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# RADIOACTIVE WASTE MANAGEMENT IN FRANCE

## OVERVIEW

Any human activity generates waste, whether tied to household, daily, economic, industrial, commercial, etc. activities.

For nuclear power, the issue is not whether or not to produce waste, the real issue is to:

- Produce as little waste as possible, thanks in particular to circular economy.
- Properly manage the waste produced (ultimate materials) so that they do not impact our environment.

Note that compared to all other industrial activities, the volume of waste produced by the nuclear power industry is very small.

From the very beginning, the French nuclear power industry has taken great care in its management of the radioactive waste produced. In particular, it has decided to exercise its responsibilities as nuclear power operator by reprocessing the spent fuel and recovering both the uranium and the plutonium as nuclear fuels (nuclear materials). This reduces the high-level long-lived waste (HLW-LL) to the fission products and minor actinides, plus the metallic structure holding the fissile product rods of the fuel assemblies, the “skeleton”. And when this becomes possible, it will close the fuel cycle almost completely thanks to the advent of fast breeder reactors. Indeed, these will be able to use as their fuel the depleted uranium (350,000 metric tons in France) left over from the enrichment process and to partially reduce the HL-LL waste to elements with shorter half-lives. It will then become conceivable to do without uranium ore extraction and processing for a very long time (on the order of a thousand years). This will eliminate waste production by the upstream segment of the industry.

In discussing the management of radioactive waste, it is important to distinguish between the term "storage" which means temporary storage and the term "disposal" which is definitive.

We review below, the management of:

- Very low level waste (VLLW): the bulk of the waste a large part of which has, in line with other countries, become eligible for recycling in the circular economy since the publication in February 2022 of decrees setting the threshold below which they enter the category of regular industrial waste,
- Low- and intermediate-level short-lived waste (LILW-SL) and their containment and disposal facilities,

- Low-level long-lived waste (LLW-LL): they are mostly radiferous[1] residues. They are currently stored on site and their disposal is planned in clay layers at a depth of about 100 m. They account for a very small part of the total radioactivity.
- Intermediate- and high-level long-lived waste (ILW-LL & HLW-LL): they are stored either on site (graphite, etc.) or in glass matrices encased in stainless steel containers ("skeleton" and fission products). Their volume is small enough that they are stored at the La Hague site ever since the beginning, pending their disposal in perfectly stable deep geological layers in CIGEO[2].

All of these disposal activities are tightly controlled under three laws enacted in 1991, 2006 and 2016 and are supervised by members of parliament. They are managed by a government agency, ANDRA (Agence Nationale pour les Déchets Radioactifs – *National agency for the management of radioactive waste*), and controlled, as are the other activities in the cycle, by the ASN (Autorité de Sûreté Nucléaire – *National Safety Authority*).

**Note that in France, with more than 50 years of nuclear power generation; more than 2100[3] reactor-years of pressurized water reactor operation; 6.1 billion metric tons of $CO_2$ emissions avoided if the same amount of energy had been produced by combined cycle gas turbines; neither the waste nor the power plants themselves have caused any harm to the environment or to man.**

**Few industrial sectors can boast such a track record.**

**To conclude, contrary to claims that the "nuclear waste" problem remains, we must hold that there is no radioactive waste problem. There is a suitable and perennial solution for all categories of radioactive waste.**

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# THE MANAGEMENT OF RADIOACTIVE WASTE IN FRANCE

## Jean Fluchère

Of all the modes of electricity generation, nuclear power is the one that contributes the least to global warming, along with hydroelectricity, according to the figures published by ADEME[4].

1 Recent and former industrial activities are the source of waste that is not very radioactive, but much more voluminous than the preceding ones: **radiferous waste**. As their name indicates, they contain traces of radium and its descendants from the decay chain of uranium, which are present in trace amounts in the earth's crust. In addition to radium, which has a long half-life (1600 years), there is radon, a natural radioactive gas with a half-life of four days. Radiferous waste is classified as low-level, long-lived waste (LLW-LL). It will be the subject of specific conditioning and disposal, currently being studied by ANDRA.

2 CIGEO is the HL-LL and Il-LL deep geological waste disposal facility project at Bures in France managed by ANDRA, the French agency in charge of nuclear waste management. Satisfactory tests have been performed and authorizations for its opening are in progress.

3 This refers to the number of years of operation of the reactors and not to the years of operation at full power equivalent, the criterion adopted by the IAEA.

4 ADEME: *Agence de l'environnement et de la maîtrise de l'énergie* – French Environment and Energy Management Agency

The public is slowly becoming aware of this fact but few people know that if all the waste[5], and emissions to the atmosphere, both industrial and generated by households[6] were managed with the same serious attention as the radioactive waste, our planet and its atmosphere would be much cleaner. We would not have to deal with the effects of land, ocean, and atmospheric pollution resulting from the massive burning of coal, oil, and natural gas, and with household and industrial waste.

**In the context of the circular economy, the depleted uranium left over from the enrichment process is classified as nuclear material intended for future use, along with the uranium and plutonium from the reprocessing of spent fuel at the Orano plant in La Hague which are reused as fuel.**

Only those elements for which, today, no future use is being considered are classified as waste. This classification could change if, in future, some waste components were to become useful. They would then be classified as nuclear material or nonradioactive material.

**Let us try to be clear on the issue of radioactive waste, also known as nuclear waste, of which we keep hearing that they pose a yet unsolved problem or even that there is no solution. There have been independent scientific evaluations of the methods that are already being implemented or are projected to manage these waste. The methods were chosen after democratic debates in the legislative assemblies, their implementation is under strict control. Particular attention is given to transparency and information to the public.**

**We will show here that there is no radioactive waste problem. There is, for each category, a suitable and perennial solution.**

Let us first remember that radioactive atoms disappear naturally through radioactive decay, frequently leading to other radionuclides which in turn decay, all the atoms eventually leading to stable atoms.

Remember also that our body contains radioactive elements. Potassium’s isotope 40 in our blood represents 4500 becquerels and carbon’s isotope 14 in our skeleton represents 3700 becquerels for a 70 kg body. A becquerel (Bq) is a very small unit: one disintegration per second, whether the radiation emitted is very weakly or very ionizing. The number of becquerels cannot therefore characterize the risk incurred by the organism receiving the emitted radiation.

Natural radioactivity is everywhere and varies greatly from one place to another. It is much more intense in the granitic ranges of Brittany than in the Rhone alluvial plains.

In France, the radioactive waste is managed and monitored by a government agency (ANDRA), which has the status of a Public Industrial and Commercial Establishment (EPIC), subject to the strict supervision of the ASN. The volume of the waste concerned is very small compared to the volumes generated by other human and industrial activities.

5 In 2018, excluding the emissions to the atmosphere, France produced 324 metric tons of waste, or 5.1 metric tons per capita.

6 Each year, a resident of France produces 354 kg of household waste.

Contrary to radioactive waste, radioactive materials are products that have potential future use, while the waste do not. Separating the radioactive materials from the waste thus pertains to the circular economy processes.

France is one of the only countries in the world to have chosen to recycle as much as possible the uranium and plutonium recovered from the spent fuel. The spent nuclear fuel is reprocessed in the ORANO facilities at La Hague. This reprocessing extracts the waste from the spent fuel and recovers the reusable nuclear materials such as the plutonium and the reprocessed uranium. The latter still contains the fissile isotope 235 of uranium at a concentration close to 1%, i.e., a higher value than that of natural uranium, which is 0.7%. Plutonium alone represents 50% of the radioactivity of the transuranics. It is mixed with depleted natural uranium to be used as a fuel called MOX which is manufactured in the MELOX plant at Marcoule (this plutonium contains non-fissile isotopes of plutonium, so that it has no military value).

France's spent fuel reprocessing is within the full responsibility assumed by a country that engages in nuclear power generation. China, too, has decided to set up a reprocessing plant. Russia has made the same decision for its civilian nuclear activities.

Finally, it should be pointed out that France was, until December 21, 2021, the only country in the world not to have set a radioactivity exemption threshold below which waste is not considered as radioactive waste and is thus eligible for use in other sectors. This issue is now resolved. Two decrees published on February 14, 2022 in the Journal Officiel de la République Française, decrees 2022-174 and 2022-175, have just brought France in line with other countries in terms of the recovery of very low-level waste that does not exceed a radioactivity value 300 times lower than natural radioactivity. This threshold was set by the ASN and the Ministry of Public Health. From now on, a large part of the very low-level radioactive waste can be recycled and enter the virtuous cycle of the circular economy. This threshold was set to ensure that these recycled products are indeed harmless.

**A structured organization, evaluation and control accompany France's radioactive waste management.**

In France, the management, treatment and conservation of artificial radioactive waste in "**storage facilities"** are the exclusive responsibility of their producers, pending their verification and acceptance by the National Public Agency for Radioactive Waste Management (ANDRA), with a view to definitive "**disposal**".

**In the public domain, the population is never in contact with this waste**, whose trajectory is rigorously controlled by the French Nuclear Safety Authority (ASN), any evolution being subject to its authorization. This supervision covers all phases of waste management (production, packaging, storage, transport, and disposal), for which approved means are used that are adapted to the level of radioactivity and the physical and chemical nature of the waste. These measures also take into account the protection of the health of nuclear workers (radiation protection), which is subjected to strict regulations.

Radioactive waste management is covered by a legislative framework (laws of 1991, 2006 and 2016). In addition to the control by the ASN, the whole process is subject to in-depth examination by the Parliamentary Office for Scientific and Technical Choices (OPECST), the High Committee for

Transparency and Information on Nuclear Safety (HCTISN), a National Evaluation Commission (CNE), as well as by the Court of Auditors for the cost aspects.

The National Radioactive Waste Management Plan (PNGMDR), drafted by the government and the ASN, is revised every five years and is submitted to public debate. This plan is based on a National inventory of radioactive waste and materials (National Inventory) compiled under the responsibility of ANDRA, that waste producers are required to provide with all necessary information (detailed radiological content, physical and chemical composition). This inventory is accessible to the public.

## 1 – A very precise classification

The classification is based on the radioactivity and the half-life of the waste. Indeed, the radioactive products, as they disintegrate, give way to other radionuclides, eventually reaching stable elements, i.e., elements with no ionizing emissions. (The period or half-life is the time after which half of the radioactive nuclei of a sample have decayed). Their dangerousness thus wanes over time.

This classification was drawn up to specify appropriate disposal modes: packaging, disposal location, surveillance.

Employees exposed to the radiation emitted by these substances are protected via management procedures adapted to the intensity of the emissions and their power of penetration into the body.

The term "storage" refers to temporary storage.

Radioactive waste comes mainly from the nuclear power industry (about 59% in volume) but is also produced in the context of other activities: research (26%), defense (11%), medicine (1%), etc.

Note that 0.2% of radioactive waste accounts for 96.8% of the radioactivity. Indeed, it is this interesting feature that makes such careful treatment possible.

To give an appreciation of this volume, all of the high-level long-lived waste (HLW-LL) produced by the nuclear power plants in France over the past 40 years are currently stored in vitrified form[7] in stainless steel containers in the ventilation shafts of the ORANO site at La Hague. They will later be transferred to the alveoli[8] of CIGEO for disposal.

The waste are ranked in 5 main categories according to their dangerousness and their half-life (Waste classification).

| **Radioactive waste category** | **Radioactvity level in Bq/g** | **Half-life** |
|---|---|---|
| Very low level waste **(VLLW)** | < 100 Bq/**g** | variable |
| Low- and intermediate-level short-lived waste **(LILW-SL)** | A few hundred thousand to a million Bq/g | ≤ 31 years |
| Low-level long-lived waste **(LLW-LL)** | From 10 000 to a few hundred thousand Bq/g | > 31 years |
| Intermediate-level long-lived waste **(ILW-LL)** | From 1 million to 1 billion Bq/g | > 31 years |
| High-level long-lived waste | Several billion to several tens of | Variable but very long |

7 They are mixed with a molten glass paste – see below

8 The horizontal holes drilled in the argillite to store HL-LL waste packages are called alveoli - see below.

| | | |
|---|---|---|
| **(HLW-LL)** | billion Bq/g | > 31 years |

According to ANDRA:

* **The radioactivity level of the waste:**
  - Very low level activity (VLL): below 100 becquerels per gram
  - Low level activity (LL): from a few hundred becquerels to a million becquerels per gram
  - Intermediate level activity (IL): from one million to one billion becquerels/gram
  - High level activity (HL): several billion becquerels per gram.

* **The radioactive half-life of the radionuclides present in the waste:**
  - Very short lived waste (VSL): contain radionuclides whose half-life is less than 100 days.
  - Short lived waste (SL): contain mostly radionuclides whose half-life is less or equal to 31 years.
  - Long lived waste (LL): contain large amounts of radionuclides whose half-life is larger than 31 years.

* Very low level waste (VLLW) and short lived low and intermediate level waste (LILW-SL) represent 91% of the total volume. They are placed in two disposal facilities managed by ANDRA, the Centre Industriel de Regroupement, d'Entreposage et de Stockage at Morvilliers (CIRES - very low level waste repository) and the Centre de stockage de l'Aube at Soulaines-Dhuys (CSA - disposal facility for low and intermediate level short lived waste). Both of these sites are open to visitors.

* The long lived intermediate and high level waste (ILW-LL and HLW-LL) are the most dangerous. They account for 3% of the volume but 96.8% of the radioactivity of all the waste. The principle of "geological disposal", i.e., deep underground disposal in a stable, anhydrous geological formation (argillite), has been approved by the ASN, endorsed by Parliament, and written into law. The application for authorization to build the CIGEO repository, at the limit of the Meuse and Haute Marne departments, was submitted in 2021. The disposal conditions and the robustness of this geological environment have been the subject of 25 years of study by ANDRA, and of extensive testing in the nearby Bures underground research laboratory (Meuse/Haute-Marne center).

* The long-lived low level waste (LLW-LL), which account for 6% of the volume but only 0.14% of the radioactivity, remain today in the storage facilities of their producers. They should eventually be moved to a dedicated subsurface disposal facility, i.e., at a shallow depth, the characteristics and location of which have yet to be defined. They present a very moderate risk, so that CIGEO was given priority.

## 2- Key figures

**In France, what is the volume of waste and the cost of its management?**

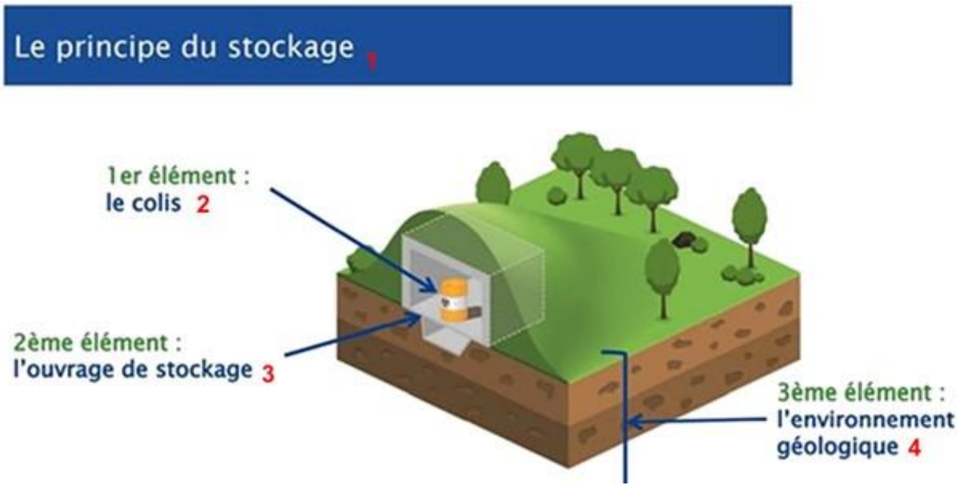
* The nuclear industry of France produces about 2 kg of radioactive waste per capita per year (not including conditioning and packaging), of which only a few grams are high-level, long-lived waste (HLW-LL), which alone account for about 96.8% of the total radioactivity.

This should be put in perspective with an average of 354 kg of household waste and a total of 5,100 kg of waste produced per capita per year in France. To this amount, we must add the emission of 315 million metric tons (or 4700 kg per capita) per year of $CO_2$, a powerful greenhouse gas. This contrasts with the radioactive waste amounts which can be treated with great care.

* ANDRA, had identified *1,640,000 m$^3$ of radioactive waste at the end of 2018, in mainland France*, 91% of which was very low or low and intermediate level short-lived (VLLW and LILW-SL).

* The cost of waste management represents about 5% of the total cost of the electricity generated and is included in the price of the MWh (around 2.5 €/MWh). A fund to finance the costs of dismantling nuclear facilities and managing spent fuel and radioactive waste (Fonds de financement) is in place and is monitored by a National Evaluation Commission (CNEF).

## 3. Treatment of radioactive waste in France




The disposal standard **1**

1st component: the package **2**

2nd component: the disposal structure **3**

3rd component: the geological environment **4**

## 3.1 - Very low level waste (VLLW): 27% of the volume but less than 0.01% of the radioactivity

VLLW is mainly made up of rubble (concrete, earth, etc.) and scrap metal (pipes, frameworks, etc.), from the deconstruction of nuclear facilities, for example.

In France, they are packaged in textile bags called "big-bags" or in metal racks at the VLLW disposal center in Aube. Some liquid waste can be desiccated. Plastic or metallic waste can be compacted before being stored in this surface disposal facility. They are simply isolated from the environment.

**The VLLW are delivered to the CIRES (very low level waste repository)**

They are disposed of in trenches a few meters deep dug in a clay layer. These trenches, or cells, are covered by a capping system composed of a layer of sand, a watertight geomembrane and a protective geotextile. A clay cover is then deposited over the cells to further ensure the waste containment. Approximately 30,000 m$^3$ of VLLW are treated yearly. The disposal will be monitored for about thirty years after filling. After 30 years, the radioactivity of the disposal cell will be of the same order of magnitude as the local natural radioactivity.

**In most countries making use of nuclear power, VLLW whose radioactivity is below a specified threshold is not considered as "radioactive" waste, its radioactivity level being comparable to that of natural radioactivity. Since the two decrees published on February 14, 2022 mentioned above, France has aligned with other countries.**

In the illustrations below, we will see that it was urgent to do so in order to send only real waste to disposal and not products that are not or only slightly radioactive.

Indeed, the issue arises with the dismantling of installations such as Chooz A or Fessenheim[9] in the near future.

* The containment building of 900 MW reactors is a tower built of prestressed concrete protected on the reactor side by a steel cladding. This building is not exposed to neutron radiation and if there is any contamination, it is on some surfaces of the metal cladding and at the level of some crossings.
This means that the radioactivity of all the aggregates resulting from the grinding of the concrete is at about the level of natural radioactivity. The same applies to the steel of the prestressing cables and their sheaths. Even inside the reactor building, a large part of the concrete does not pose a radioactivity problem and should be returned to the normal aggregate circuit after grinding. Finally, if there are a few contaminated spots on the inside of the metal cladding, they can be located and cleaned.
With this requirement, all these materials can be recycled as ordinary waste and thus join the circuit of the circular economy. They do not have to clutter up the CIRES. The same will apply to a large part of the thickness of the UNGG reactor blocks (natural uranium graphite gas reactors, the first reactors built in France), which are 8 m thick in the standard thickness. It will be sufficient to define a thickness beyond which the concretes are not activated[10] for those that face the reactor block, and for the concretes facing the exchangers, the entire thickness can be recycled.

* As for metallic materials, French regulation had until now considered that all metals from controlled areas are radioactive. A reasonable approach is needed. If we retain the figures given by the engineer in charge of the deconstruction of Chooz A, there were 160,000 metric tons of scrap metal, much of it stainless steel. With a precise inventory, half of this material, or 80,000 metric tons, is not radioactive at all and 40,000 metric tons can perfectly be decontaminated.
The Swedes at the Sandwick steel mills remelt this steel. Once it is molten, the radioactive particles that are lighter than steel float to the surface. It then suffices to eliminate them by

9 Chooz A is a 300MW PWR reactor which is currently being dismantled. Fessenheim is a pair of PWR reactors that were shutdown in 2020 whose dismantling is forthcoming.

10 An activated material is one that has been made radioactive by neutron capture. Contaminated materials just present a surface deposit of a radioactive substance that can be removed.

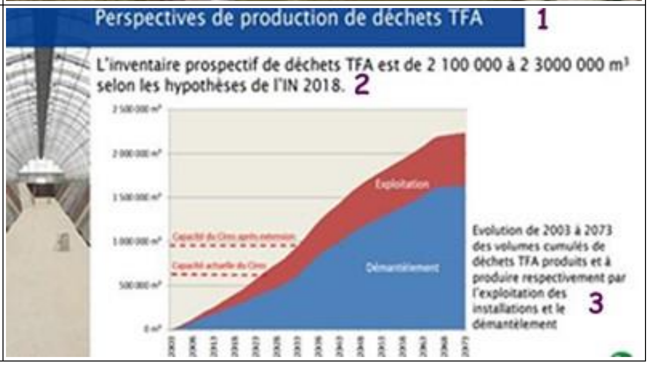
skimming in order to recover a sound metal. This is the project that EDF wants to develop in its techno-center.

Thus, we note that it is possible to recycle large amounts of steel, much of which is stainless steel with a high market value.

To conclude, the 2 recent decrees setting a threshold for the release of materials will allow, on the one hand, to avoid unnecessary saturation of the disposal facility for very low level waste and, on the other hand, to allow the materials concerned to return to the virtuous cycle of the circular economy that the world badly needs.

Below are pictures to illustrate the disposal of very low-level waste for thirty years.



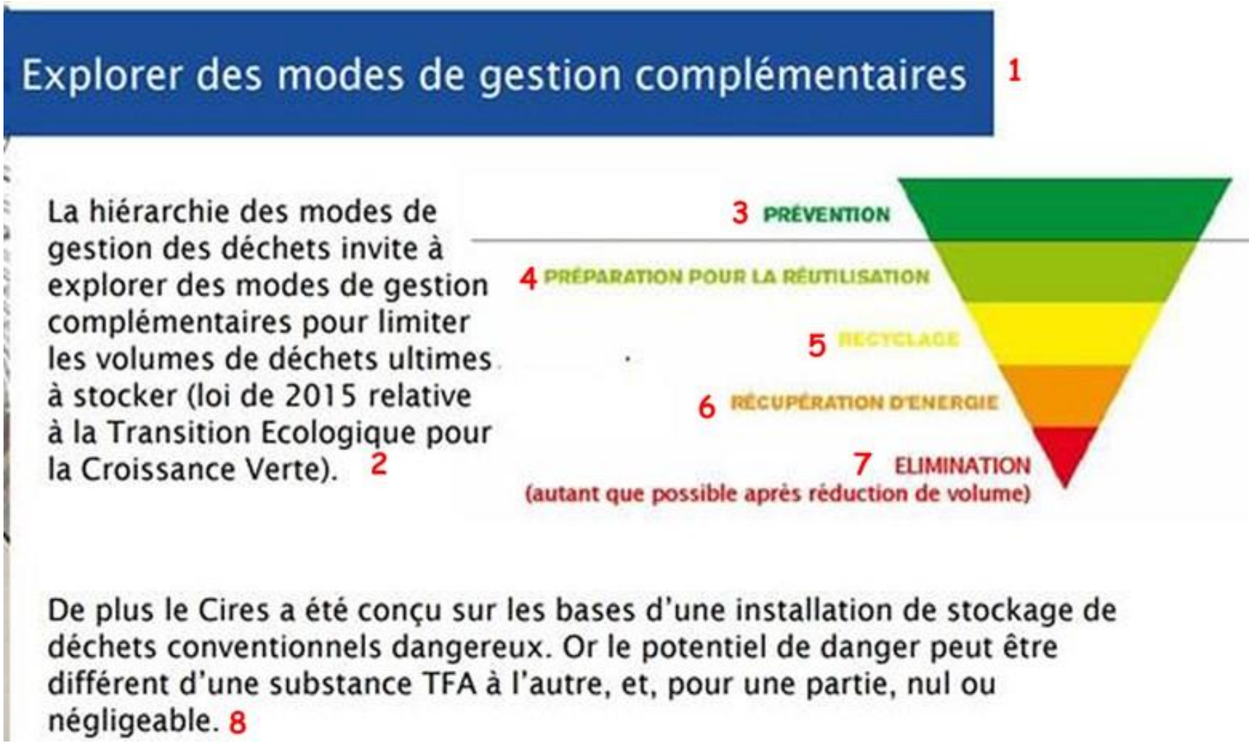

CIRES the very low level waste repository 1
2003 : The facility is opened for disposal of the first VLLW 2
46 hectares (1 hectare = 10,000 m$^2$) for the zone dedicated to disposal 3
650,000 m$^3$ authorized capacity 4
57.9% filling ratio as of end 2018 5

CIRES aerial view 1

Interior view of a CIRES disposal cell 1

VLLW production prospects 1
The prospective inventory for VLLW is 2,100,000 to 2,300,000 m$^3$ according to the National Inventory 2018 hypotheses.
*In the graph, in the red area:* Operation
*in the blue area:* Dismantling 2
Evolution from 2003 to 2073 of the cumulative VLLW produced during operation and dismantling of the facilities 3

CIRES current capacity *(graph upper marker)*
Post extension CIRES capacity *(graph lower)*




Exploring complementary management modes 1

The hierarchy of waste management invites the exploration of complementary management methods to limit the volumes of final waste to be disposed of (2015 law bearing on the Ecological Transition for Green Growth) 2

Prevention 3

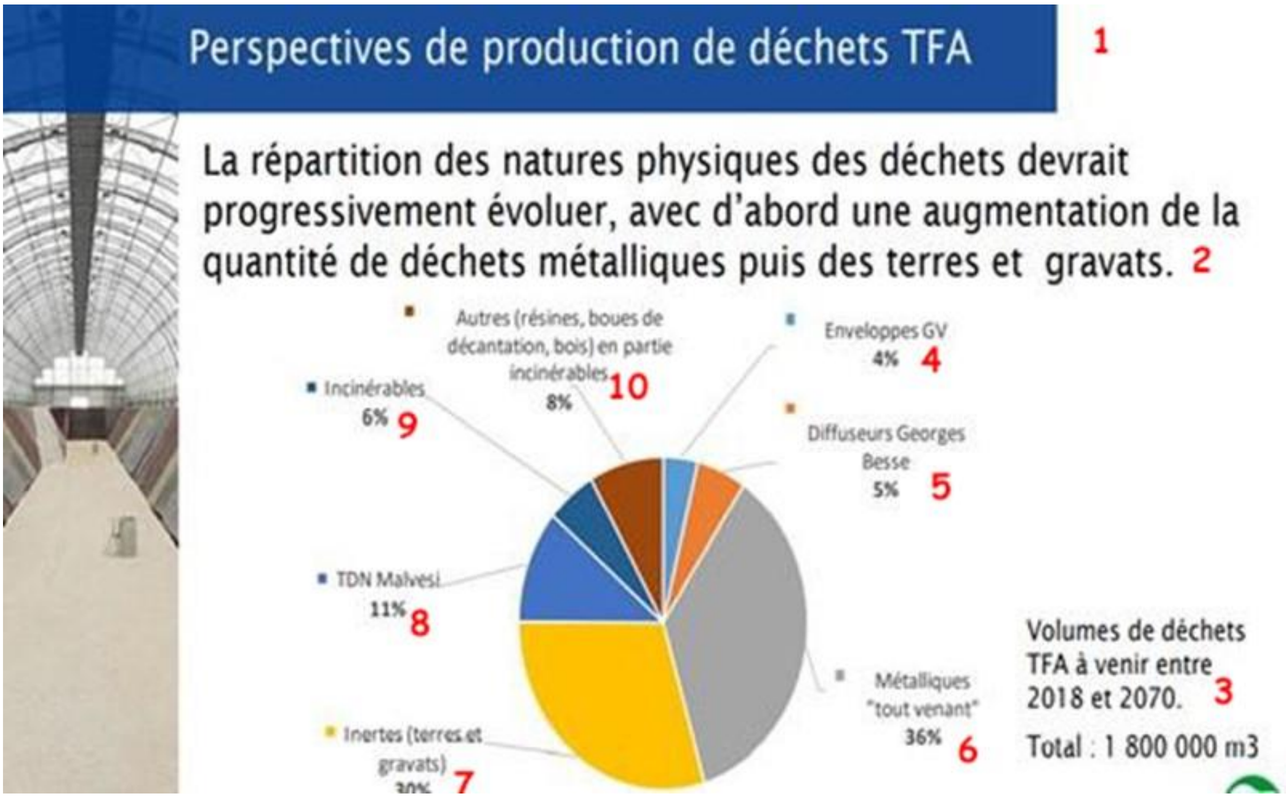
Preparation for Reuse 4

Recycling 5

Energy recovery 6

Disposal (after reduction of the volume in so far as possible) 7

In addition, CIRES was designed as a disposal facility for conventional hazardous waste. However, the hazard potential may be different from one VLLW substance to another and, in some cases, it may be non-existent or negligible 8




VLLW production prospects 1

The distribution of the physical nature of the waste should progressively evolve with first an increasing amount of metallic waste and later of earth and rubble 2

Volume of future VLLW from 2018 to 2070. Total 1,800,000 $m^3$ 3

4% Steam generator sheathes 4

5% George Besse factory diffusers 5

36% "sundry metals" 6

30% Inert waste (earth and rubble) 7

11% Nitrate treatment (TDN) at Malvesi 8

6% Incinerables 9

8% Other (resins, sludge, wood) partly incinerable 10


Metals 1

* Large homogeneous batches (200,000m$^3$) 2
  - recycling could be preferred (fusion)
  - pre-recycling control easier thanks to initial batch homogeneity and to fusion. Procedure needs clarification
* the issue of "sundry metals" must be better looked at flow by flow 3
  - immediate or differed recycling possibility for very very low level waste?
    ° what controls, what traceability?
  - significant potential for reducing the volumes to be disposed of


Earth and rubble

The main uncertainties on the potential VLLW volumes to be disposed of concern earth and rubble

It will be a case by case arbitration between:
- limiting the volumes of waste to be handled on site (in situ controls and traceability?)
- Reuse on nuclear site (backfills...)
- Non-nuclear reuse for the least radioactive fraction (controls and traceability?)
- Local disposal on dedicated sites
- Transport for disposal at CIRES or its successor (environmental impact?)

Refers primarily to dismantling-remediation strategies

### 3.2 - Low- and intermediate-level short-lived waste (LILW-SL): 63% of the volume but only 0.02% of the radioactivity

LIL-SL waste come mainly from equipment used in nuclear facilities: clothing, gloves, filters, tools, etc.

They are confined in metal or concrete packages at the LIL waste disposal center in Aube (CSA: disposal facility for low and intermediate level short lived waste). A package typically consists of 15 to 20% radioactive waste and 80 to 85% encapsulating materials.

**LIL-SL waste are delivered to the CSA**, compacted, solidified and packaged in a solid matrix (mortar, resin). They are inserted in reinforced concrete structures with a watertight lining, immobilized by concrete or gravel. A cover consisting in particular of clay ensures the containment of the waste. About 12,000 m$^3$ of waste packages are stored each year. At the end of its operation, the CSA will continue to be monitored for at least 300 years, after which its safety will no longer require human intervention.



CSA the disposal facility in Aube **1**
1992: Facility opening **2**
95 hectares (1 hectare = 10,000 m$^2$ ) of which 30 ha for the disposal zone **3**
1,000,000 m$^3$ authorized capacity **4**
34% filling ratio as of 2018 **5**

Inside view of a disposal cell

### 3.3 - Low-level long-lived waste (LLW-LL): 5.9% of the volume but 0.14% of the radioactivity

Most LL-LL waste come from the use of slightly radioactive ores ("radiiferous" waste) from which rare earths, in particular, are extracted. They also come from first-generation graphite nuclear power plants ("graphitic" waste). Today, these plants are all shutdown, they are being dismantled, so that the volume of LL-LL waste will not increase.

These LL-LL waste generally present:

* low radiological activity that does not justify deep storage in CIGEO

* a long half-life that is not compatible with surface disposal of large amounts at the CSA facility

Currently, these waste are most often stored at the place of production in metal drums. In the future, they could be transported to sub-surface disposal facilities (from 15 to 200 m).

Geological surveys are being carried out in the Aube and Marne regions, among others, to find sub-surface clay layers where these waste could be permanently disposed of in order to protect them from natural and human aggression. They would then no longer be part of the waste to be monitored by future generations.

## 3.4 - Intermediate level long-lived waste (ILW-LL): 3% of the volume but 4% of the radioactivity.

**A parliamentary decision voted June 28, 2006 stipulates that HL-LL and IL-LL waste are to be disposed of in a deep geological repository.**

This is the internationally accepted solution. Indeed, this long-lived, high-level and intermediate-level waste was produced by our generation. It is our ethical responsibility to relieve future generations of the task of monitoring it. Disposal in a geological layer of argillite that has been and will be stable for millions of years complies with this moral requirement.

## 3.5 – High level long-lived waste (HLW-LL): 0.2% of the volume but 96% of the radioactivity.

At the La Hague reprocessing center, the unusable materials (fission products and transuranics or minor actinides[11]) that make up the HL-LL waste are incinerated. The resulting black powder is mixed with a molten glass paste that is itself poured into a stainless steel container. This container is called a package.

Each package contains nearly 11 kg of HL-LL waste for 400 kg of glass and initially gives off considerable heat (nearly 350°C) because of the high-level radioactivity. To reduce this radioactivity and lower the temperature, the packages are stored in ventilated shafts located in specific facilities at La Hague (ORANO factory), Marcoule and Cadarache (CEA sites). After a cooling period of a few years, these packages are placed in shafts where natural convection is sufficient to cool them.

The 2016 law sets, moreover, a reversibility requirement of at least 100 years from the time the first waste package is received.

From the outset, provision was made for an underground repair facility in the event of failure of the leakproof qualities of a package. Thus, the interior capacities are designed to allow the repair of failing packages.

But reversibility, here, covers a different concept. It means being able, for a duration of one century after their introduction into CIGEO, to recover the disposal packages and bring them back to the surface in order to reprocess them in the event that transmutation techniques are developed,

11 These elements do not exist in nature. They are heavier than uranium and result from neutron captures that produce Neptunium, Americium and Curium. Plutonium, being a nuclear fuel, is recovered during reprocessing and becomes a reusable nuclear material.

allowing to reduce long-lived waste to much shorter half-lives. The legislator made this decision without first having obtained a cost estimate of this requirement. It turns out that this reversibility concept has practically doubled the cost of CIGEO. Moreover, specialists consider that if a transmutation technology were to emerge, it would be used for new packages but those already in the disposal cells would remain as is.



High level (HL) and Long lived Intermediate level (IL-LL) waste **1**

1 – waste from spent fuel reprocessing **2**

Vitirified fission products and minor actinides (HL) **3**

shells and tips (IL-LL) **4**

2 – Waste produced by reactor operation and other facilities (IL-LL) **5**

Waste volume projected 70,000m$^3$ IL-LL waste (with 60% already produced) and 10,000m$^3$ HL waste (with about 40% already produced) **6**

High level (HL) and Long lived Intermediate level (IL-LL) waste **1**

They are stored in surface facilities: Marcoule, Cadarache, La Hague and, soon at Bugey (ICEDA) **2**

Storage of the vitrified packages (Areva) **3**

Storage of Marcoule vitrification workshop products **4**

Because of the level of radioactivity and the half-life of HL and IL-LL waste, they cannot be disposed of safely and over the long term in surface or sub-surface repositories. **5**

The public debate on CIGEO has recently taken place. What remains now is the public inquiry and the decision to be made by the public authorities after the authorization given by the ASN. The examination of this matter should not take too long, since there have been ongoing exchanges between ANDRA and ASN throughout the preparation of the project and the applied research phase in the underground laboratory at Bure.

**The President of the ASN regularly reminds the government that it must make its decision rapidly in order that the first packages be lowered before 2035.**

The CIGEO repository should be commissioned before 2030, after a pilot industrial phase. Excavation and operation, at a depth of about 500 m in a very low permeability clay rock called argillite[12], more

12 150 million years is not the duration of stability of this geological layer, but the age of its deposition in a sedimentary basin called the Paris Basin. It then sank very slowly - 1 to 2 mm per century for about 120 million years, the initial silt expelling its water and turning into a very compact rock called argillite. Then the Paris Basin

than 130 m thick and stable over the past 50 plus million years, will be gradual and could last more than a hundred years. The waste will be disposed of with robots, in horizontal tunnels called alveoli, dug into the core of the clay layer. The eventual transit of radioelements to the surface by leaching[13] will be extremely unlikely and slow (several million years). Only radioelements with a very long half-life can eventually reach the surface, generating a radioactivity level identical to the local surface radioactivity.

(In the underground laboratory at Bure, cells were hollowed out and heated in situ long enough to verify if the argillite's structure was altered. No alteration was detected during these conclusive tests which were supervised by the ASN).

**The IL-LL waste (about four times the HL-LL waste volume and 3% of the total waste volume but 4% of the radioactivity).**

Spent fuel processing operations also give rise to IL-LL waste. They derive mainly from metallic objects such as cladding and shells that enclose the fuel in nuclear reactors. Some of the ILW also come from residues produced during nuclear fuel manufacture. Finally, the graphite from the early French graphite-gas reactors is also in this waste category. The main characteristic of these waste is that they generate almost no heat because of their moderate radioactivity.

Once processed, the IL-LL waste are for the most part compacted to pancake-like elements so as to reduce their volume. These are then inserted into concrete or metal packages. Other conditioning methods such as cementing, asphalting and vitrification can also be used for the other IL-LL waste.

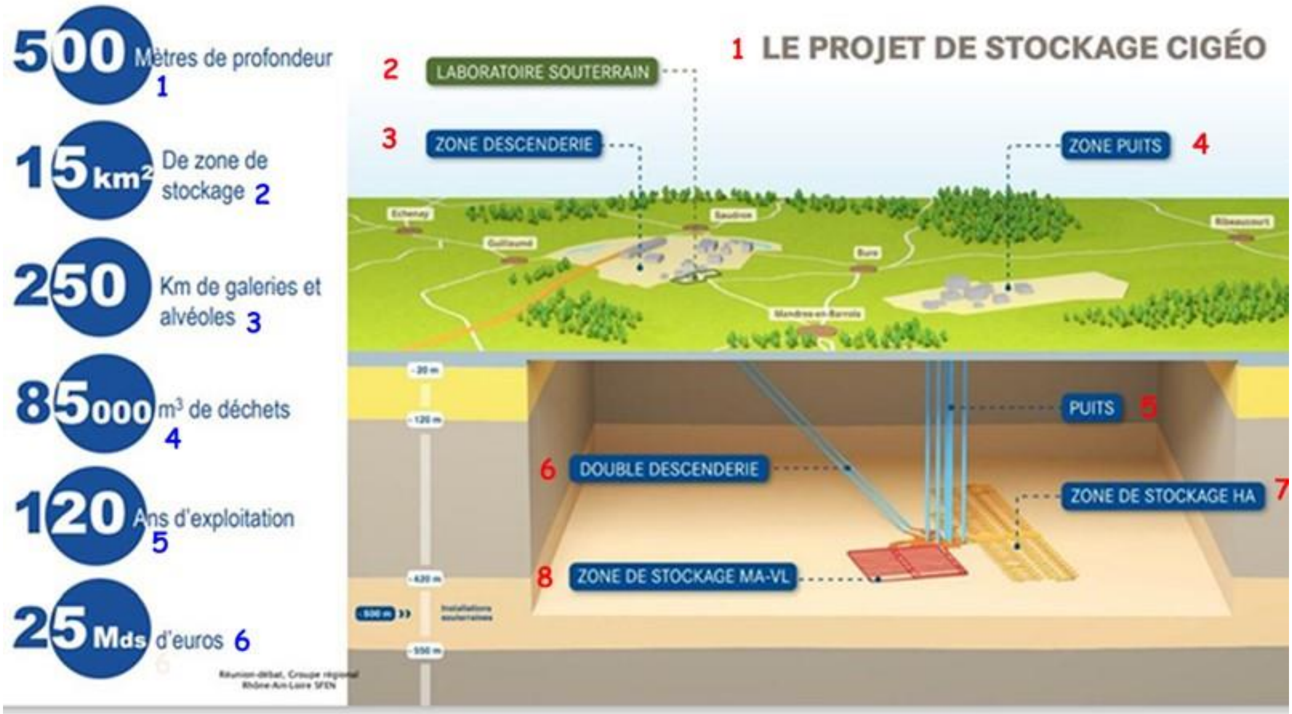
Like HA-VL waste, IL-LL waste are stored at the production site in dedicated facilities.

Given their radioactivity level and their half-life, they are also intended for disposal in CIGEO. These will in fact be the first packages placed in the repository.

Their very big difference with the HL-LL waste is that they do not generate heat so that they can be placed next to each other.

underwent what is called a tectonic inversion under the effect of the thrust of the Alps to the southeast. Its content was thus brought towards the surface, and the rocks which progressively emerged were subjected to erosion. This relative ascent occurred at a speed of the order of that of the burial and did not much alter the physical state of this rock, whose physical state can be considered to have hardly changed over about 50 million years.

13 Leaching is a phenomenon in which water rises to the surface and carries with it any buried residues. Since the layers of argillite selected were chosen because of their thickness and their perfect watertightness, this phenomenon is highly unlikely in the sector chosen for CIGEO.

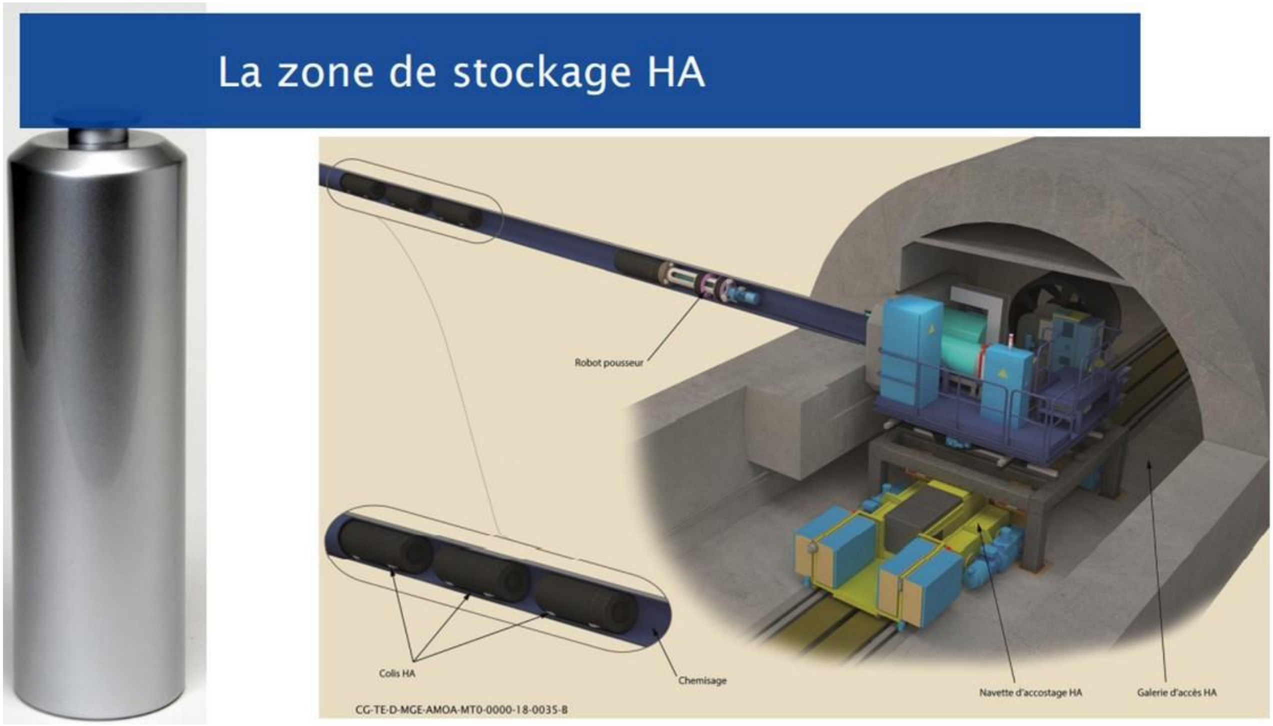



500 m deep **1**
15 km$^2$ disposal zone **2**
250 km galleries & alveoli **3**
85,000 m$^3$ waste volume **4**
120 years operation **5**
25 billion Euros **6**

The CIGEO disposal project **1**
Underground laboratory **2**
Lowering zone **3**
Well zone **4**
Wells **5**
Double lowering shafts **6**
ILW-LL disposal zone **7**
HLW disposal zone **8**

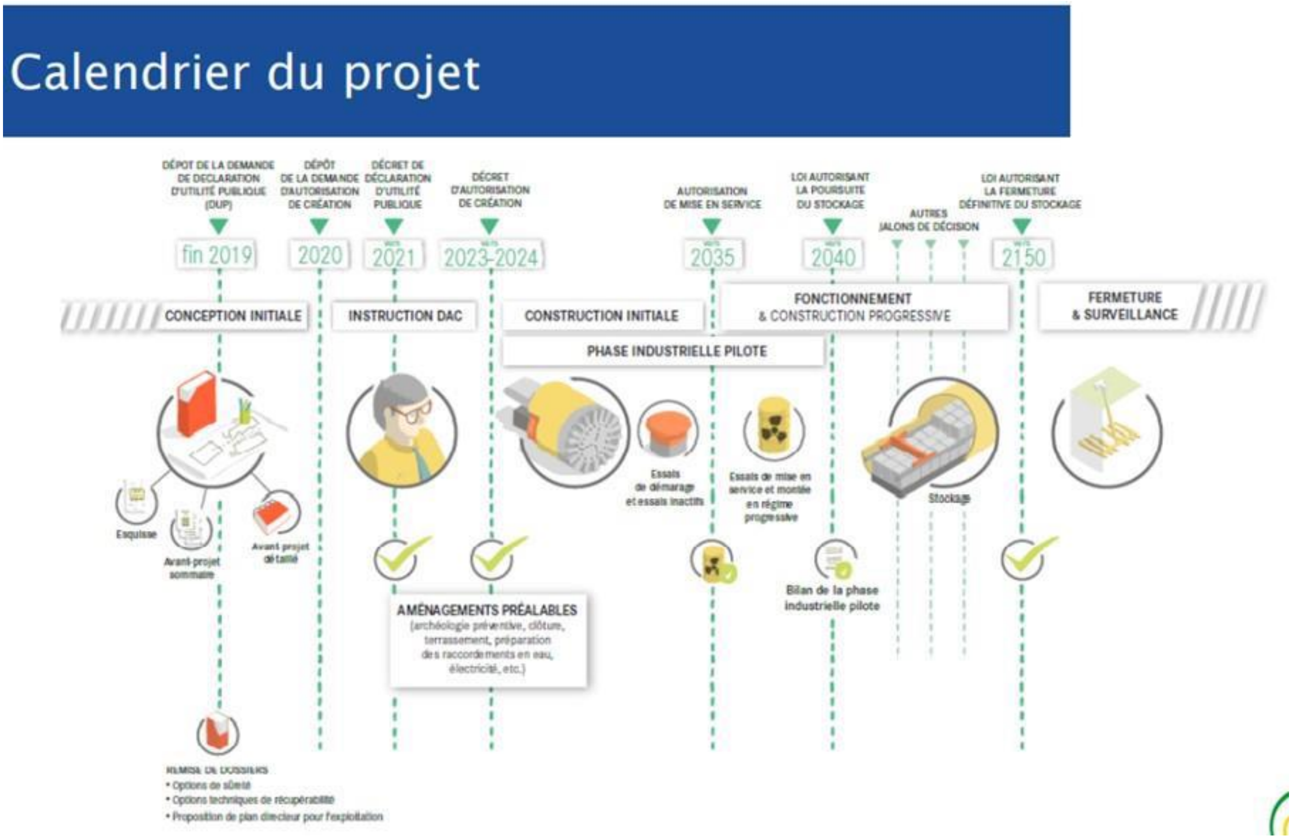
This top view shows that the HL waste disposal zone consists in spaced out horizontal alveoli or cells forming a "radiator" that allows heat to diffuse, while the IL-LL waste disposal zone consists in contiguous large volume chambers because they do not generate heat.


The ILW-LL disposal zone




The HLW disposal zone

Note that the stainless steel packages are housed in devices with ventilation gills allowing both the introduction of the packages into the cells and the circulation of the ventilation air.



Project planning

## 4. Fourth generation fast neutron reactors

Radioactive waste transmutation is possible in 4th generation fast neutron reactors. This has been demonstrated in experiments conducted at the Phénix facility.

The principle consists in placing HL-LL waste in fuel consisting of depleted uranium and plutonium from the reprocessed fuel. The very energetic neutrons fission these waste nuclei thus producing energy and fission products with a shorter half-life.

These reactors are thus very interesting devices because they allow the use of both depleted uranium, of which France holds 350,000 metric tons (hundreds of years of electricity production in France), and plutonium from fuel reprocessing (used today in "MOXed" PWR[14]s), and they reduce the amount of HL-LL radioactive waste.

The law enacted in 2006 had put the CEA in charge of preparing a demonstrator reactor, ASTRID, which would have been built at Marcoule in view of preparing the progressive deployment of fourth-generation reactors. This project was being carried out in cooperation with Japan.

Considering that the uranium resource is abundant, the CEA decided in 2019 not to launch the construction of ASTRID, without even notifying the Japanese partners. The reason invoked was that the price of natural uranium did not justify the use of depleted uranium for yet a few decades. Meanwhile, the Russians have industrialized this technology with the BN 600 MW reactor, then the

14 MOXed PWRs are the 20 PWRs in France that have been adapted to accept MOX fuel. MOX fuel stands for mixed oxyde fuel, a fuel comprising a mixture of uranium oxyde from depleted uranium and plutonium oxyde from spent fuel processing.

BN 800 MW reactor, and are currently preparing the BN 1,200 MW reactor. The Chinese have a test reactor. Everyone recognizes that between a "paper" reactor and its construction and operation, there is a long-term learning effect that France is setting aside, despite the experience acquired with the Phénix and Superphénix reactors.

## To conclude

The rigorous procedures for the management of radioactive waste and of the disposal facilities are designed to protect the population and the environment. They provide for the containment of the waste whatever their characteristics long enough to ensure that they do not pose a risk to present and, above all, future generations.

**We can thus strongly assert that there is no radioactive waste problem.**