France’s Strategy on the Back-End of the Fuel Cycle and the Management and Disposal of Radioactive Waste:

Is final disposal still the Achilles' heel of the nuclear industry?

Patrick Landais, High Commissioner for Atomic Energy. France

NSA - September 28 and 29, 2021 - Virtual Meeting

French strategic priorities in the energy field: Consequences on nuclear energy policy

The Energy Transition Law for Green Growth
was passed in July 2015 by Parliament

This law sets key objectives for French energy policy:

- Establishment of a Multiannual Energy Plan (PPE) to be reviewed every 5 years and a National Strategy for Low Carbon Emissions (SNBC)
- Reduction by 30% of fossil fuel use
- Reduction by 40% of GHG emissions by 2030
- Total energy consumption divided by 2 by 2050 compared to 2012
- Share of renewable energies increased to 23% in 2020 and 32% in 2030
- Nuclear capacity capped at its current level (63 GWe) and nuclear share in the electricity mix reduced to 50% in 2025 *[now postponed to 2035]* with the closure of 14 (out of 58) reactors by 2035. the government has asked EDF to submit a list of sites for closure, amongst the 900 Mwe, reactors in order to minimize both the economic and social impact

- In France, the current fuel cycle strategy is the mono-recycling strategy and is enshrined in a long-term objective of complete closure of the fuel cycle, which is meant to be achieved by the multi-recycling of spent fuels in fast-breeder reactors (FBRs).

- So far, research efforts have been focused on the deployment of Generation IV sodium-cooled fast-breeder reactors (SFBR). The design studies of a technological FBR reactor, called ASTRID, have been launched since 2010.

- However, since natural uranium resources are important and available at low cost, at least until the second half of the 21st century, the need for a demonstrator and the deployment of FBRs are not necessary before this horizon. Furthermore, in the short and medium terms, the priority for the French nuclear industry as far as nuclear reactors are concerned is the success of 3rd generation reactors.

FRANCE REMAINS COMMITTED TO THE CLOSED FUEL CYCLE POLICY (2/2)

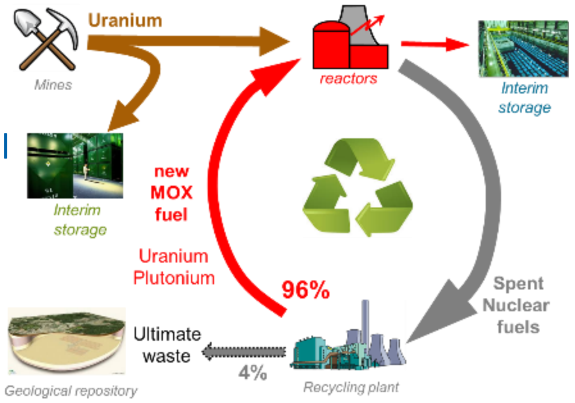
- For the short and medium term, in order to maintain the fuel reprocessing strategy and to stabilize plutonium and spent fuel reserves, the draft MEP has decided :
  - the Moxing of a number of 1300 MWe reactors will be undertaken (in order to take into account the closure of several 900 MWe MOx reactors in the next 10 to 20 years) ;
  - The strategy for treatment and recycling of nuclear fuel is maintained until the 2040's horizon. To this end, several 1300 MW reactors will use MOx fuel. Furthermore studies will be conducted for the deployment of nuclear fuel multi-recycling in PWR reactors.
- Furthermore, R&D efforts on 4th generation technologies will still be made to prepare the future, focusing on R&D based on simulation and experimental works, led by CEA.

❶ Reactors

- ❑ Manage lifetime extension (ageing)
- ❑ Reduce severe accidents
  - Decrease of core fusion probability
  - Avoid any RN release preventing the population evacuation
- ❑ Develop innovative & competitive design
  - GEN3: EPR
  - SMR: NUWARD
  - New technologies: MSR, new applications (H2, heat…)

❷ Fuel Cycles

- ❑ Reduce environmental footprint of front-end activities
- ❑ Enhance recycling to improve overall sustainability
  - Reuse of nuclear materials: U, Pu
  - Better use of natural uranium (^{238}U)
  - Reduce ultimate waste
- ❑ Implement deep repository
  - CIGEO project (2025)



“FRANCE RELANCE” PLAN: 470 MILLION EUROS FOR THE NUCLEAR INDUSTRY

- Creation of an investment fund aimed at consolidating the shareholding and supporting the capital increases of companies;
- Financing of initiatives aiming at strengthening skills and maintaining the high level of industrial know-how (strategic components for power plants);
- Funding of R&D projects:
  - innovations for developing the "Factory of the future" (digital twin, additive manufacturing, connected factories, 3D printing, etc.);
  - the development of innovative solutions for the management of radioactive waste, including alternatives to deep geological disposal;
- Financing of studies for the design of SMR;
- Support for the Fessenheim technocentre dedicated to metal recycling.

HL and IL final waste management: Societal and political issues; uncertainties

MAJOR CONCERNS OF FRENCH POPULATION CONCERNING NUCLEAR ENERGY

- There is no consensus on an optimal mix and it is still very difficult to profitably debate on this topic between the different stakeholders. Nuclear power bears of an ambivalent imaginary: the bomb versus electricity, the rays that heal versus the rays that kill, the radioactive waste that lasts versus nuclear as an essential tool for a low-carbon future, the scientific and industrial flagship versus technological excess and poorly manages construction costs.
- The symbolic halo of nuclear power is mostly determined by the accidents that have marked its history and the emerging technologies (SMR, FNR…) do not seem –at this stage- able to change the public image of nuclear industry. The symbolic halo of nuclear power is specific because it mixes short-term fears (linked to possible accidents in NPPs currently in operation) and long-term fears, induced by time scales of the issue of nuclear waste.

THE REPORT OF THE EXPERTS GROUP ON SUSTAINABLE FINANCE (MARCH 2020)

The in-depth report lists 70 business sectors whose combined activities represent 93% of Europe's CO2 emissions. Experts have agreed on everything except nuclear energy, which remains a grey area.

"The evidence provided on the potential substantial contribution of nuclear energy to climate mitigation objectives is extensive and clear. The potential role of nuclear energy in low-carbon energy supply is well documented …/… However, with regard to significant potential damage to other environmental objectives, including the circular economy and waste management, biodiversity, water systems and pollution, the evidence is more difficult and complex to assess in a taxonomic context".

Experts noted that a safe, long-term waste storage solution has yet to be found anywhere in the world.

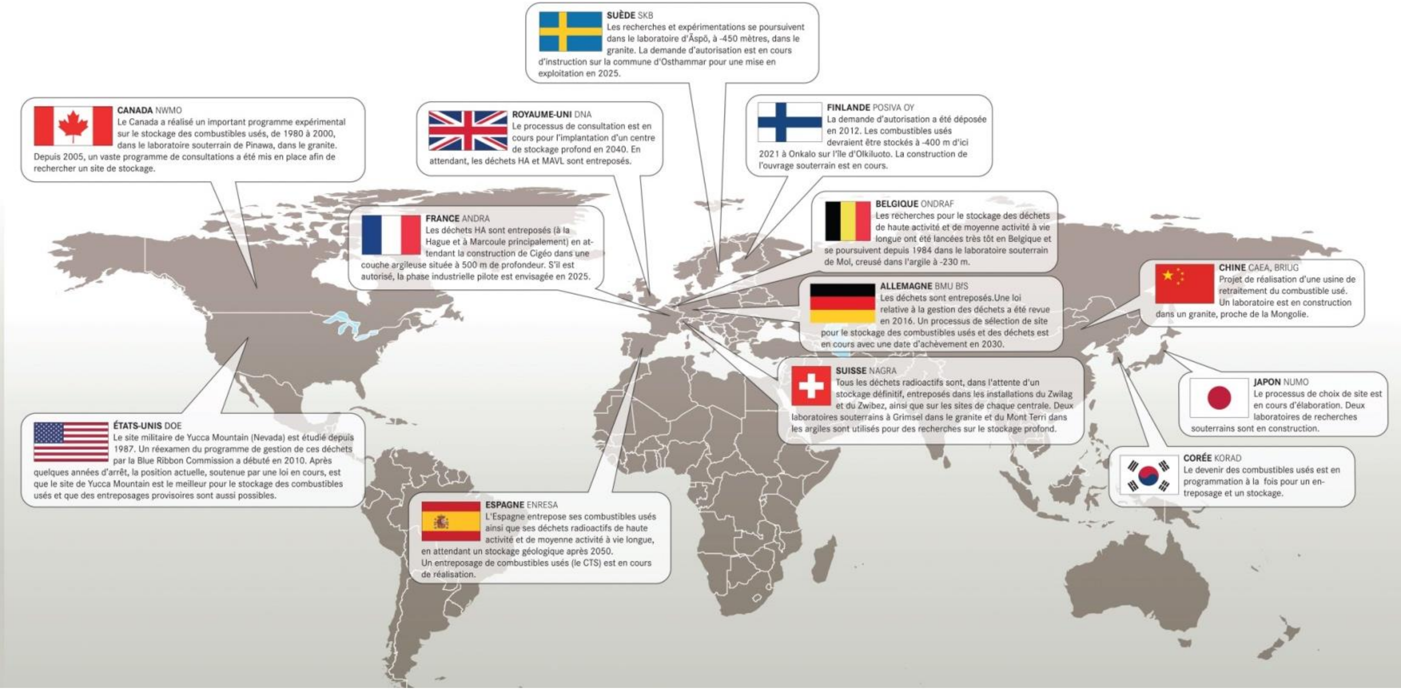
There is broad consensus in the scientific community that deep geological disposal is the safest long-term solution for spent nuclear fuel and high level radioactive waste …/ …Disposal facilities are designed to be passively safe after closure. The DGR are designed so that potential radioactive release from them occurring in the remote future are well below the maximum allowed dose limit set by the relevant regulation, which, in turn are orders of magnitude below natural background dose levels, and which ensure that no significant harm will be caused to humans by the repository. There are presently no deep geological repositories in operation, but after four decades of research and technology development the construction and operation of several repositories is expected in the present decade. The process for the design, licensing, construction, operation and final closure of deep geological repositories is regulated by national law, based on international conventions and European directives; this means that there is a common ground shared by all programmes based on the best available principles and concepts.

The European Commission plans to launch its first “green bond” from October to finance the 750 billion euro post-Covid stimulus package.

“The EU's plan to issue up to € 250 billion in green bonds by 2026 will make us the largest green bond issuer in the world,” said Johannes Hahn, EU Commissioner. Budget.

The debates on European taxonomy, aiming at defining investments favorable to the energy transition are not definitively settled. They still divide on the sensitive subject of the nuclear energy status and Brussels excludes using green bonds for nuclear power plant projects.

INTERNATIONAL SITUATION



Among the 30 countries operating NPPs, 15 have opted for deep geological disposal to manage their HLW waste.

13 countries have already identified a storage site or are in the process of doing so (England, Canada, United States, etc.).

11 countries already have or will soon have an underground research laboratory (Belgium, Switzerland, Sweden, etc.). Finland, Sweden and France are the most advanced countries with regard to the licensing of their disposal facility.

French strategic orientations for HL and IL waste management

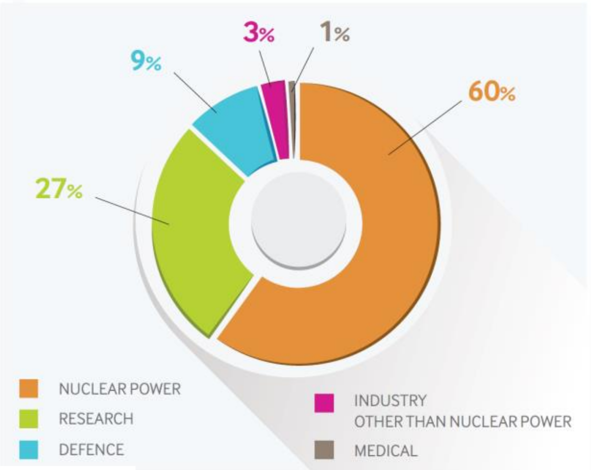
MAJOR RADIOACTIVE WASTE MANAGEMENT OPTIONS IN FRANCE

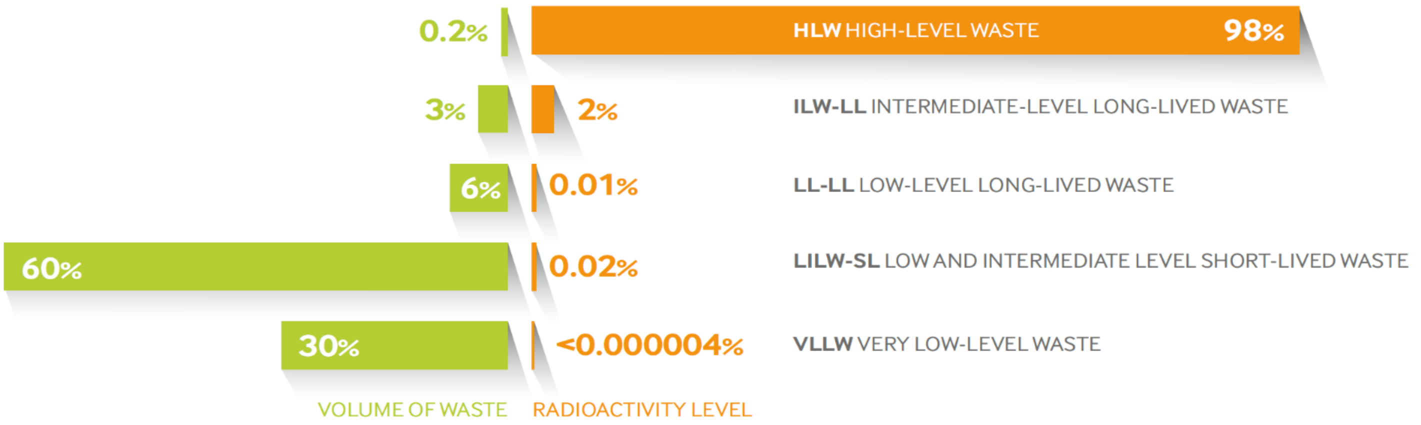
- Safety of the population and protection of the environment is the first priority
  - A national framework set by law since 1991
  - An independent agency (Andra), responsible for the long-term management of all radioactive waste produced in France
  - Inventory and forecast, leading to a National Management Plan
  - A safe and sustainable solution for all types of radioactive waste
- Reprocessing of used fuel and reuse of the resulting valuable material
- Reversible geological disposal (Cigéo Project) is the reference solution for the high-level waste
  - Host clay formation already studied in an underground laboratory
  - Vitrified waste and IL-LL (hulls and end-caps) waste to be disposed of
  - Alternative solution of direct disposal of SF under study
- No clearance level for the materials coming from a nuclear classified zone

Categories of radioactive waste and breakdown by volume

- On average, each person in France generates 2 kg of radioactive waste per year
- By way of comparison, each resident produces on average 573 kg of household waste and 1,500 kg of waste from economic activities (excluding waste from the construction industry).

Over 1200 producers





5 radioactive waste categories

The Cigéo inventories include existing or future waste (average operating life of 50 years for all reactors), resulting from the operation and dismantling of:

- Installations in operation or shut down:
    - relating to the nuclear power industry (58 power generation reactors, fuel fabrication and processing plants)
    - dedicated to research activities
    - carrying out activities related to the nuclear deterrent
- Installations under construction which obtained their licensing decree on December 31, 2016, in particular:
    - the Flamanville 3 EPR
    - the ITER installation in Cadarache

Treatment-recycling of all spent fuels (UOX, MOX, URE and fuels from fast neutron reactors and research facilities)

Predicted volume of waste:

- around 75,000 m³ ILW-LL (of which 60 % has already been produced)
- and 10,000 m³ HLW (of which 40 % has already been produced)

French Nuclear fleet

Processing of UF

HLW: 10,000 m³

6 type of containers to dispose of 22 primary waste package families

IL-LLW: 75,000 m³

13 type of containers to dispose of 68 primary waste package families

Technology waste, research activities and legacy waste

A variety of waste types

SCENARIOS FOR THE CIGEO INVENTORY

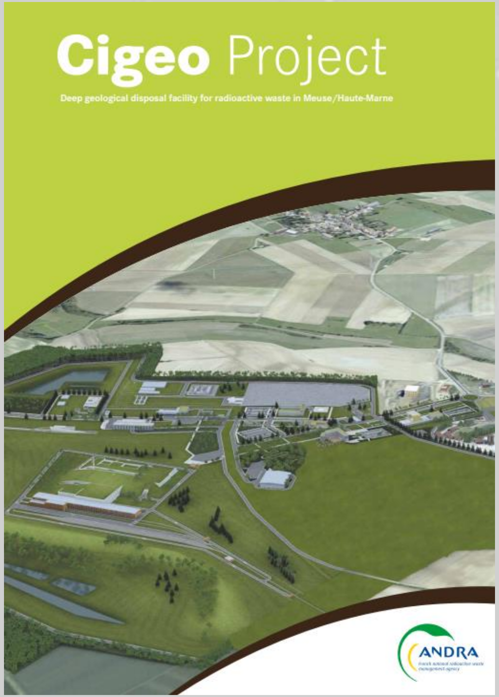
	SR1	SR2	SR3	SNR	SNR envelope
Continuation or cessation of nuclear power generation	Continuation	Continuation	Continuation	Cessation	Cessation
Operating time of reactors in the current fleet	50 to 60 years	50 years	50 to 60 years	40 years and 60 years for EPR	50 to 60 years
Types of reactors installed in the future fleet	EPR then FNR	EPR then FNR	Only EPR	-	-
Spent fluel reprocessing	all	all	Only Uox	No further reprocessing	No further reprocessing
Reclassification of spent fuels as waste	None	None	URE, Mox, FNR (Phoenix…)	All spent fuels	All spent fuels

240 m³ ILW
3695 m³ HLW

Reference inventory

Covered either in SR1 or SNR envelope

55000 m³ SF
6600 m³ HLW



Implementing the final disposal: The Cigéo project

A PROGRESSIVE AND APPROACH FOR SITING

3- Area defined for location of repository U/G facilities after local consultation (2009) and detailed geological survey from the surface

Detailed survey in 2010

Additional above-ground geological survey 2007-2008

2- Transposition zone of URL results (proposed 2005)

4- Location of repository surface facilities to be presented during the Public Debate

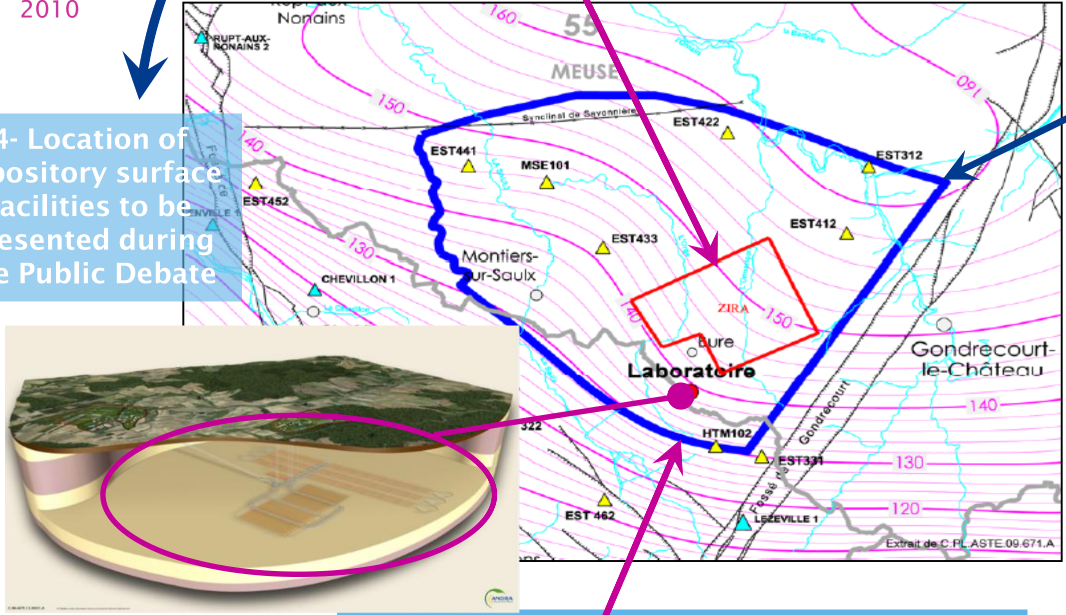
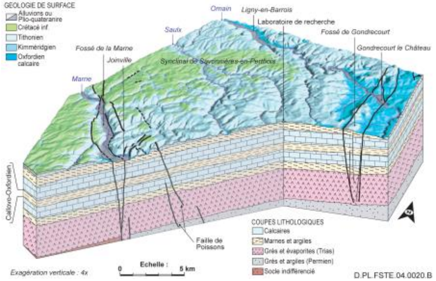
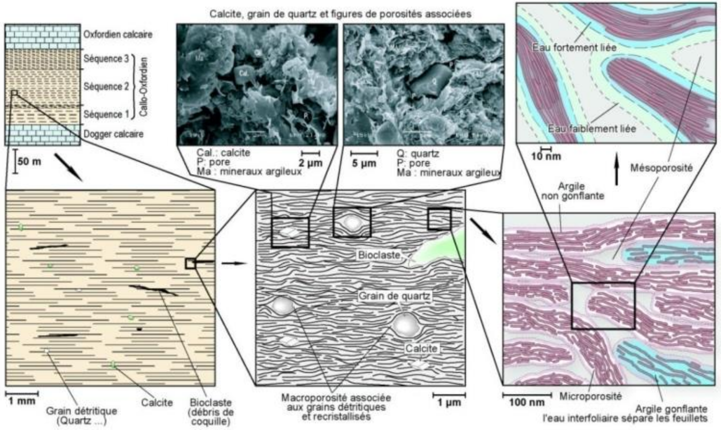


Schéma de principe du stockage à terminaison

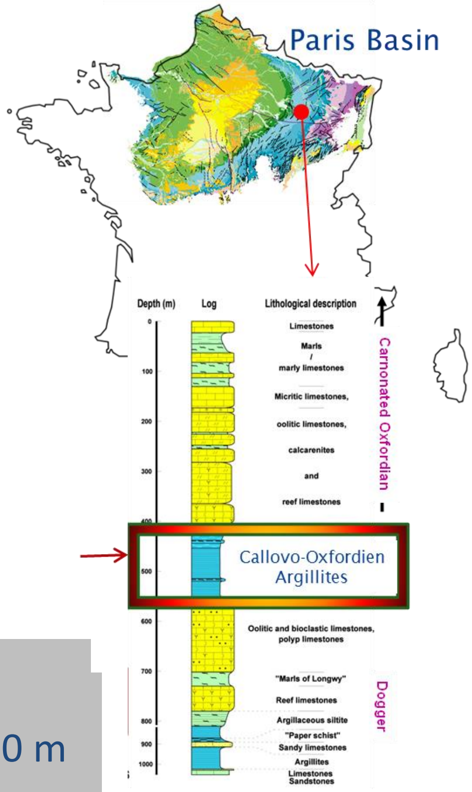


1- Siting started in 1992 with a National call for volunteering; URL licensed 1998



A courageous choice and commitment: the major nuclear countries opt for granite.

A scientific and technological commitment associated with the major strategic choice of the back-end (reprocessing)



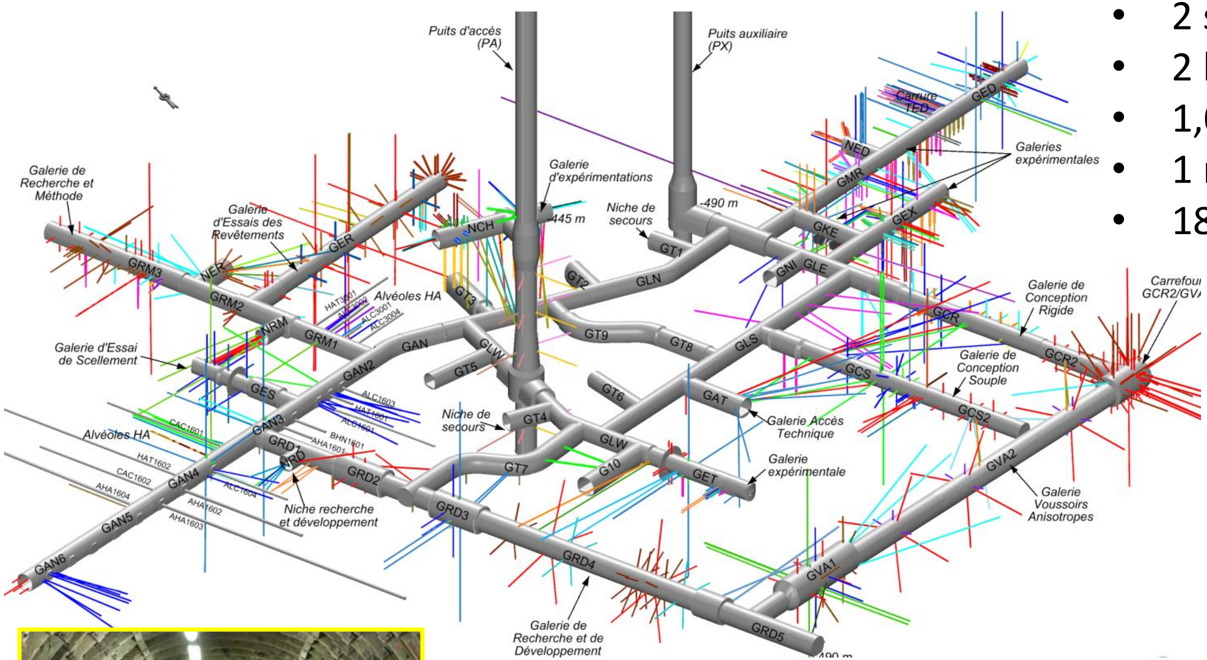
A geological formation with interesting characteristics:

- suitable geometry
- undisturbed geodynamic environment
- favorable properties (retention, permeability)

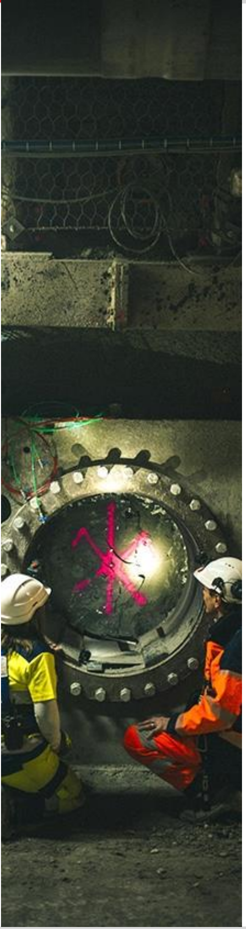
A clay material with a 3D organization and complex responses to stresses:

- Anisotropy
- mechanically damaged area during excavation
- creep and convergence
- temperature sensitivity

- Age :160 ma
- Thickness : 130 - 170 m
- Depth : 420 – 580 m



- 2 shafts
- 2 km of drifts
- 1,000 boreholes
- 1 million data per day
- 18,400 measurement points



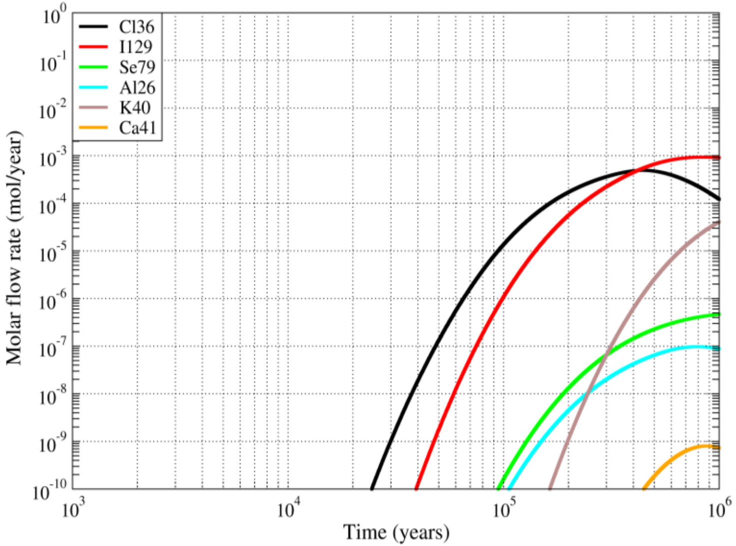
Technology

- 2 shafts of 500m depth
- 1,7km of drift excavated
- 3 excavation methods
- Soft up to rigid support
- 13 HLW cells constructed (100m long)
- Sealing plug at drift scale
- Operating and maintaining by Andra

RD&D

- Systematic geological survey during excavation
- 10 000 sensors measurements with on line acquisition and continuously
- 30 on going experiments designed and performed on its own, with a network of institutes and industrial integrators

- Normal Evolution Scenario
- Reference situation



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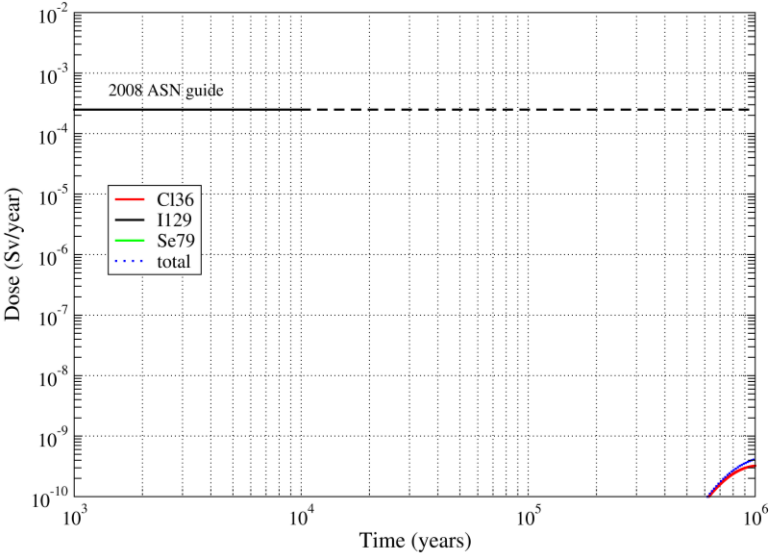

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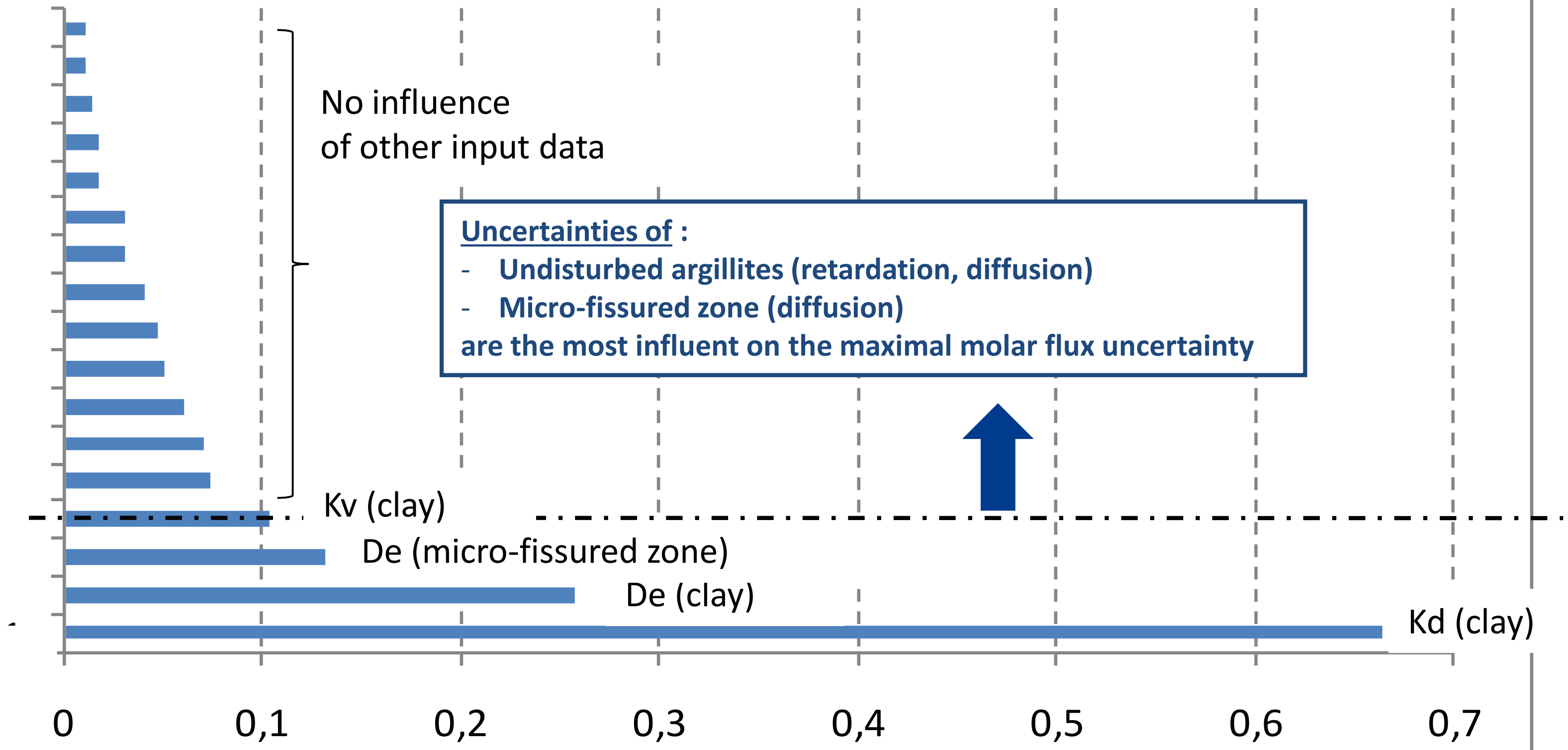


<u>Uncertainties of</u> :

- **Undisturbed argillites (retardation, diffusion)**
- **Micro-fissured zone (diffusion)**

are the most influent on the maximal molar flux uncertainty

CIGÉO INSTALLATIONS

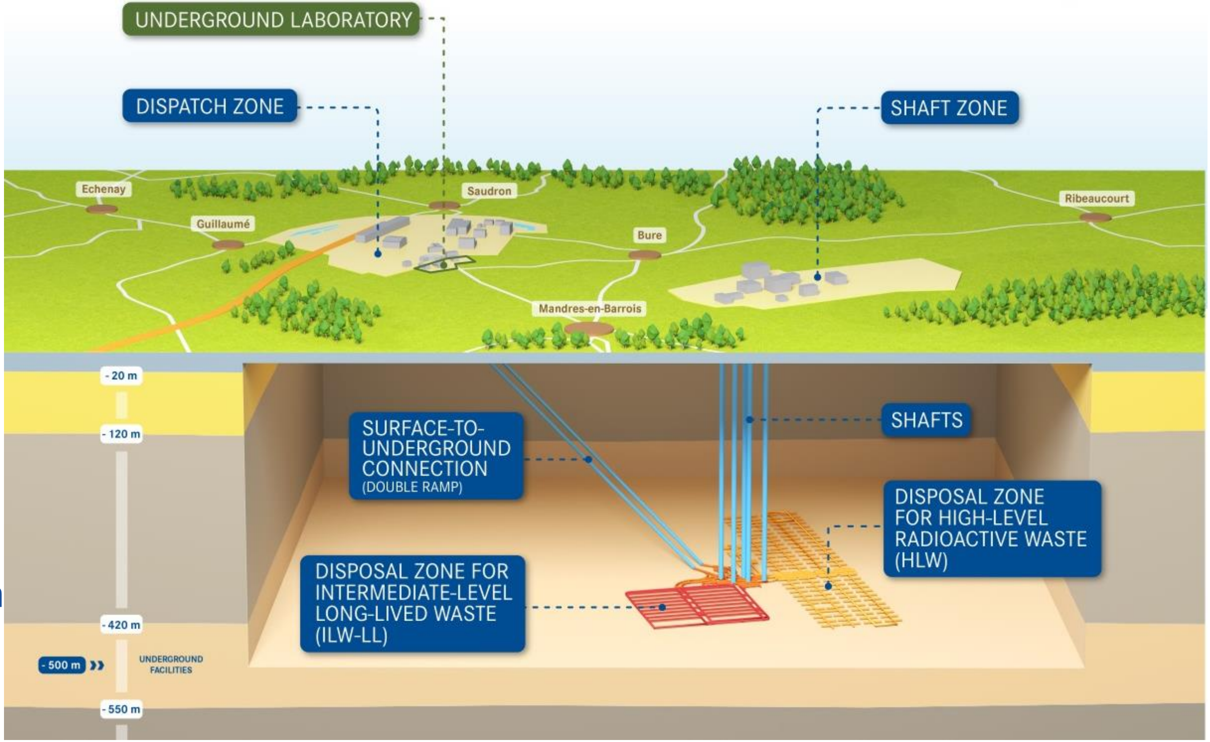
500 metre depth

15 km² of underground footprint

85 000 m³ of waste

120 years of operation

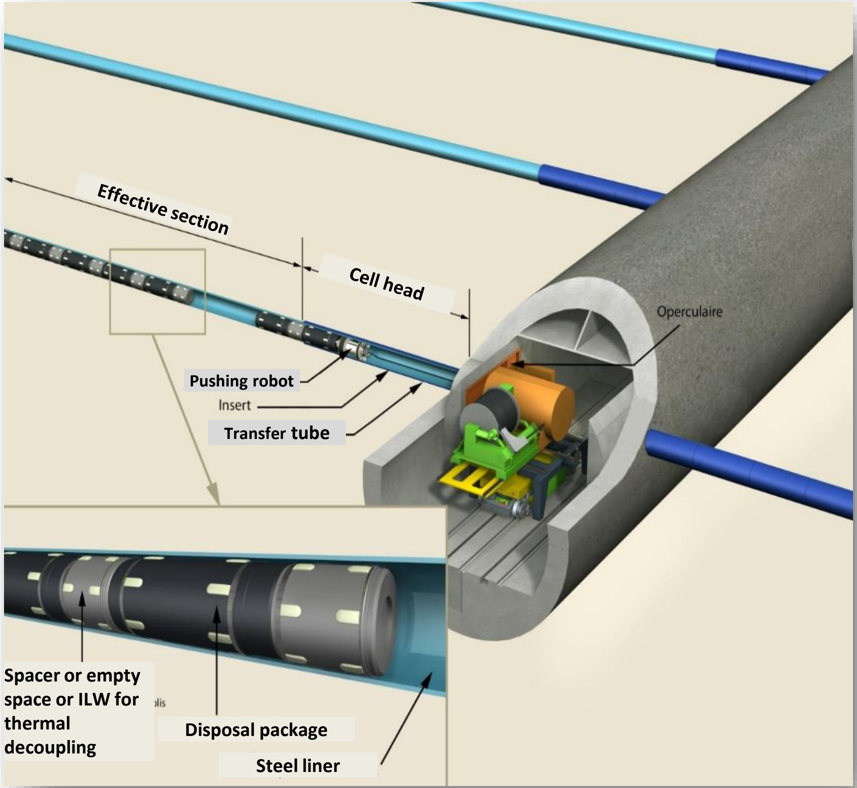
25 bn Euros



The packages will be positioned one behind the other in the cell by a pusher robot.

The packages will either be separated by a spacer or an empty space or an ILW package for thermal decoupling.

The objective is to respect the maximum temperature of 90 ° C in the rock so that it preserves its properties and to limit THM effects on a large scale.



- < 1,000 cells
- L: 150 m
- Ø 0.7 m

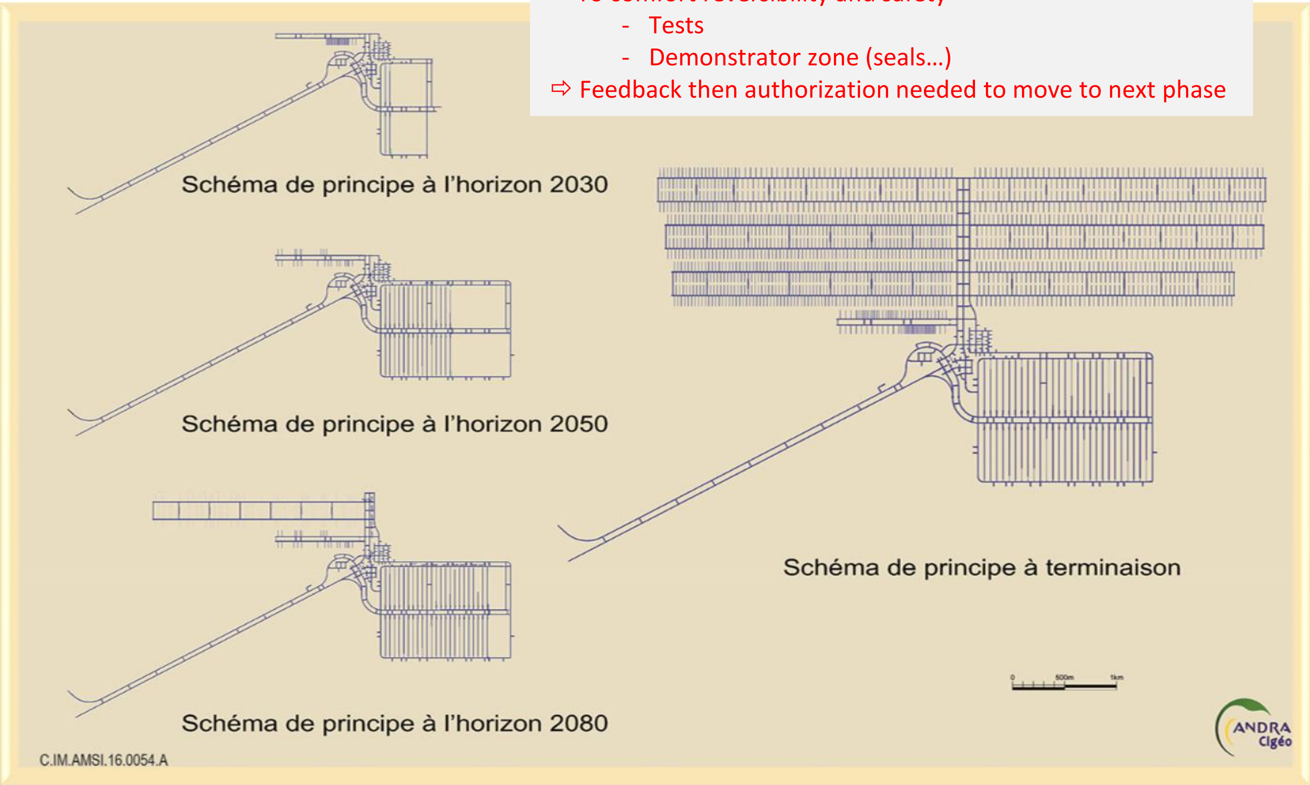
Phenomenology

- Maximum temperature in contact with clay: 90 ° C
- Steel liner for reversibility and limitation of THM effects
- Injection of cementitious grout on the outer surface to buffer the acid transient

Industrial pilot phase if authorized

- To comfort reversibility and safety
  - Tests
  - Demonstrator zone (seals…)

⇨ Feedback then authorization needed to move to next phase

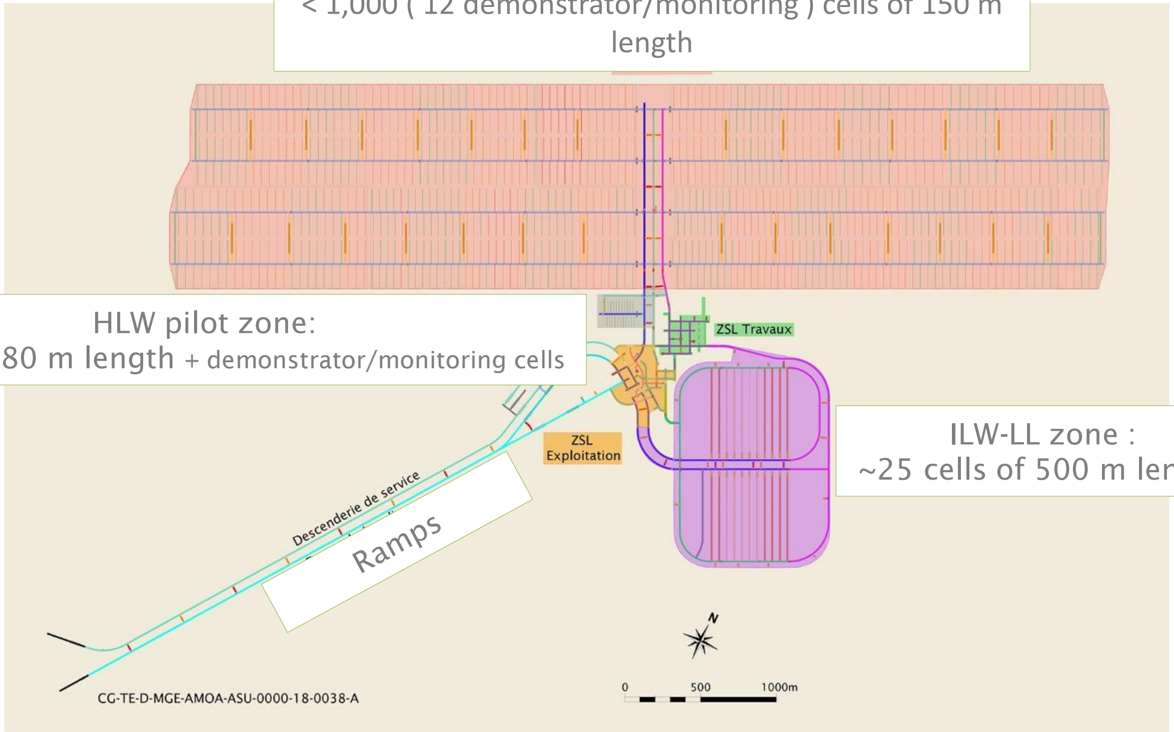


Initial industrial pilot phase:

A small zone dedicated to HLW 50 years before the start of the disposal of all the HLW packages

Then, the progressiveness of deployment: a tool for reversibility, flexibility and adaptability.

HLW zone :
< 1,000 (12 demonstrator/monitoring) cells of 150 m length

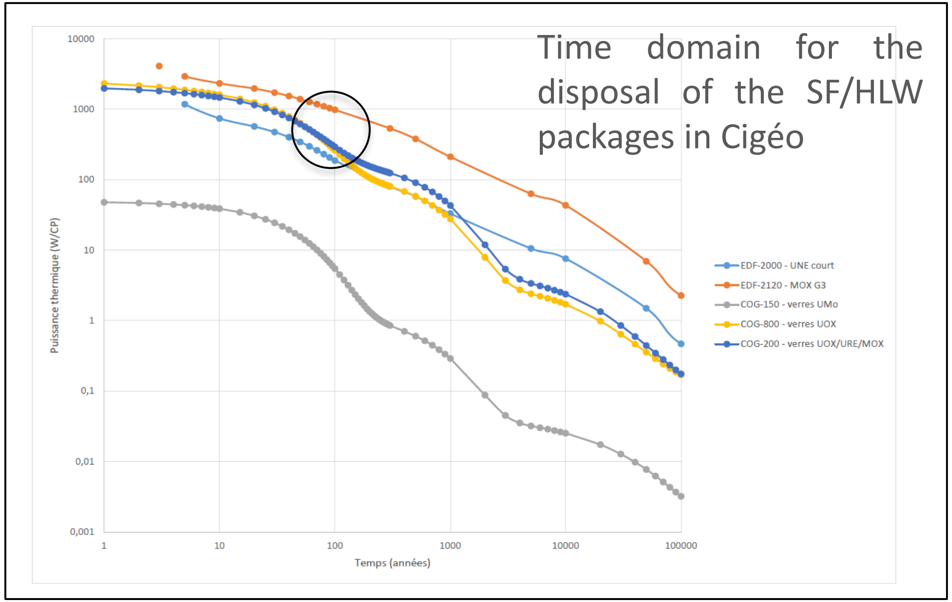


HLW pilot zone:
18 cells of 80 m length + demonstrator/monitoring cells

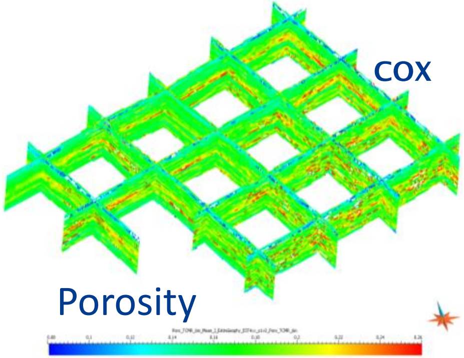
ILW-LL zone :
~25 cells of 500 m length

Disposal cells

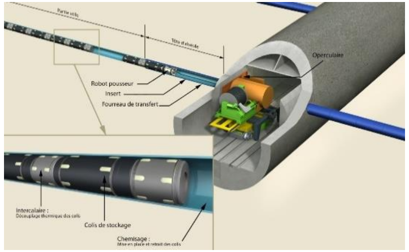
- around 1,000 HLW cells (150 m long),
- 25 ILW cells (500 long)
- 18 HLW cells (80 long) in the pilot area where low thermicity HLW packages will be disposed of.

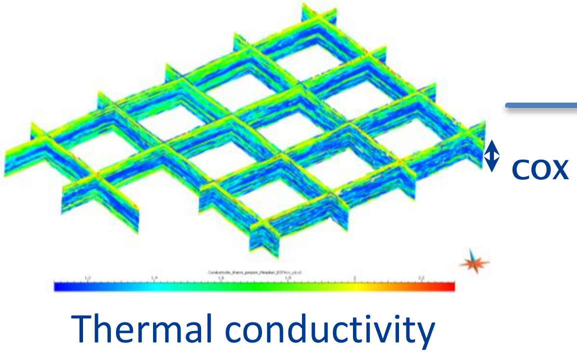


Time domain for the disposal of the SF/HLW packages in Cigéo
Puissance thermique (W/CP)
Temps (années)
EDF-2000 - UNE court
EDF-2120 - MOX G3
COG-150 - verres UMo
COG-800 - verres UOX
COG-200 - verres UOX/URE/MOX



COX
Porosity





COX
Thermal conductivity

ADAPTABILITY OF CIGÉO TO THE DIRECT DISPOSAL OF SPENT FUELS

Input data

- Thermal (conductivity), Hydraulic (permeability) and mechanical characteristics of the Callovo-Oxfordian formation
- Callovo-Oxfordian formation thickness
- Thermal powers of individual waste packages

Applicable requirements / functions

- Preservation of favorable properties of the Callovo-Oxfordian
- Preservation of operating systems and the durability of concrete
- Temperature criteria
- Callovo-Oxfordian fracturing criterion

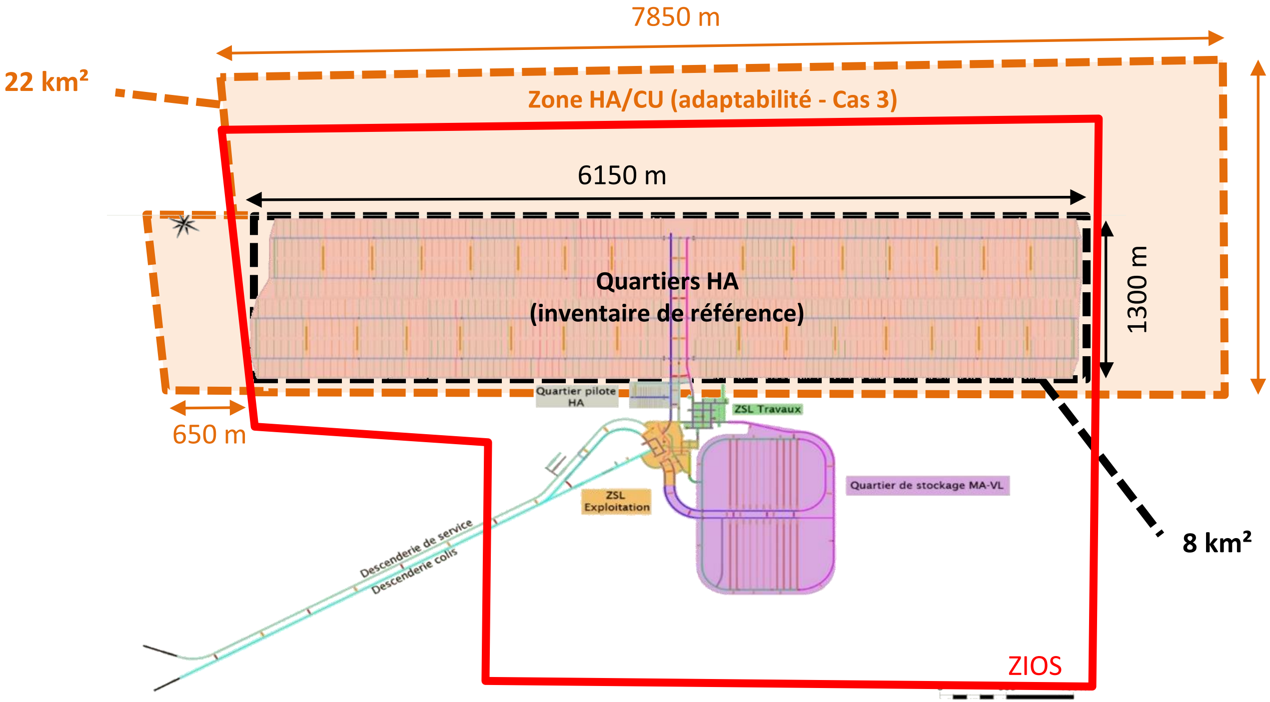
Safety choices

- THM behavior of the Callovo-Oxfordien
- Parameter values: "Best estimate" approach; Envelope / conservative approach

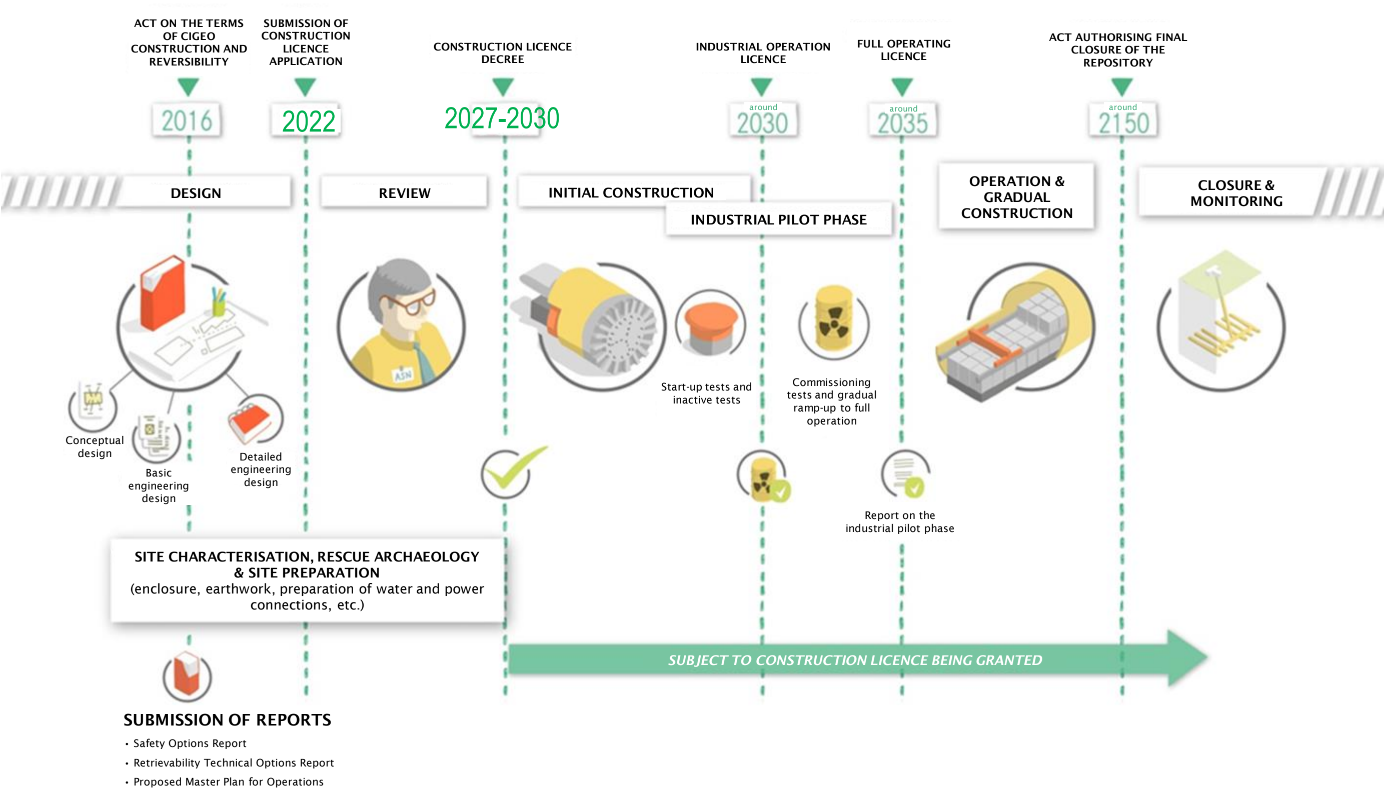
Design

- Thermal power when disposed in Cigeo
- Spacing between storage cells
- Number of packages per cell
- Spacing of packages within the cells

Disposal Footprint


7850 m
22 km²
Zone HA/CU (adaptabilité - Cas 3)
6150 m
Quartiers HA
(inventaire de référence)
1300 m
Quartier pilote HA
ZSL Travaux
650 m
Quartier de stockage MA-VL
ZSL Exploitation
Descenderie de service
Descenderie colis
8 km²
ZIOS

PROVISIONAL SCHEDULE



The debate confirmed that the 2006 law, by making deep geological disposal the "reference solution" for the high level waste management, did not not solve the question of the modalities of this management. Two alternative and very clear cut options are identified and each defended by a part of the actors: deep geological disposal and subsurface storage for a period long enough to allow research advances on transmutation, in order to finally reduce waste radioactivity and toxicity.

Public questions relate, on the one hand, to the safety of the disposal and its reversibility and, on the other hand, on the prospects of transmutation research, prerequisite for them to the development of a reliable and secure industrial tool which would allow its implementation as an alternative option.

These findings, resulting from the complexity of projects and their unusually long timeframes, led to identify the timing as a central issue of the public decision process. In order that relevant decisions, accepted by the society, can be taken and adapted within, public participation in the preparation of these decisions appears in the debate results to be of paramount importance.

The strong need for setting a mechanism for effective participation in the preparation of decisions continuously adapted to scientific, technical, socio-economic and political changing circumstances, within the evolving framework set by law, thus constitutes for the commission the major contribution of the debate on this sensitive issue.

- Highlight the key milestones in the management of HLW and ILW, in order to provide an integrated vision of all the issues and by making the meetings with the public and their nature more visible;
- Define the objectives and principles of the future governance of the Cigeo project;
- Specify the conditions for applying the reversibility of the Cigeo project and its conditions for implementation, in particular with regard to the retrievability of packages;
- Define the main objectives and success criteria and points of attention for the industrial pilot phase of Cigeo;
- Rely on the long implementation time of the Cigéo project to continue research on alternative management options for HLW/ILW;
- Publicize the update of the cost of the disposal project during the Cigeo licensing process.

CONCLUSION: IDENTIFIED SUCCESS FACTORS

- Political framework with independant review bodies
- Site selection on the basis of voluntary sites
- Step by step approach
- Mobilization and involvement of national representatives
- Mobilization and involvement of local elected representatives
- Independence of Andra
- Strong involvement of Andra
  - Local participation
  - Dialog with local and national stakeholders
  - Local involvement
- Involvement of waste producers
- Local development project/scheme and funds for it
- Information and Oversight Committee

Thank you