. It evaluates the waste management policy and practices of radioactive waste producers.

MANAGEMENT OF VLLW AND LILW-SL ON WASTE PRODUCER SITES

Each producer is responsible for its own strategy concerning the manufacture of radioactive waste packages, the method of upstream treatment if necessary, and their on-site storage before shipment to Andra disposal facilities.

These strategies focus on common issues:
- limiting the volume of radioactive waste produced and stored;
- sorting waste by type and level of radioactivity;
- treating and conditioning waste according to type;
- limiting the effects on health and the environment;
- disposing of waste as quickly as possible after production using the appropriate management solutions.

LIMITING THE VOLUME OF RADIOACTIVE WASTE PRODUCED AND STORED

This challenge includes actions to limit waste at the source, for example by reducing the entry of equipment into nuclear areas through training and worksite preparation actions or maintenance interventions. Actions are also taken to optimise dismantling as early as plans to build new installations.

In general, the sectoring of all production areas, called "waste zoning", has been carried out in order to identify and limit as much as possible the sectors where radioactive waste can be produced, and to allow for reliable and functional waste management.

SORTING WASTE BY TYPE AND LEVEL OF RADIOACTIVITY

VLLW and LILW-SL waste from operations and dismantling is collected and sorted from the outset, i.e. as soon as it is produced. The management of radioactive waste produced on the sites is carried out in such a way as to ensure traceability from its production to its final destination.

The sorting at source and the precise inventory of radioactive waste then make it possible to direct waste as soon as it is produced towards the appropriate disposal solution, but also to plan the development of optimised sectors such as the recycling of metal waste or the development of solutions for the management of waste electrical and electronic equipment.

Operating feedback on waste zoning

As part of the previous edition of the PNGMDR 2016-2018, the main waste producers prepared a report to share their experience with waste zoning. This report made it possible to highlight the actions implemented to reduce the volume of waste at the source and the ways forward to continue in this direction.

https://www.asn.fr/Media/Files/00-PNGMDR/PNGMDR-2016-2018/Retour-d-experience-de-la-mise-en-oeuvre-du-zonage-dechets-dans-les-installations

Radiological inspection** of **a truck upon arrival at the CSA

TREATING AND CONDITIONING WASTE ACCORDING TO TYPE

Treatment steps can be put in place, in particular to reduce the volumes or toxicity of certain waste, or to make the waste suitable for long-term management in the disposal facility.

LILW-SL waste is packaged in suitable containers, stored within the perimeter of BNIs or ICPEs, then shipped to the Aube Disposal Facility (CSA).

VLLW waste is packaged in large flexible bulk containers big-bags, crates or large-volume containers and stored for short periods awaiting disposal at the Industrial facility for grouping, storage and disposal (Cires), in external areas or inside buildings. The floors of the installations intended for the temporary storage of waste packages before departure to Andra are leaktight and equipped with retention systems to collect any liquid effluents.

Aerial view of Cires

Aerial view of CSA

The various processes used for the treatment and conditioning of radioactive waste are detailed in the dedicated special report available on the *National Inventory* website:

[*https://inventaire.andra.fr/sites/default/files/documents/pdf/fr/dossier02_in2018.pdf*](https://inventaire.andra.fr/sites/default/files/documents/pdf/fr/dossier02_in2018.pdf)

FOCUS — WASTE IN SURFACE DISPOSAL FACILITIES

Very low-level waste (VLLW) and short-lived low- and intermediate-level waste (LILW-SL) is sent to operational disposal facilities managed by Andra:

- since 2003, the Industrial facility for grouping, storage and disposal (Cires) for disposal of VLLW waste;
- between 1969 and 1994, the Manche Disposal Facility for LILW-SL waste. This facility is now in the closure phase and no longer accepts new waste;
- Since 1992, the Aube Disposal Facility (CSA) for LILW-SL.

These disposal facilities make it possible to provide a safe, long-term management method for this waste by ensuring continuous acceptance of waste to limit storage times and upstream capacity needs on producer premises. The reference process for all nuclear power producers is to send waste packages to these disposal facilities immediately (just-in-time), as and when the waste is produced, after approval from Andra.
This reference process applies in the same way for waste resulting from the operation of sites, as for waste resulting from the dismantling of nuclear installations.

LIMITING THE EFFECTS ON HEALTH AND THE ENVIRONMENT

These measures aim to protect workers, the public, and the environment by limiting, in all circumstances, the dispersal of radioactive substances contained in radioactive waste packages.

To reach this objective, radioactive waste storage facilities are designed and operated in accordance with the defence-in-depth concept, which ensures normal operation by preventing and considering possible failures, detecting them as early as possible, and imagining accident scenarios in order to limit their effects. This defence-in-depth concept is implemented on all nuclear installations.

Detection of abnormal situations is ensured continuously: monitoring of gaseous effluent discharges in the facility outfall by means of sensors and atmospheric sampling, monitoring of liquid effluent transfers by sampling downstream of the installation discharge points.

DISPOSING OF WASTE AS QUICKLY AS POSSIBLE AFTER PRODUCTION USING THE APPROPRIATE MANAGEMENT SOLUTIONS

The storage capacities of VLLW and LILW-SL waste on waste producer premises are sized to ensure a buffer function, and thus absorb waste production over a relatively short period of time before shipment to disposal facilities. These storage capacities are managed according to the forecast shipment flows planned annually, updated each quarter, and confirmed monthly.

The flexibility of these storage facilities also makes it possible to overcome certain constraints or uncertainties that can slow down forecast shipment flows:

- a quality problem may occur from time to time during the process of preparing the waste package, which may then lead to the implementation of a corrective and preventive action plan before resumption of shipments to disposal facilities;
- some non-standard waste requires a specific design phase to define conditioning adapted to the acceptance requirements of the disposal facilities, and therefore generates a longer acceptance period;
- characterisation and preparation operations for so-called "legacy" waste, which are necessary before acceptance in a disposal facility.

Monitoring indicators of the PNGMDR

For VLLW waste that cannot be shipped immediately, the PNGMDR 2022-2026 defines the following indicators in order to monitor over time the management of waste with an existing management solution:

- **i1, monitoring by operator of the annual volume of VLLW waste produced per site and conditioned in the form of final packages that will not be evacuated in less than 24 months to Cires;**
- **i2, monitoring by operator of the volumes of VLLW waste produced by site (excluding legacy VLLW waste and waste awaiting a management solution) pending or in the process of being conditioned for more than 24 months;**
- **i3, ratio of the volume of legacy VLLW waste produced/the volume of historic VLLW waste disposed of.**

Digging of a disposal cell at the Industrial facility for grouping, storage, and disposal

THE PROCESS FOR VLLW AND LILW-SL PACKAGES HANDED OVER TO ANDRA

Before packages are accepted at disposal facilities, producers must first demonstrate and provide evidence of compliance with Andra specifications and requirements (knowledge and measurements of radiological and toxic elements, expectations and performance of packages containing waste).

As a result, each production site obtains:

- an overall "**authorisation**" for its installations to be able to request handover of radioactive waste to Andra;
- an "**approval**" (LILW-SL) or "**acceptance file**" (VLLW) for each stream of packages that will be produced;
- and finally, an "**acceptance**" for each package that will be subject to a handover request.

For the conditioning of their waste, producers must comply with precise specifications defined by Andra. The requirements formulated in the specifications come from rules published by ASN (technical requirements, fundamental safety rules, etc.) or regulatory files that are regularly updated (safety report, general operating rules, etc.).

Once they are authorised, before any shipment and for each package, producers electronically declare the type of waste, the radiological elements and the toxic elements present.

Once the declaration and handover have been validated by Andra, scheduling and transport are organised. The packages are routed to the CSA or Cires directly by trucks from the producer sites, which are responsible for transport. This represents more than 2,500 transport operations per year.

There are several levels of inspection:

- Upstream, on producer premises, through audits and inspections by Andra (verification of requirements, advice, corrective measures if necessary);
- upon arrival at the disposal facility: 100% of packages are subject to an information check and radiological check (dose rate check and smear test to ensure that there are no traces of contamination on the surface);
- then, certain packages are selected, most of the time randomly, to carry out further checks: non-destructive checks (gamma spectrometry, radiography, tritium gas release measurement) and/or destructive checks (coring, package opening).

If a discrepancy between the producer's declaration and the result of one of these checks is found, measures are taken according to the degree of severity:

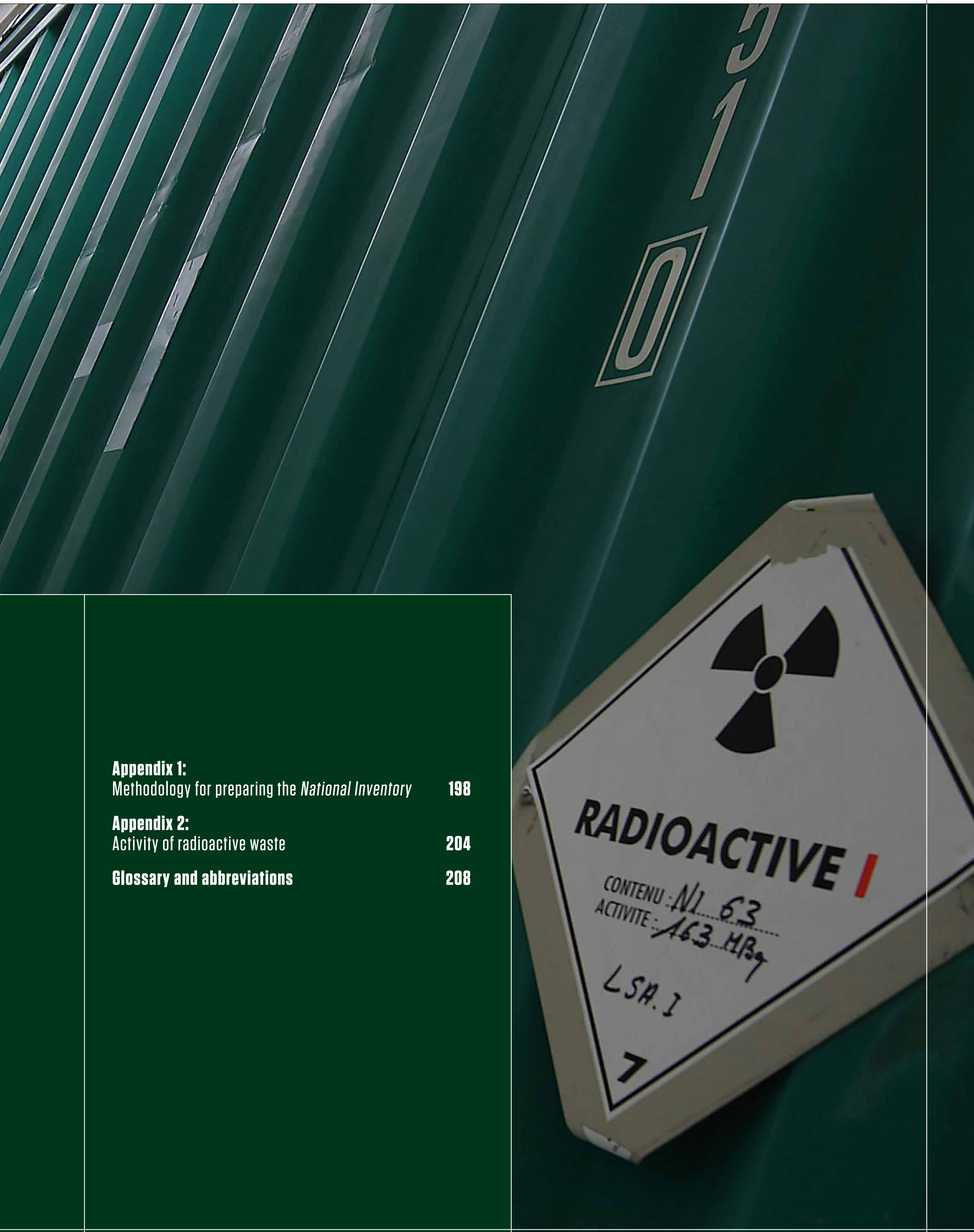
- reporting and awareness-raising;
- return of the package to the producer site;
- interruption of acceptance of packages from the producer site;
- suspension of the producer site's authorisation.

It should be noted that waste management at producer sites (methodology, conditioning, storage, etc.) is also subject to inspections by ASN.

Positioning of a radioactive waste package in a disposal structure at the CSA

07

Appendices and glossary


RADIOACTIVE I
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Appendix 1

Methodology for preparing the *National Inventory*

HOW THE *NATIONAL INVENTORY* IS CARRIED OUT

REGULATIONS

Article L. 542-12 of the French Environmental Code, amended by the Law of 9 December 2020[1], requires Andra to *"draw up, update every five years and publish a national inventory of radioactive materials and waste present in France or intended for disposal, and the location of these materials and waste in France."*

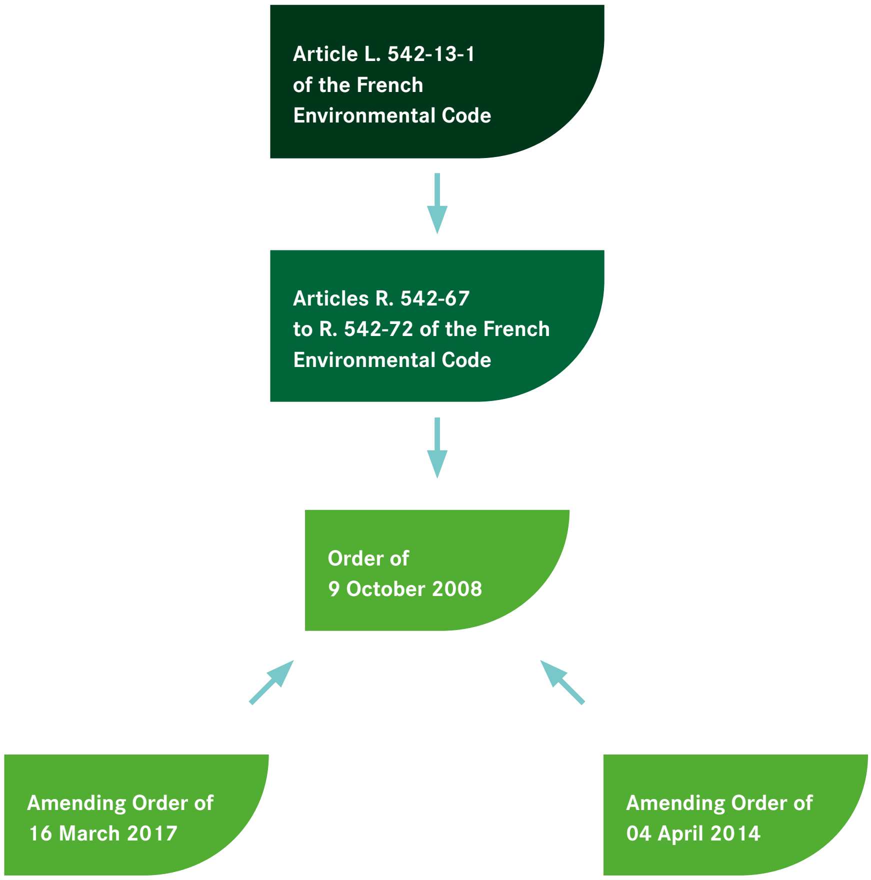
Articles R. 542-67 to R. 542-72 of the Environmental Code and the Ministerial Order of 9 October 2008[2], amended by the Ministerial Orders of 4 April 2014 and 16 March 2017[3], define the reporting obligations of producers and holders of radioactive materials and waste.

For the 2023 Edition of the *National Inventory*, the existing stores of waste were established at the end of 2021, the forecasts are established for the 2030 and 2040 horizons and at end-of-life, that is to say at the end of dismantling of the nuclear installations licensed by the end of 2021.

Only waste from the operation and dismantling of installations that already existed or were licensed at the end of 2021 is included in the *National Inventory*.

The operation of a nuclear installation includes its operating phase and its dismantling phase.

REGULATIONS APPLICABLE TO THE *NATIONAL INVENTORY*



1 Article 1 of the Law of 9 December 2020, requires Andra to draw up, update every five years, and publish an *inventory of radioactive materials and waste* present in France or intended for disposal, and the location of these materials and waste in France.

2 Order of 9 October 2008 on the nature of the information that managers of nuclear activities and the companies mentioned in Article L. 1333-10 of the French Public Health Code are required to establish, maintain, and periodically transmit to the French National Radioactive Waste Management Agency.

3 Orders of 4 April 2014 and 16 March 2017 amending the order of 9 October 2008 relating to the nature of the information that managers of nuclear activities and the companies mentioned in Article L. 1333-10 of the Public Health Code are required to establish, maintain, and transmit periodically to the French National Radioactive Waste Management Agency.

PRINCIPLES

A strict methodology and rigorous data verification procedures underpin the completion of the *National Inventory of Radioactive Materials and Waste.*

There are several objectives:

- identify radioactive materials and waste on French territory from each producer or holder. This identification includes foreign waste destined for return to its country oforigin. Andra has been carrying out this work since 1992. Initially carried out on the basis of voluntary declaration by producers and holders, this work has been performed since 2008 within the regulatory framework described on page 199;
- establish a summary view of existing and future radioactive materials and waste according to various contrasting scenarios, with, for some of them, photographs of stores at key dates defined by ministerial decree, as well as at term, i.e. once the nuclear installations have been dismantled.

FOCUS — RADIOACTIVE MATERIALS AND WASTE IN FRANCE

The*National Inventory* lists all of the radioactive materials and waste present in France. It therefore takes into account radioactive materials and waste from the reprocessing of foreign fuels, even though these are to return to their country of origin.

The operators of nuclear installations carrying out reprocessing operations on behalf of foreign customers, make public each year a report that lists all the radioactive materials and waste belonging to their foreign customers, in accordance with Article L. 542-2-1 of the French Environmental Code.

Five guiding principles govern the development of the *National Inventory* and ensure its reliability, quality, and its character as a reference:

- **availability of information:** formatting data that can be understood by a wide audience makes it possible to meet the requirement to inform citizens. At the same time, the objective is to provide public authorities with a realistic inventory for the development of the National Radioactive Materials and Waste Management Plan (PNGMDR), an inventory corresponding to the best visibility of waste producers at the time of their declaration;
- **exhaustiveness:** the *National Inventory* identifies existing waste related to recent and ongoing production, but also to past production since the beginning of use of radioactivity properties, whether industrial, for defence, medicine, or research. The objective is to present a "snapshot" of all waste present on French territory at any given time, regardless of its physical or chemical state, conditioned or not, liquid or solid, of high or low radioactivity. The scope of the inventory is not limited to disposal or storage of waste. It also applies to all installations housing, even temporarily, radioactive waste to be handed over to Andra, for example in medical or academic research laboratories. It also extends to radioactive materials;
- **neutrality:** the *National Inventory* transcribes the information collected in a factual manner, without judging whether or not the situations and management methods described are hazardous;
- **transparency:** The *National Inventory* presents all radioactive waste and materials, regardless of their origin. This approach is intended to complement the transparency efforts that have been undertaken for several years by public authorities, waste producers and the Nuclear Safety Authority[1]. To follow this principle, a steering committee (*see below "Actors"*), chaired by the Director General of Andra and composed of members from outside the Agency, steers the development of the *National Inventory*;
- **the responsibility of the declarant and the verification by Andra of the management solution:** the *National Inventory* presents the data declared by the waste producers. Each producer is therefore responsible for their own declaration. If necessary, Article R. 542-71 of the French Environmental Code allows Andra to appeal to the administration in the event of failure by a waste producer or holder to comply with its reporting obligations. In addition, Andra checks the suitability of the waste management solution proposed by the producer. However, the reporting obligations of waste producers or holders do not exempt the Agency from ensuring the exhaustiveness of its inventory by cross-checking various sources of information. When the presence of radioactive waste is proven on sites not yet listed, they integrate the *National Inventory* at the next update.

The management solution proposed in the *National Inventory* does not prejudge the acceptance of the waste in the corresponding waste disposal facility.

The *National Inventory* presents all waste, whether or not it is already conditioned; assumptions about conditioning methods are therefore also needed to quantify waste volumes. They correspond to the best assessment that producers have at the time of declaration, but do not always prejudge the conditioning that will actually be used.

1 Law No. 2006-686 of 13 June 2006 on transparency and nuclear safety.

ACTORS

For the vast majority of waste producers and holders, declarations are made digitally. The procedures for verifying the reported data depend on the type of producer:

- **major actors in the nuclear industry** (Andra, Orano, CEA, EDF) who manage several sites. Each site has correspondents who know precisely the state of the inventories and they make the declarations (the declarants). These declarations are then verified and validated by a manager at the level of each organisation (the declaring supervisor). Forecasts are directly declared by supervisors;
- **producers outside the nuclear power industry** produce lower volumes of radioactive waste. Each nuclear activity manager makes their declaration directly without validation by a superior. Each declared data item is verified by Andra: comparison with the previous declaration, consistency check, cross-checks with possible other sources of information, analysis of the waste management system chosen by the producer, etc. Once analysed, the declarations are then validated by Andra, if necessary after discussions with the producer and resumption of the declarations.

The Steering Committee of the *National Inventory* was created with a view to transparency and efficiency. It makes it possible to share a consensual vision for this inventory. The main mission of the Steering Committee is to validate the assumptions necessary for carrying out the *National Inventory* and the main conclusions resulting from the analysis of the declarations before they are made public. It also checks that the information is provided to the general public with optimal transparency.

In addition, Andra presents an update on the quantities of materials and waste disposed of or stored each year at a meeting of the PNGMDR working group, based on annual declarations from producers.

Non-nuclear power producers refers to producers or holders of radioactive waste from the medical, research (excluding the CEA), defence sectors, and industrial sectors other than nuclear power.

These are mainly producers referred to under article R. 542-68 of the Environmental Code.

FOCUS — COMPOSITION OF THE NATIONAL INVENTORY STEERING COMMITTEE

This committee comprises:

- representatives of the Directorate General for Energy and Climate (DGEC) within the Ministry for Ecological Transition and Territorial Cohesion;
- representatives of the French Nuclear Safety Authorities (ASN, ASND);
- representatives of the main waste producers (nuclear power and non-nuclear power);
- representative from the French national assessment board for evaluating research and studies concerning the management of radioactive materials and waste (CNE2), as an observer;
- representatives of civil society and defence of the environment associations, and local information committees (CLI).

AVAILABILITY OF INFORMATION

ANDRA is in a privileged position to fulfil the inventory mission entrusted to it by the Environmental Code, because of its knowledge of waste, production sites and management solutions. The information collected is correlated with the various other sources available to the Agency.

This information is made available:

- in paper hard copy and Web version for:
  - this *Summary Report;*
  - *the Catalogue describing the categories of radioactive materials;*
  - *the Essentials.*
- in Web version only for:
  - *the Geographic Inventory;*
  - *the Catalogue describing the radioactive waste streams;*
  - *open data files.*

The *National Inventory* website allows filters to be set up to generate and print personalised documents or all of the proposed documents.

THE *SUMMARY REPORT*

This document provides a detailed presentation of the radioactive materials and waste currently in France and expected in the future. The quantities are grouped by category and economic sector.

The quantitative part is supplemented by special reports that focus on certain topics such as the treatment and conditioning of waste or the dismantling and clean-up of nuclear installations.

ESSENTIALS

The Essentials document presents an annual update of the stores of radioactive materials and waste produced in France.

THE *GEOGRAPHIC INVENTORY*

The *Geographic Inventory* is simply the direct reporting of producers' declarations.
It presents each site by administrative region, département, and municipality. It also includes Andra disposal facilities, National Defence establishments, non-nuclear power producer sites and legacy sites. These legacy sites include mining sites and historic disposal sites.

The information is reported in a factual manner, in the form of geographical data sheets. These sheets contain information on the radionuclides present, the volume of the waste (when this information is available), and the management solutions.

The category of the waste, as defined in Chapter 1, is specified as well as the stream to which it belongs (described in the *Catalogue of Waste Streams*). Each type of waste present on the site is mentioned, associated with its activity and volume, once conditioned.

THE *CATALOGUE OF WASTE STREAMS*

Information gathering according to the above principles leads to a high number of declared wastes. The waste has been grouped by stream (a stream is defined as a set of radioactive waste with similar characteristics), for the sake of simplification and presentation. The detailed description of each stream of the *National Inventory* is the subject of the *Catalogue of Waste Streams*.

The *Catalogue of Waste Streams* presents for each waste stream data sheet, the stores of waste at the end of 2021, specifying the proportion on the producer or holder site and the proportion stored in the Andra centres, the total activity of the waste declared by the producers and holders at the date of the inventory (31 December 2021), as well as the production forecasts at the end of 2030 and at the end of 2040.

These forecasts are based on scenario S1 of renewal of the nuclear power fleet by EPR2, and then FNR with an operating life for the reactors of the current nuclear power fleet equal to 60 years.

THE *CATALOGUE OF RADIOACTIVE MATERIAL CATEGORIES*

The *Catalogue describing the categories of radioactive materials* presents a description of all the categories of nuclear materials, as defined in the Order of 16 March 2017.

The material categories are grouped into chapters according to their position in the fuel cycle, as currently implemented in France.

For each of them, their stores, forecast, holder(s) and location(s) at the end of 2021 are presented.

FOCUS — CAN THE *NATIONAL INVENTORY* CLAIM TO BE EXHAUSTIVE?

Since 1993, thanks to the successive updates of the information, the location of the waste and some of its characteristics have been further specified and completed in each sector, with the producers themselves progressing in the knowledge of their waste.

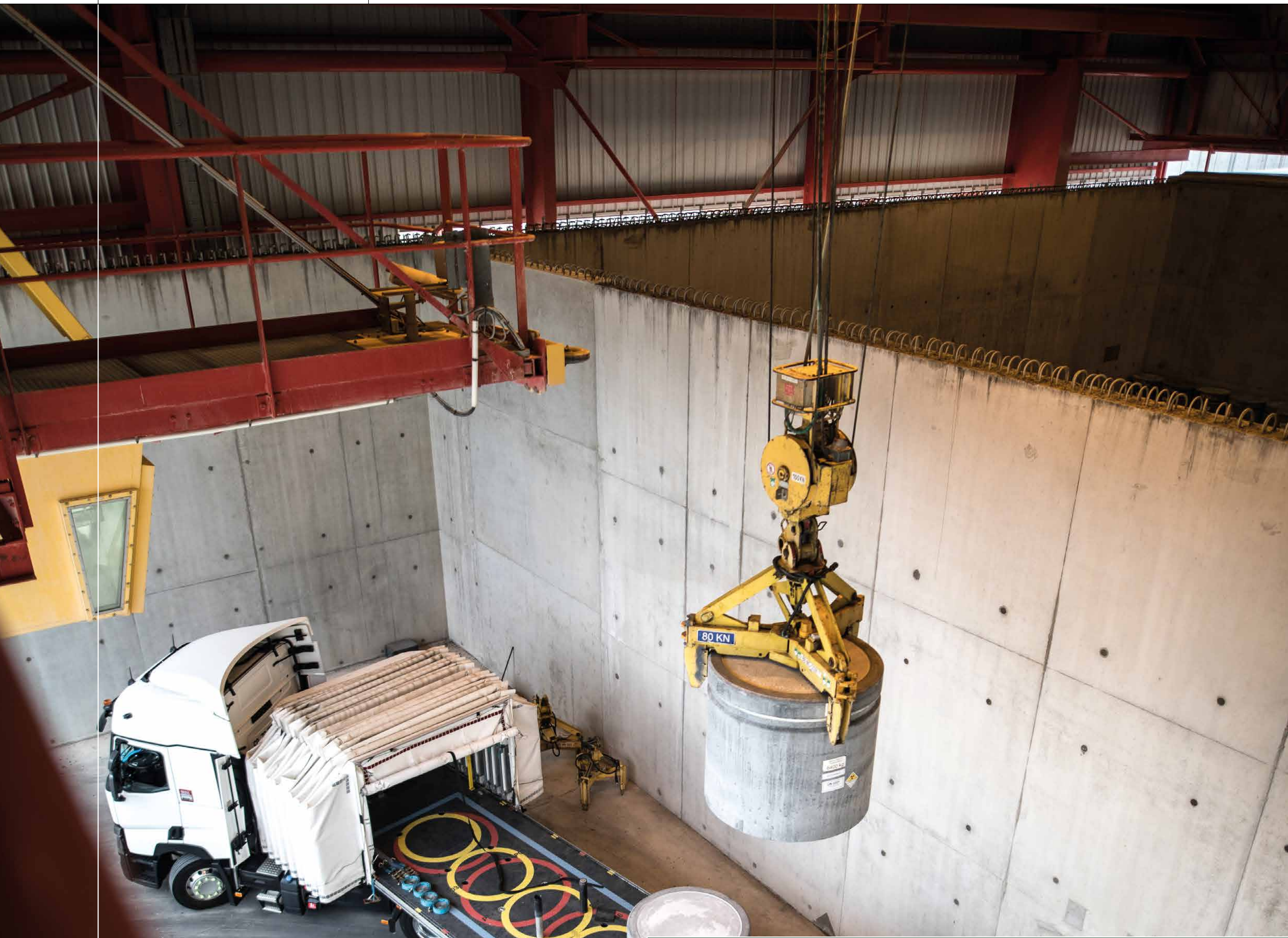
The question of exhaustiveness arises on two levels: the location of the sites on which radioactive waste is located and the quantities and type of the waste for each listed site.

A producer may forget some waste at the time of their declaration. However, as the largest producers also report their waste stores to the Nuclear Safety Authority, this risk is limited. The two declarations are generally compared by the producer, or drawn up jointly. In addition, the Nuclear Safety Authority regularly carries out on-site verifications of the declarations it receives.
In the case of Orano, the waste stores are also audited by an organisation appointed by its customers.

Over the years, some facilities are no longer listed, because they no longer contain radioactive waste (dismantled and remediated sites). On the other hand, new waste-producing facilities are created.

The regulatory nature of the declarations, from 2008 onwards, has contributed to increasing the exhaustiveness of the data reported for this edition of the *National Inventory*. In addition, the incidents at the Tricastin site in the summer of 2008 led the Minister for Ecological and Inclusive Transition (formerly the Minister for Ecology, Energy, Sustainable Development and Regional Planning) to refer the matter to the High Committee for Transparency and Information on Nuclear Safety (HCTISN). Following this referral, the information concerning certain legacy sites presented in the *National Inventory* was clarified. However, there may be potential holders of radioactive waste who have never reported to Andra.

Finally, as explained in Chapter 1, the very notion of "radioactive waste" is subject to interpretation for certain waste with very low levels of radioactivity.



Appendix 2

Activity of radioactive waste

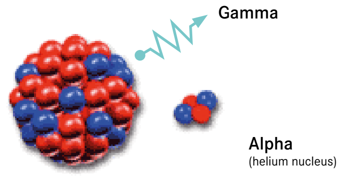
RADIOACTIVITY

In nature, most atoms (constituting matter) have stable nuclei. The others have unstable nuclei: they have an excess of particles (protons, neutrons or both) which leads them to be transformed (by decay) into other nuclei (stable or not). They are then said to be radioactive because, as they transform, they emit radiation of different types and properties.

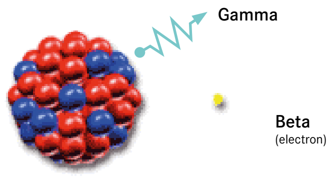
RADIATION

There are three types of radiation, corresponding to three forms of radioactivity:

- α **radiation:** emission of a helium nucleus (consisting of two protons and two neutrons) also called "α particle". The range in air of these particles is a few centimetres, they are stopped by a simple sheet of paper;



- β **radiation:** transformation of a neutron into a proton accompanied by the emission of an electron. All it takes is a sheet of aluminium or a window made of ordinary glass to interrupt the path of the electrons;



- γ **radiation:** emission of electromagnetic radiation, of the same nature as visible light or X-rays, but with much higher energy and therefore more penetrating. Several centimetres of lead or several decimetres of concrete are needed to stop them.

ACTIVITY LEVEL AND LIFESPAN

Radionuclides are radioactive atoms which, as they decay, emit radiation which causes the phenomenon of radioactivity. Some radionuclides are very radioactive (several trillion becquerels), others have low activity (which is measured in millibecquerels).

Furthermore, the lifespan of radionuclides (the length of time for which they emit radiation) varies greatly from one radionuclide to another. A radioactive half-life is the time after which half of the quantity of the same radionuclide will have naturally disappeared by decay. The level of radioactivity of a sample containing atoms of this single radionuclide is therefore halved at the end of one half-life. At the end of ten half-lives, activity has been divided by 1000.

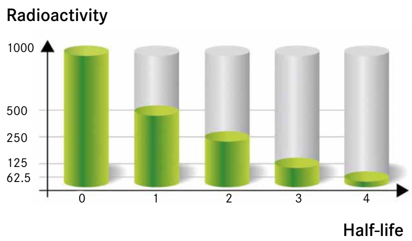
This half-life can range from a fraction of a second for polonium-214, for example, to 4.5 billion years for uranium-238.

The radioactive half-life of a radionuclide is systematically linked by an inverse function of the activity: the longer the half-life, the lower the activity. The following table gives examples of activities for 1 gramme of sample (iodine-131, caesium-137, plutonium-239, and uranium-238).

EXAMPLES OF RELATIONSHIP BETWEEN HALF-LIFE AND ACTIVITY

Radioelement	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

In nuclear physics, activity is often compared to a volume (activity concentration in Bq/L or Bq/m^3), a mass (specific activity in Bq/g) or a surface area (surface activity in Bq/m^2).
The specific activity of a radioactive substance is the number of disintegrations per unit of time and per unit of mass. In the *Catalogue of Waste Streams*, it is expressed in becquerels per gramme of the finished package.



MEASURING RADIOACTIVITY

Radiation from radioactivity is not directly perceptible by our senses. We measure it by quantifying its effects.

The methods for achieving this are based on the fact that radiation leaves a trace within the material it passes through. The detectors commonly used are of various designs (meters containing a gas, scintillators, semiconductors), but they all use the same principle: they convert the photons or electrons created by the radiation into an electrical signal, to count the number of disintegrations.

Radioactivity measurement units

The becquerel and gray are the units that measure radioactivity and its energy.

The sievert is a quantity that estimates its effects.

- **The becquerel (Bq).** This unit measures the level of radioactivity, also called activity. It corresponds to the number of atoms that disintegrate per unit of time (second).
  The former unit was the curie (Ci): 1 Ci = 3.7×10^{10} Bq, in reference to the scientists who discovered radium (Pierre and Marie Curie).
- **The gray (Gy).** The gray measures the amount of energy absorbed (absorbed dose) by matter (organism or object) exposed to ionising radiation. One gray corresponds to an absorbed energy of 1 joule per kilogram of material.
  The former unit was the rad: 1 Gy = 100 rad.
- **The sievert (Sv).** The sievert makes it possible to evaluate the biological effects of radiation, of natural or artificial origin, on humans, according to the type of radiation. The former unit was the rem: 1 Sv = 100 Rem.

Radiological inspection: measurement of radiation from a waste package

MAIN QUANTITIES MEASURED

Quantity measured	Definition	Units
Activity	Number of disintegrations per second	becquerel (Bq)
Absorbed dose	Amount of energy transferred to matter	gray (Gy)
Effective dose	Effects of radiation on the organism	sievert (Sv)

Although the becquerel is an infinitely small unit, the measuring devices available are often sensitive enough to detect radioactivity when in optimal conditions. In addition, radioactivity is measured on portable devices and by instantaneous reading, provided that the device used is adapted to the radiation actually present.

MEASURING THE ACTIVITY OF WASTE PACKAGES

Each disintegration is accompanied by the emission of radiation (gamma) or particles (alpha, beta, neutron). Since their energy is representative of the nucleus that has disintegrated, the measurement of this radiation (intensity and energy) by suitable and correctly calibrated instruments makes it possible to evaluate the activity of the waste and to quantify the various radionuclides.

The measurements are carried out by spectrometry on packages and/or samples.

However, some radionuclides are difficult to measure due to their low quantity and/or their low-energy radiation. Correlation factors are then established between the activity of these radionuclides and that of a more easily measured radionuclide used as a tracer.
The distribution of the activities of the different radionuclides in the waste (radiological spectrum) is thus evaluated.

The producer most often evaluates the activity of the waste during its production or conditioning.

Inspecting a package in the Cires treatment building

Glossary and abbreviations

	Term	Definition
A	**Actinide**	Natural or artificial radioelement 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 disintegrations 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 reprocessing of spent fuel reprocessing to disposal of radioactive waste.
	Baddeleyite	Rare natural zirconium oxide mineral (ZrO_2).
	Basic nuclear installation (BNI)	In France, this is a nuclear installation that, due to its characteristics or the quantity or activity of the radioactive substances it contains, is subject to specific regulations.
	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 disintegrations 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 of the becquerel are more 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 sludges	Sludge resulting from co-precipitation operations in treatment plants for liquid radioactive effluents and conditioned in bitumen.
	Breeding	Phenomenon in a FNR where the production of fissile material by neutron capture in the enclosure exceeds the consumption of fissile material in the core.
	Burnup	Total energy released per unit mass of a nuclear fuel. It is often expressed as gigawatts-day per tonne of heavy metal (GWd/t).
C	**Cigéo**	Industrial geological disposal facility.
	Cires	Industrial facility for grouping, storage and disposal.
	CNE	National Assessment Board for research and studies pertaining to the management of radioactive materials and waste.
	Conditioned equivalent volume	This is the unit used to prepare the waste reviews. 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 conditioning called a disposal package may be necessary for handling, safety, or retrievability purposes. Only the volume of primary packages is indicated in this report.
	Conditioning of radioactive waste	Operations that prepare radioactive waste to be suitable for transport, storage, or disposal. *Note: these operations may include encapsulation, vitrification, cementation, bituminisation, and containerisation.*
	Container	In the nuclear industry, a term referring to a sealed vessel that can be handled, used for transport, storage, and disposal operations.

	Term	Definition
C	**Containment (of radioactive materials)**	Retaining radioactive waste in a predetermined area using a set of devices (barriers) to prevent the dispersal of unacceptable quantities of radioactive material outside this area.
	Contamination (radioactive)	Unwanted presence of radioactive substances on a surface or within any environment.
	CSA	Aube disposal facility.
	CSD-C	Standard container for compacted waste.
	CSD-V	Standard container for vitrified waste.
	CSM	Manche disposal facility.
	Current fleet	The 56 reactors in operation in France as of 31/12/2021 and the Flamanville EPR (FLA3).
D	**Dismantling**	Technical operations performed to dismantle and possibly scrap nuclear equipment or part of a nuclear installation. In French regulations, term referring to the demolition phase of a nuclear facility, comprising all operations following 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 conditioning is required for handling, safety, or retrievability functions.
E	**Enriched reprocessed uranium (ERU)**	Uranium from spent fuel reprocessing that has been enriched.
	Enrichment of uranium	Process by which the concentration of uranium-235 is increased.
	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 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 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 short-lived (approx. 10%). A few (approx. 5%), for example ^{99}Tc, ^{129}I, are long-lived.
	FNR fuel	Plutonium and uranium mixed oxide fuel (MOX) for fast neutron reactors (Superphénix, Phénix). Fuel for the Superphénix reactor is 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.

	Term	Definition
F	**Fuel (nuclear fuel)**	Material containing nuclides that are consumed by fission in a nuclear reactor to sustain a nuclear chain reaction.
	Fuel assembly	Group of fuel elements that remain attached to each other, particularly during reactor core refuelling or unloading operations.
	Fuel rod	Small diameter tube, sealed at both ends and 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 containment 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 containing the radioactive materials inside the box.
	Graphite waste	In France, this is a category for radioactive waste containing graphite components (stack sleeves and bricks) from the operation and dismantling of old GCRs (approximately 20,000 tonnes). This graphite contains tritium and long-lived isotopes (carbon-14, chlorine-36).
H	**HCTISN**	French High-level 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 gramme.
	Holder of radioactive waste	Waste producer or any other person in possession of waste (Article L. 541-1-1 of the French Environmental Code).
	Hulls and end caps	Radioactive waste comprising fuel assembly hulls and end caps once the rods have been cut and the fuel has been dissolved.
I	**IAEA**	International Atomic Energy Agency (iaea.org).
	ICPE	Classified environmental protection facility
	ILW-LL	Long-lived intermediate-level waste comes primarily from the reprocessing of spent fuel. The activity of this waste ranges from around one million to one billion becquerels per gramme.
	Industrial volume	The volume of water displaced by submersion of a waste package.
	ISD	French acronym for conventional waste disposal facility.
	Isotope	Any nuclide of a given element. All the nuclides of a single element.
L	**LILW-SL**	Short-lived low- and intermediate-level 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 gramme.
	LLW-LL	Long-lived low-level waste is mainly graphite waste from GCRs and radium-bearing waste. Graphite waste has an activity level between 10,000 and a few hundred thousand becquerels per gramme. Radium-bearing waste has an activity level between a few dozen becquerels per gramme and a few thousand becquerels per gramme.
	Long-lived waste	Radioactive waste containing a significant quantity of radionuclides with a radioactive half-life greater than 31 years.

	Term	Definition
M	**"Marked" site**	Site exhibiting traces of natural or artificial radionuclides that can be detected without necessarily requiring any specific action.
	Matrix (conditioning)	Solid material used to immobilise or contain radioactive waste, or simply to improve the mechanical resistance of waste packages to crushing.
	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 in nuclear fuels
	Moderator	Material made of light nuclei that slow down neutrons by elastic scattering. 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 generated by the use or transformation of raw materials that contain naturally-occurring radionuclides, but are not used for their radioactive properties. This waste may require a specific type of management.
	Nuclear fission	Disintegration 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 an installation.
P	**Package with core source elements**	These ILW-LL packages contain spent sealed sources collected from "small producers". 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 fertilisers 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, it is currently used as a component of MOX fuel in certain light-water reactors. It is also the fuel selected in most fast neutron reactor designs.
	PNGMDR	French National Radioactive Materials and Waste Management Plan.
	Polluted site	In a radioactive contamination context, term used to describe an area or site significantly contaminated by natural or artificial radioactive substances.

	Term	Definition
P	**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.
	PUREX	Plutonium Uranium Reduction Extraction, process for extracting plutonium and uranium contained in irradiated fuels.
R	**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 clean-up	Operations performed in a nuclear installation or on a nuclear 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 “depollution” with regard to pollution by radioactive substances.
	Radioactive half-life	The time after which half of the quantity of the same radionuclide will have naturally disappeared by decay. The radioactivity of a sample of a single atom would then be halved. After 10 such half-lives, the radioactivity would be divided by a factor of 1,000.
	Radioactive material	A radioactive substance for which subsequent use is planned or intended (after treatment, 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 that remain in a given environment after remediation.
	Radioactive source	A device, radioactive substance or installation 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	waste that includes radioactive substances which cannot or will not be re-used in the future. Final radioactive waste is radioactive waste that can no longer be processed under current technical and economic conditions, in particular by extracting the recyclable part or by reducing its polluting or hazardous nature.
	Radioactive waste disposal	Operation consisting in placing radioactive waste in a facility specially designed for the 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 facilities may be considered, depending on the radiological risks associated with the waste.
	Radioactive waste package	Conditioned and packaged radioactive waste.

	Term	Definition
R	**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 of which all the isotopes are radioactive. Term to be avoided, sometimes used for a radioisotope or radionuclide.
	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).
	Remediation	All clean-up and redevelopment operations carried out to make a site suitable for a given use.
	Reprocessed uranium (RepU)	Uranium from spent fuel reprocessing.
	Reprocessing of spent fuel	Operations performed on spent fuel taken 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.
	Secret basic nuclear installation (SBNI)	A secret basic nuclear installation (SBNI) is a geographic perimeter including at least one basic nuclear installation that concerns defence and justifies particular protective measures against nuclear proliferation, malicious acts, or the disclosure of classified information. All installations and equipment, whether nuclear or non-nuclear, within the perimeter are part of the SBNI. Nuclear installations included in an SBNI are called "individual installations of the SBNI". The control of nuclear safety and radiation protection of SBNIs is the responsibility of the Nuclear Safety Authority for Defence-related facilities and activities (ASND), under the authority of the Delegate for nuclear safety and radiation protection for activities and facilities involving defence (DSND). ASND defines the regulations for the nuclear safety of SBNIs in a coherent and coordinated manner with the regulations defined by the French Nuclear Safety Authority (ASN). Like ASN, ASND is an independent entity from nuclear operators.
	Short-lived waste	Radioactive waste mainly containing 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, also called "irradiated fuel".
	SPM	Suspended particulate matter, residues from the processing of rare earths containing thorium.
	Storage (of radioactive material or waste)	The temporary placement of radioactive material or waste in a specially designed facility, pending subsequent retrieval.
	Structural waste	Radioactive waste comprising 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.

	Term	Definition
T	**tHM**	Tonnes of heavy metal.
	Toxic element	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 element 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 sector 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.
	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.
	Tritium-bearing waste	Radioactive waste containing tritium, possibly requiring specific management due to the high mobility of this element.
V	**Vitrified waste**	Radioactive waste conditioned in a glass matrix.
	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 100 becquerels per gramme.
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 Environmental Code).
	Waste recovery and conditioning	Recovery and conditioning waste is legacy waste that was not conditioned at the time of its production, and that has been or will be recovered by the waste holder for conditioning and disposal.
	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 Installation of a concrete LILW-SL waste package in a disposal structure at the Aube disposal facility (left) / HLW waste package storage hall at the Orano La Hague site (right).

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ANDRA
Agence nationale pour la gestion des déchets radioactifs

inventaire.andra.fr, the reference website for all radioactive materials and waste on French territory.