28 years of R&D and Design activities to prepare the license application of Cigéo

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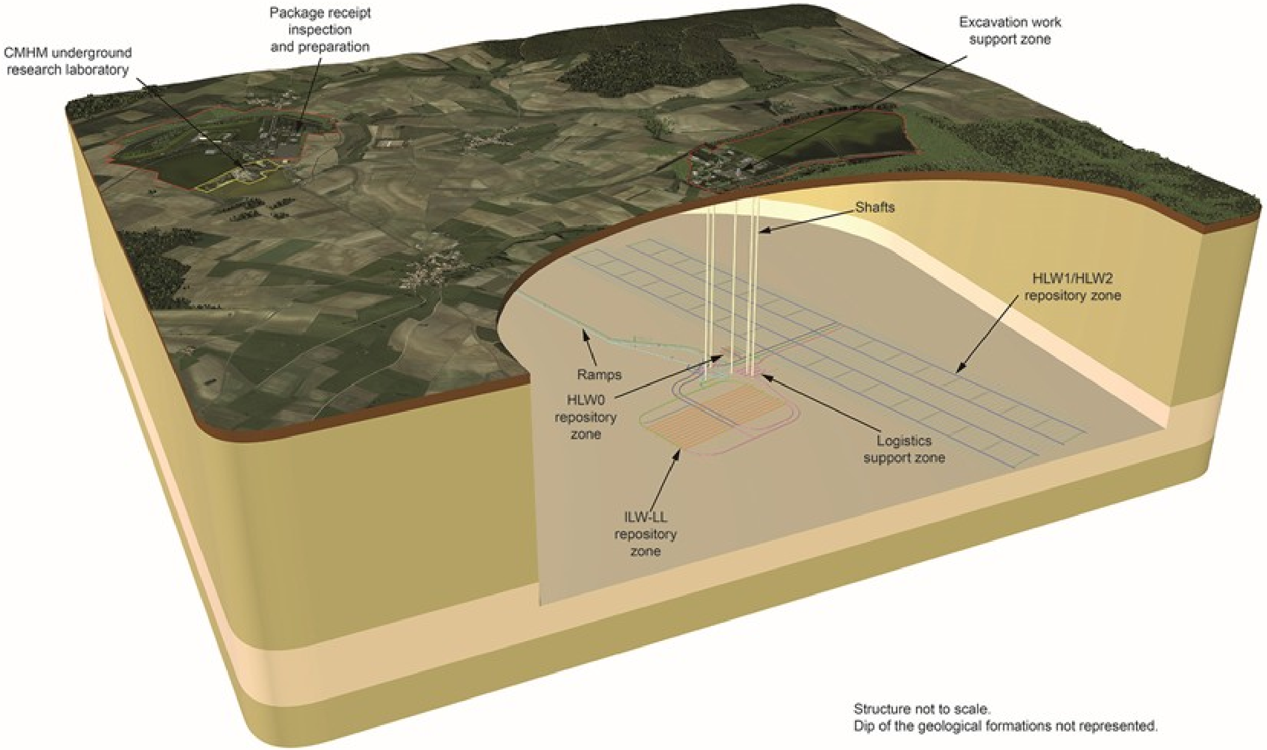
Andra, who are we?

- French National Radioactive Waste Management Agency
- Created in 1991, missions governed by three laws (1991, 2006 and 2016)
- Responsibility: Design and R&D, licensing, construction, operation and closure of radioactive waste disposal
- Independent from radioactive waste producers
- 2017 budget: 325 M€, mainly funded by radioactive waste producers (commercial contracts for industrial activities, tax for RD&D activities – i.e. Cigéo project)
- Website: https://international.andra.fr/

Cigéo history in a nutshell

(French project for Deep Geological Disposal of HLW in the Meuse/Haute Marne districts)

The underground facility is hosted 500 m deep in thick argillite (hard clay) formation



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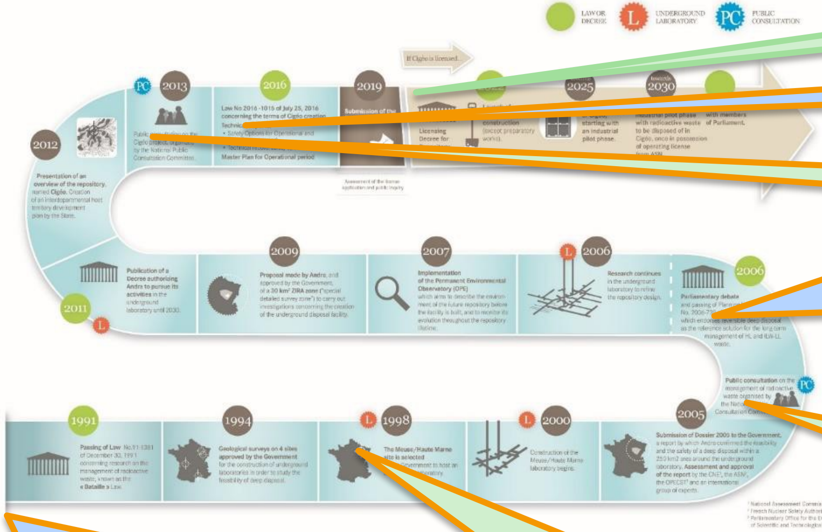
Overview of Cigeo roadmap



New Public debate (2019) : 5th version of French radioactive waste and material management plan

Reversibility act of 25 July 2016

Public debate 2013

Planning act of 28 June 2006 / French Environmental Code
and
Transparency act of 13 June 2006

Public debate 2005
- ✓ **Three R&D options** in debate
- ✓ Long term storage preferred option of the Public…despite Nuclear Authority position

Program act of 30 December 1991 (first law on the management of RW)
- ✓**Three R&D options**
- ✓**15 years R&D programs**
- ✓**Creation of Andra**

Siting phase for a URL (s) - voluntarism based
- ✓ 1992 – 1994: call for volunteers
- ✓ 1995 - 1996: site investigation, 3 URL license applications
- ✓ 1996 – 1998: Instruction including public inquiries/hearings

ANDRA

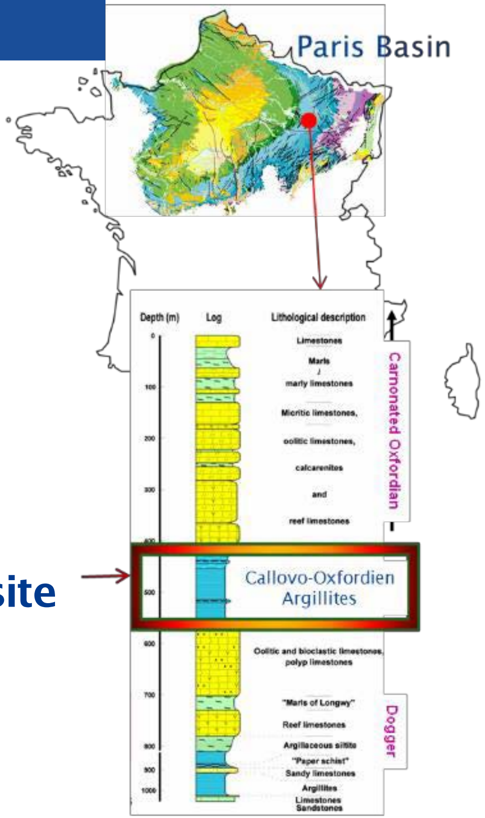
Geological context of Cigéo in brief

Parisian basin

- Well-known geology (Oil&Gas, water,…)
- Simple sedimentary basin with continuous, gently dipping sedimentary layers (limestone, marls and clays…)
- Limited and well-documented geodynamic structures
- Stable stress field for 20 million years

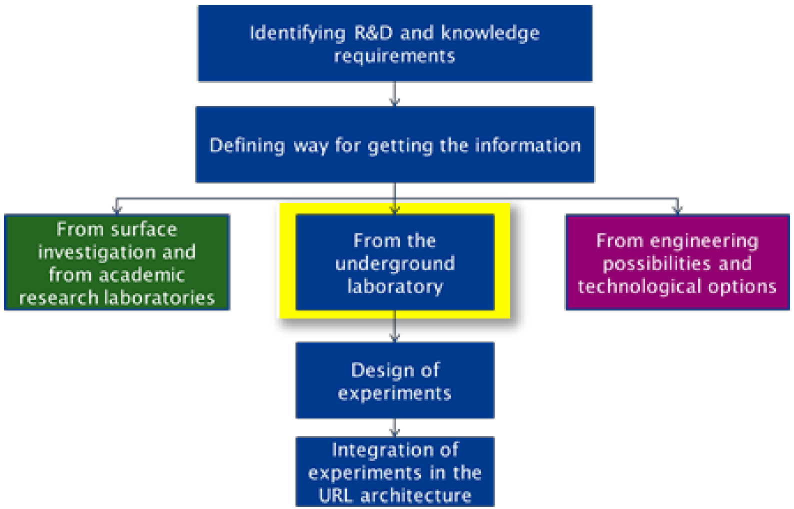
Callovo-Oxfordian clay (160 millions years) near Bure site

- Local thickness : 130-170 m
- Homogeneous
- “Simple” hydrogeological context
- Local depth : 420 – 580 m

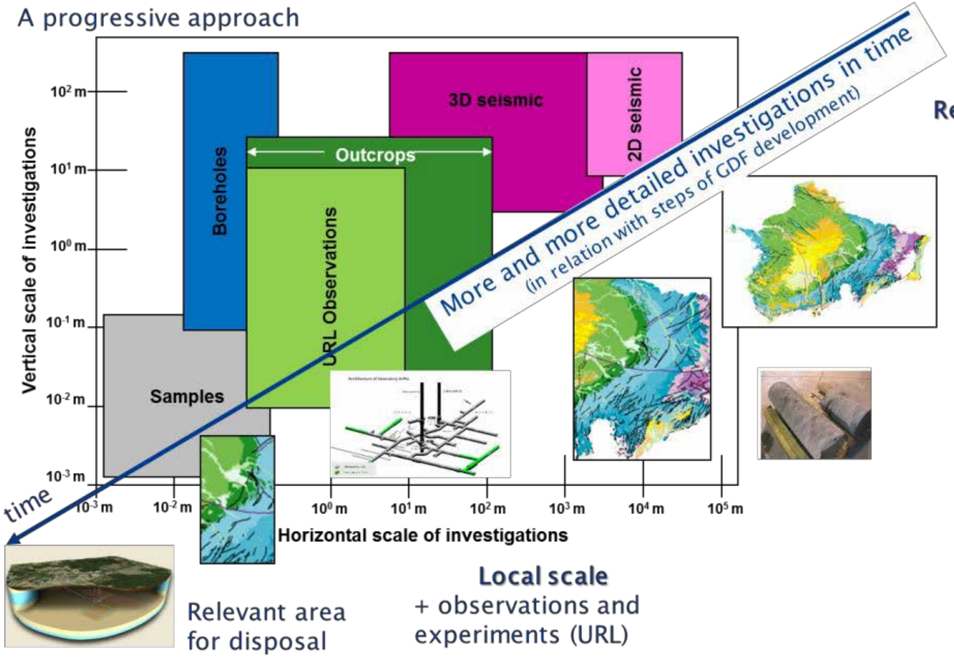


Bure URL as a tool for the Cigeo R&D program

The Work (in R&D)

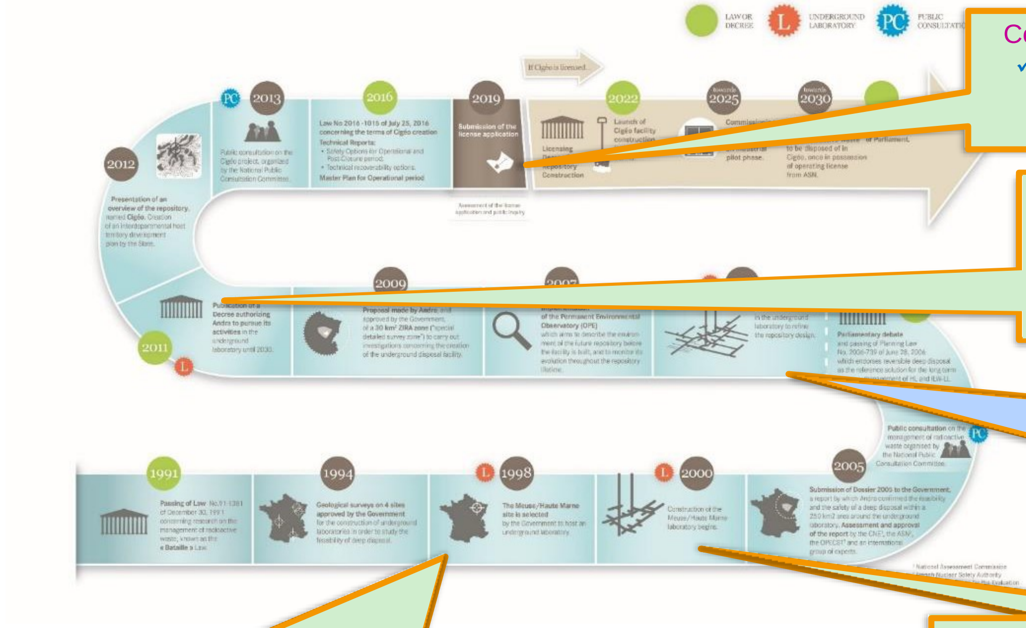


A progressive approach



Andra's URL at Bure (Meuse Haute-Marne); history in a nutshell

A progressive development of the URL



Coming…

- ✓ **4th set of experiments**
  - ➢ Construction technologies, support and lining
  - ➢ Crossings, seals…

Operational license extension (2030)

- ✓ **3rd set of experiments**
  - ➢ Construction technologies (HLW tunnels), galleries excavation (road header, tunnel boring machine)
  - ➢ Support and lining, seals…

Extension of the laboratory (drifts, niches…)

- ✓ **Utility revamping (construction to operation)**
- ✓ **2nd set of experiments**
  - ➢ Coupled processes
  - ➢ Limitation of disturbance (drifting, lining…)

Siting phase for a URL (s) - voluntarism based

- ✓ 1992 – 1994: call for volunteers
- ✓ 1995 - 1996: site investigation, 3 URL license applications
- ✓ 1996 – 1998: Instruction including public inquiries/hearings

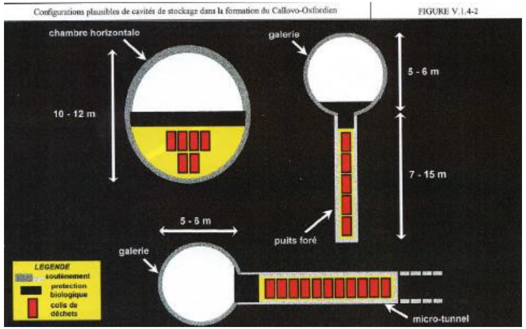
Bure URL construction starting (initial configuration)

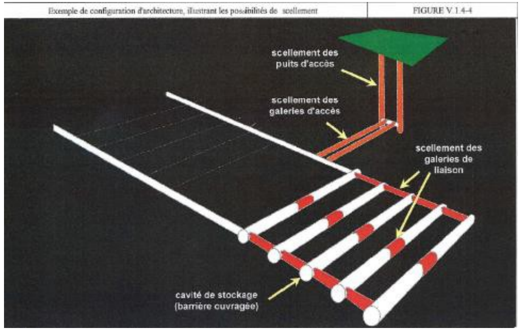
- ✓ **Two shafts and 1 experimental gallery on top of clay layer**
- ✓ **1st set of experiments**
  - ➢ Intrinsic properties of the clay
  - ➢ Induced damage of the clay by shaft sinking

Pre-construction phase…1993 - 2000

First site investigation results + First disposal concepts

- Simple geometry of the Callovo-Oxfordian argillite layer (large extent, continuity and sub-horizontal stratigraphy…), appropriate depth and thickness
- Very low permeability of the Callovo-Oxfordian formation and no aquifer of interest
- No major construction difficulties
- Favorable geochemical properties
- Absence of seismicity and a stable geo—dynamic context (millions of years)
- No particular valuable natural resources (mining, oil and gas, geothermal…)





R&D Program (→ 2005 milestone)

→ Characterize the containment properties of the rock mass (Callovo-Oxfordian)

→ Analyze the mechanical damage of the rock due to construction

→ Verify the possibility to seal excavated drifts

The URL shall:

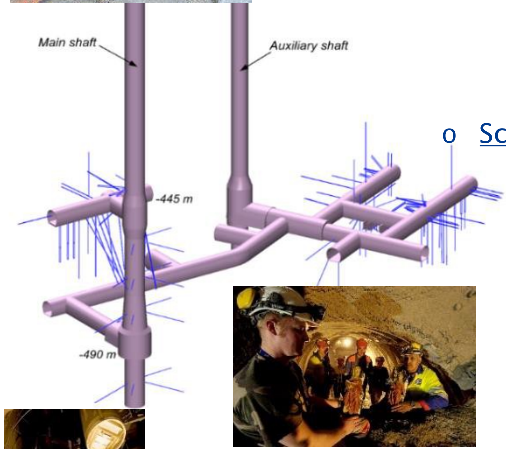
→ Allow the execution of test and samplings during the construction in repository like conditions

→ Provide enough place and access to perform the experimental program (disturbed and undisturbed rock mass), and avoid interferences

→ Test construction techniques

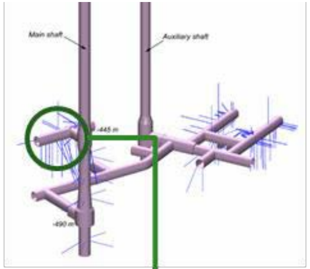
→ Give flexibility for further experimental program up-dates

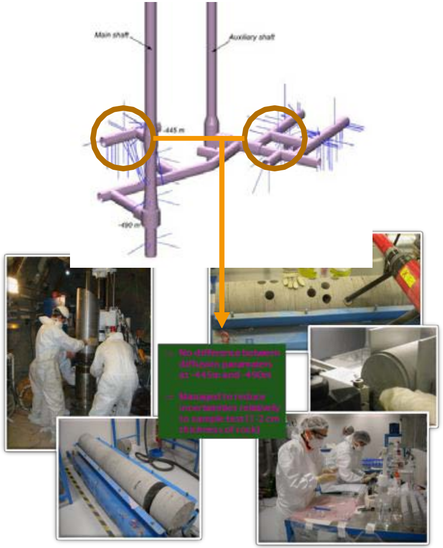
First development phase 2000 - 2005



Program objectives

- o Technology:
  - Shafts
    - By blasting
    - Poured concrete
  - Drifts
    - Pneumatic hammer
    - Sliding support/rock bolt/shotcrete
- o Science:
  - Geological detailed description/mapping
  - Rock confining properties (445 & 490 m)
    - Geological survey
    - Pore water composition
    - Permeability
    - Diffusion/retention
    - Geo-mechanical behavior
  - Effects of perturbations induced by
    - Excavation [excavation damaged zone (EDZ), by mine test]
    - Ventilation (chemical effect)
    - Heating





Second development phase 2006 - 2010

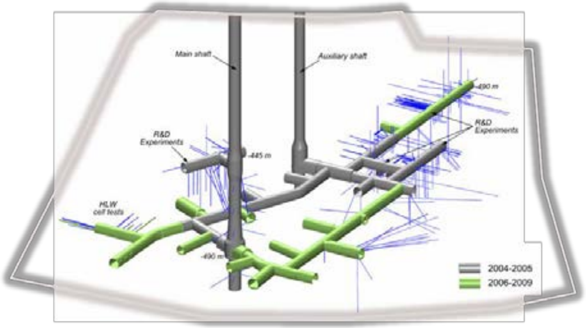
Program objectives

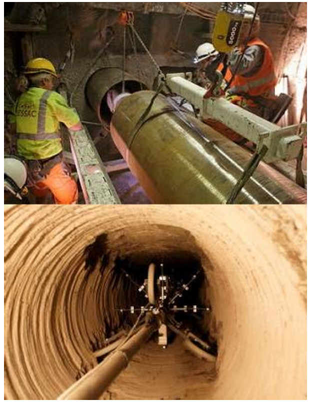
o **Technology:**

- Drifts construction improvement
  - Various shapes (horseshoe => circular)
  - Various soft supports + count-vaulted
- First trial construction of HLW disposal cells
  - Micro-tunnel boring machine (TBM)
  - Liner
  - 2 directions (σH and σh)

o **Science:**

- Continuation of first period experiments and monitoring the effects of excavation and ventilation on containment properties of the clay (5 years…data acquisition)
- Characterization of heat and bacterial disturbances
- Hydro-mechanical coupled processes generated by gas
- Interactions between materials, rock and pore-water (Cement/Iron/Glass)
- Monitoring of the mechanical response of the rock to excavation of HLW cell and rock behaviour after excavation with/without liner)
- Natural hydration of sealing plug at small scale (boreholes)

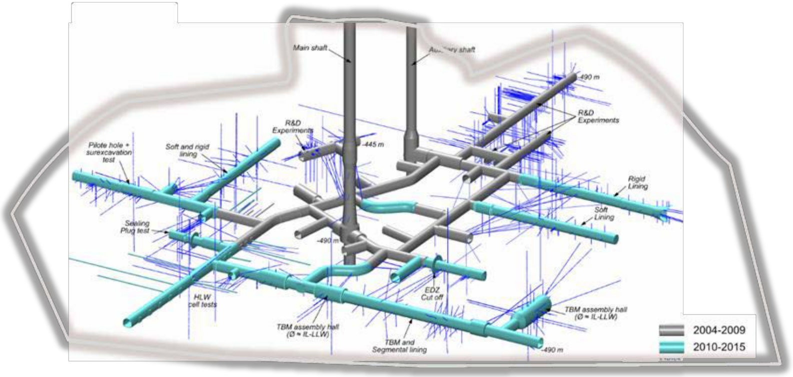




Third development phase 2011 - 2018

Program objectives

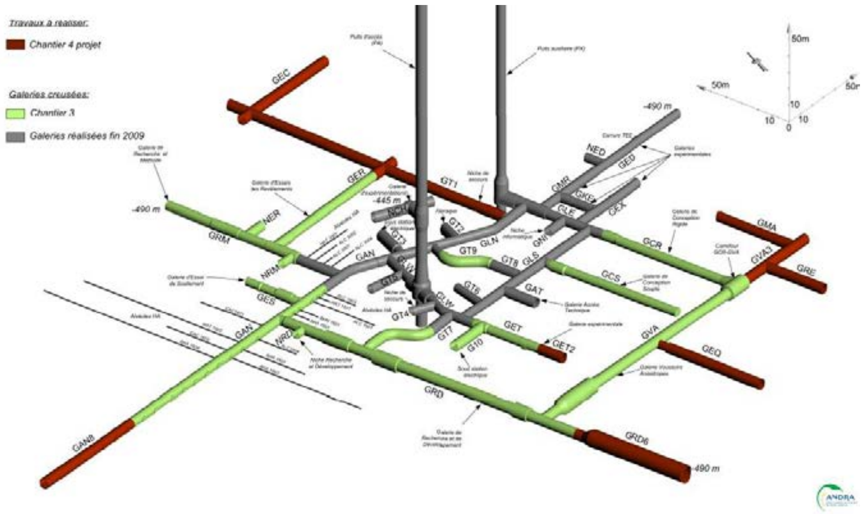
- Technology :
  - Drifts
    - Road-header /TBM + compressible material between the concrete liner intrados and the rock walls
    - 2 excavation phases (pilot hole + sur-excavation)
    - Soft up to rigid support
    - Large diameter drift (9 m ~ IL-LLW disposal cells) with pneumatic hammer + flexible support (compressible segments)
  - HLW disposal cells (at scale 1:1)
    - Longer cells (100m)
    - Heating cell
    - Instrumented liner
    - Annular Injection trails
  - Sealing plug, EDZ cut off (360°)



- Science:
  - Monitoring over 15 years of the rock properties of the Callovo-Oxfordian layer, excavation work and ventilation effect, heating effect
  - Monitoring over 10 years of interactions between rock and materials (Cement/Iron/Glass)
  - Monitoring of HLW cells (thermo-hydro-mechanical behavior of the rock, behavior of the liner, gas characterisation inside and outside the liner, effect of the bentonitic cement grout)

About 20 years of experience… in programming design, construction and operation of an URL

Today: the world biggest URL in operation, in Clay



- o Technology :
  - 2 shafts of 500 m depth
  - 1.7 km of drift excavated
  - 3 excavation methods (traditional and TBM)
  - Soft up to rigid support + compressible materials
  - Diameter : up to 9 m (IL-LLW cell diameter)
  - 13 HLW cells constructed (up to 100 m long)
  - Sealing plug at drift scale
  - 2 safety niches + 2 mobile safety rooms + ventilation systems
  - Devices for electricity power, compressed air, data acquisition system
  - Remote control
  - Operating and maintaining by Andra
- o RD&D
  - Systematic geological survey during shafts and drifts excavation
  - 850 observation boreholes
  - 8 km of Callovo-Oxfordian cores
  - 58,000 solid samples
  - 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

About 20 years of experience… in programming design, construction and operation of an URL

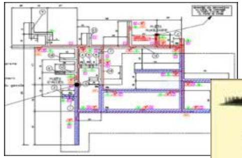
		Experiment	Start
1	REP	Shaft mine by test	2004
2	SUG	Drift geological survey	2004
3	DIR	RN diffusion test n°1	2005
4	GIS	In situ geotechnical measurements	2005
5	KEY	EDZ cut-off experiment (180°) test n°1	2005
6	PAC	Pore water chemistry	2005
7	PEP	Permeability measurements	2005
8	TER	Heater experiment 1	2005
9	TSF	Wireless transmission	2007
10	ACC	Seismic waves experiment	2008
11	OHZ	EDZ survey	2008
12	RES	Regional seismic survey	2008
13	SDZ	EDZ under saturation and dewatering	2008
14	TED	Heater experiment 2	2008
15	ALC	HLW disposal cell construction phase 1	2009
16	BAC	Microbiological disturbances	2009
17	MCO	Metal corrosion	2009
18	MLH	Chemical interaction between rock and concrete	2009
19	MVE	Vitrified waste behaviour	2009
20	PGZ	HM disturbances crea	2009
21	POX	Oxyg	2009
22	ALC	HLW disp	2010
23	ALC		2010
24	CAC		2010
25	ORS		2010
26	TEC		2010
27	TSS		2010
28	CDZ	haviour	2011
29	DRN	usion test n°2	2011
30	MHS	ace hydrogeological survey	2011
31	ALC	HLW isposal cell construction Phase 3.1 (Heater test) (**HAC**)	2012
32	ALC	HLW disposal cell construction ALC3004 (Gas) (**HAG**)	2012
33	ALC	HLW disposal cell construction ALC3002 (Gas) (**HAG**)	2012
34	BPE	Shotcrete layers as support	2012
35	EPT	Pore water chemistry with temperature	2012
36	GGD	Large diameter drift test	2012
37	NSC	Real scale sealing plug	2012
38	TPV	Tunnel boring machine	2012
39	ALC	Pilot holes for HLW cell	2013
40	DPC	Two phases construction test	2013
41	ERA	Filling liner/rock annulus of an HLW cell	2013
42	FSS	Full Scale Sealing	2013
43	BBP	Low pH concrete test	2014
44	BHN	Hydrated bentonite behaviour	2014
45	DCN	Steel rib removal test	2014
46	FRO	Effect of oxidized rock on pore water composition	2014
47	REM	Bentonite block watering	2014
48	CCC	Compressible blocks behaviour at galleries crossing	2015
49	AHA	HLW disposal cell/liner behaviour	2016
50	MCC	Metal corrosion in contact with concrete materials	2016
51	NIH	Slanted bentonite sealing plug	2016
52	MAG	Chemical interaction between rock an filling material	2018

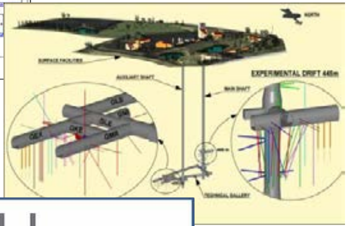
More than 70 experiments since 2000

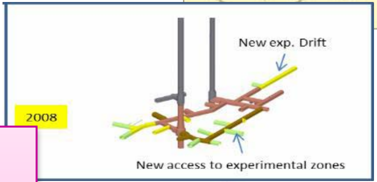
Containment performance of the Clay

Impact of the DGR on the containment performance of the Clay

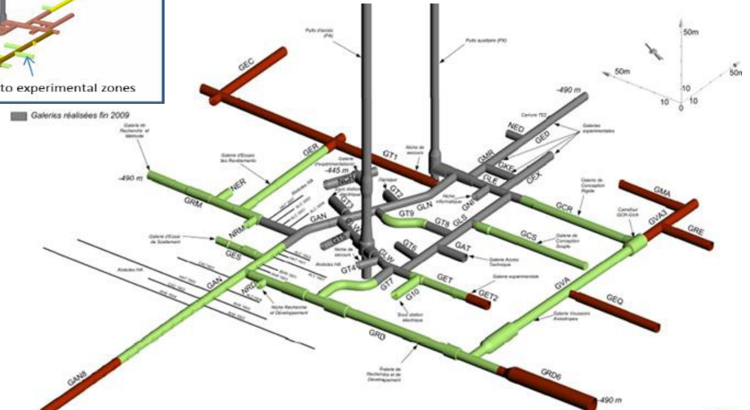
Construction technologies for the DGR







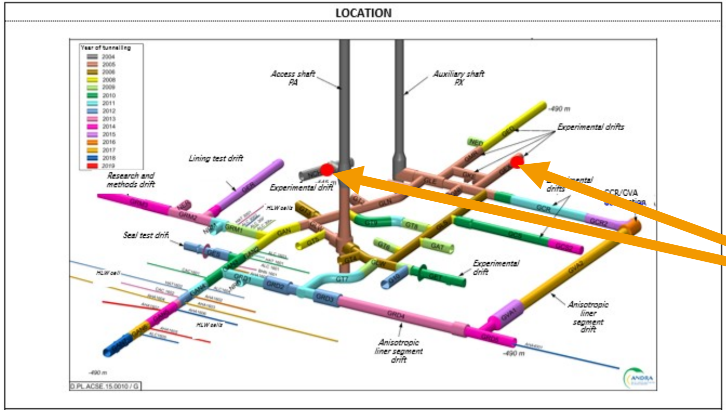
Bure URL developed consistently with Cigéo project Roadmap

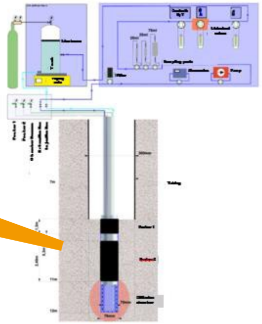


5 Examples of experiments (> 70) performed by Andra in Bure URL

- DIR (tracers diffusion)
- ALC (HLW cells behavior)
- TPV (tunneling/lining behavior)
- NSC (Seal core)
- MVE (Glass alteration)

DIR (tracers diffusion) experiment of Andra in Bure URL





Schematic diagram of the tracer injection tests for DIR experiments in the Underground Laboratory

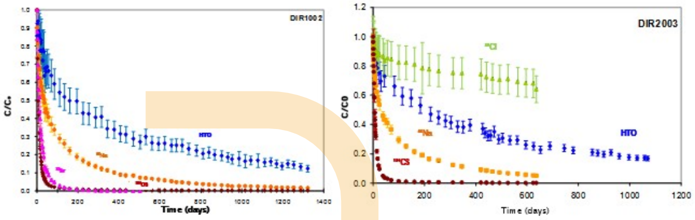


Figure 2 *Variation over time in relative concentration of HTO, ²²Na⁺, ⁸⁵Sr² and ¹³⁴Cs in borehole DIR1002 (left) and relative concentration of ³⁶Cl, HTO, ²²Na⁺ and ¹³⁴Cs⁺ in borehole DIR2003 (right)*

Diffusion parameters obtained by modelling of the DIR tests, and comparison with parameters derived from laboratory tests on rock samples

Tracer	DIR200X C2b2 De (10^{-12} m²/s)	DIR100X C2b1 De (10^{-12} m²/s)	EST208* C2a De (10^{-12} m²/s)	Callovo-Oxfordian Sample De (10^{-12} m²/s)
HTO	$35 \le De_R \le 49$ $14\% \le \omega \le 17\%$ $De_Z = 27$ $\omega = 20\%$	$35 \le De_R \le 60$ $14\% \le \omega \le 17\%$ $27 \le De_Z \le 36$ $13\% \le \omega \le 15\%$	$De_R = 41$ $\omega = 18\%$ $De_Z = 22$ $\omega = 18\%$	$31 \le De_R \le 47$ $15\% \le \omega \le 23\%$ $20 \le De_Z \le 37$ $18\% \le \omega \le 22\%$
Anions	$2.5 \le De_R \le 2.7$ $\omega = 5\%$	$5 \le De_R \le 8$ $4\% \le \omega \le 8.5\%$	$De_R = 7.8$ $\omega = 9\%$	$5{,}2 \le De_R \le 9.0$ $6\% \le \omega \le 8\%$ $5{,}1 \le De_Z \le 8.8$ $8\% \le \omega \le 12\%$
Cation ^{22}Na	$De_R = 100$ $\omega = 18\%$ $K_d = 0.74$ L.Kg^{-1} $De_Z = 66$ $\omega = 18\%$ $K_d = 0.74$ L.Kg^{-1}	$110 \le De_R \le 200$ $\omega = 18\%$ $K_d = 0.65$ L.Kg^{-1} $79 \le De_Z \le 132$ $\omega = 18\%$ $K_d = 0.65$ L.Kg^{-1}	-	$62 \le De_R \le 95$ $0{,}7 \le \omega R \le 0.8$ $K_d = 0.3$L.Kg^{-1} $42 \le De_Z \le 64$ $0{,}8 \le \omega R \le 0.9$ $K_d = 0.3$L.Kg^{-1}
Strong cation ^{134}Cs	$De_R = 190$ $\omega = 18\%$ $K_d = 21$ L.Kg^{-1}	$De_R = 44$ Langmuir isotherm	-	-

*For EST208, the results are derived solely from fluid monitoring, since the borehole was not overcored

De_R: effective radial diffusion coefficient in the mid-height plane perpendicular to the borehole;

De_Z: effective axial diffusion coefficient perpendicular to the mid-height plane;

ω: porosity;

K_d: distribution coefficient.

Experiment Objective

- In-situ measurement of diffusion parameters: diffusion coefficients, anisotropy, accessible porosity and retention parameters

✓ Over distances ranging from a few centimeters to several decimeters
✓ For three types of solutes: inert species (e.g. tritium [HTO]), anions that undergo anionic exclusion and cations that interact with the rock by sorption
✓ For the different rock types found in the Callovo-Oxfordian layer [clay unit (UA) and silty-carbonated unit (USC)]

ALC (HLW disposal cell) experiment of Andra in Bure URL

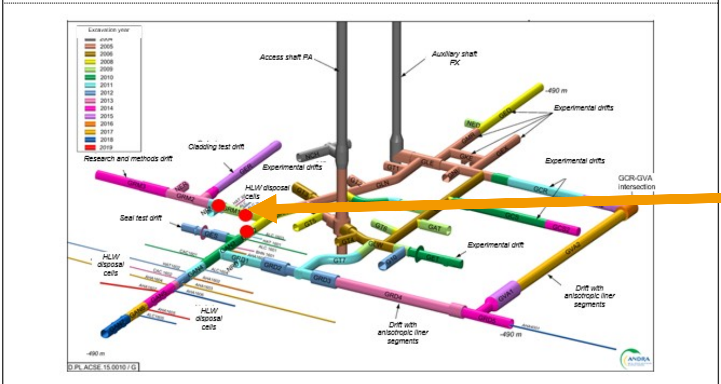
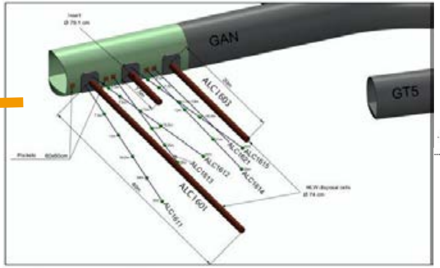
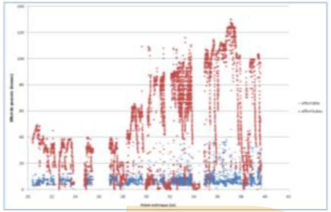


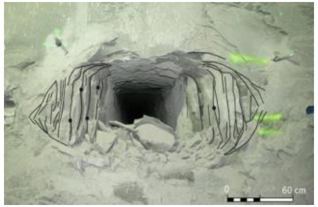
Figure 1 – Location of the 6 ALC experiment cells (drifts GRM1 and GAN2)



Boreholes and cells made in drift GAN2



Thrust force on the drill head and on the sleeve train (ALC1601)



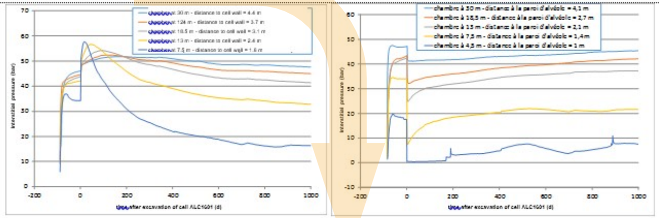


Figure 5 – Time course of pore pressure around cell ALC1601 – Measurements made in the horizontal plane (borehole

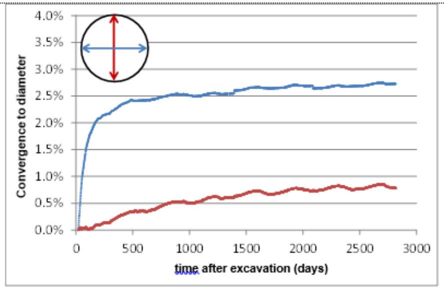
Experiment Objectives

- Test the feasibility of construction of an HLW cell conforming to the 2009 concept (i.e. without filling the annular space)

✓ Test the feasibility of excavating a micro-tunnel and installing a sleeve in various directions with the stress field in situ

- Acquire data on the hydromechanical (HM) behavior of HLW cells

✓ HM impact on the surrounding rock of excavation of a cell
✓ Mechanical behavior of the cell (convergence)
✓ Damage generated around the structure by the excavation



Horizontal and vertical convergences of unsleeved cell ALC1603 at 16 m from the access drift

TPV (tunneling/lining behavior) experiment of Andra in Bure URL

LOCATION

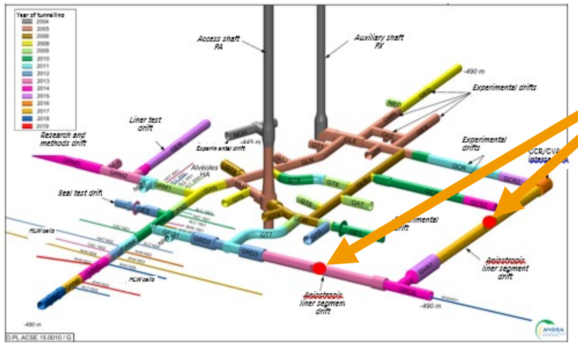
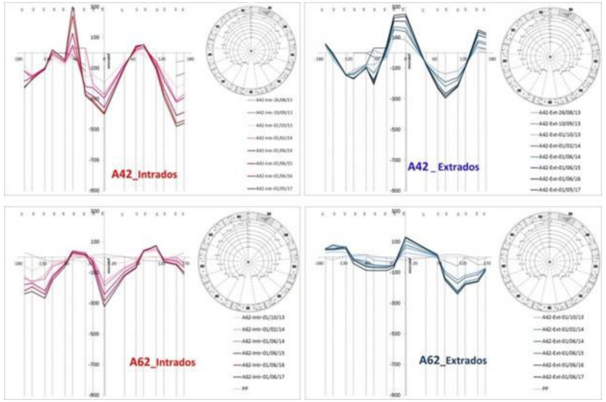


Figure 1 – Location of GRD4 and GVA2

Drift GRD4 is oriented along the principal major stress (σ_H). Drift GVA2 is oriented along the principal minor stress (σ_h).



Experiment Objectives

- Demonstrate the feasibility of using a tunnel bring machine (TBM) for tunneling and installation of liner segments
- Analyze the interaction between the rock and structure in the event of mechanized tunneling using a TBM with installation of prefabricated liner segments
- Study the mechanical behavior of different “packing mortar/prefabricated liner” combinations, taking account of the mechanical characteristics of the materials used
- Compare this tunneling method and the effect of the time delay for liner installation with other tunneling techniques used in the laboratory and different types of roof supports/liners used in other drifts

NSC (Seal core) experiment of Andra in Bure URL

Experiment acronym / Name	NSC	Seal Core (*Noyau de SCellement*)			
Background					
Type	☒ Scientific ☒ Technological	**Component(s)**	Closure structures	**Sub-component(s)**	Clay core Retaining plug Damaged zone
Topic	Technological feasibility and hydromechanical behaviour				
Phase in the Cigeo facility's life	☐ Operation ☒ Post-closure 0 10^1 10^2 10^3 10^4 10^5 years		**Level in the Callovo-Oxfordian**	☒ UA ☐ USC	

LOCATION

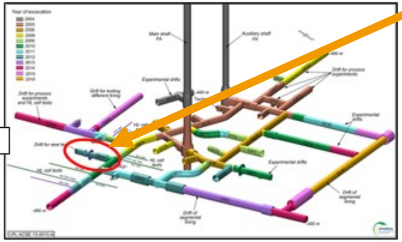
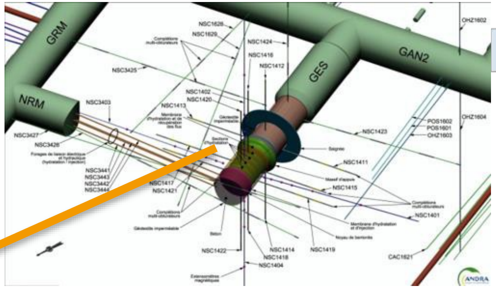
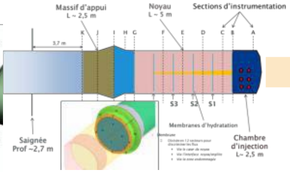
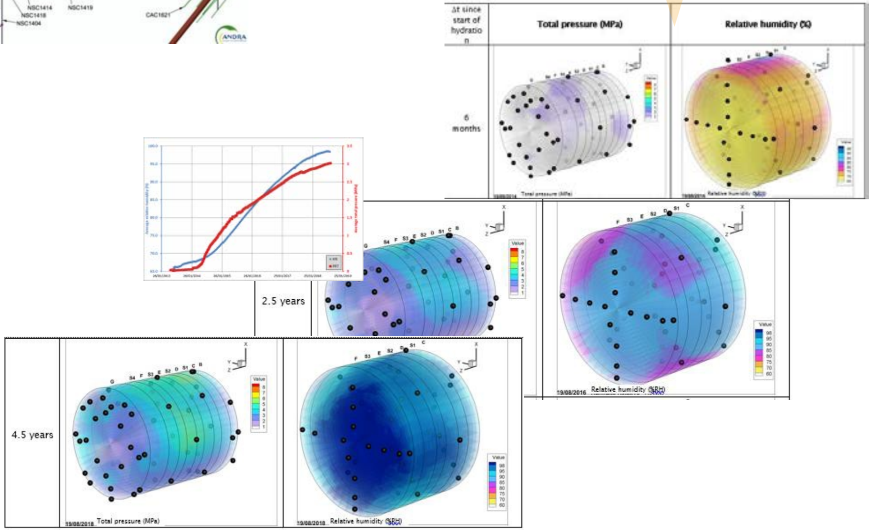


Figure 1 - Location of the NSC experiment







Experiment Objective

- Assess the overall hydraulic performance of a drift seal: this includes not only the seal itself but also the interface zone with the clay rock and the damaged zone in the vicinity of the seal

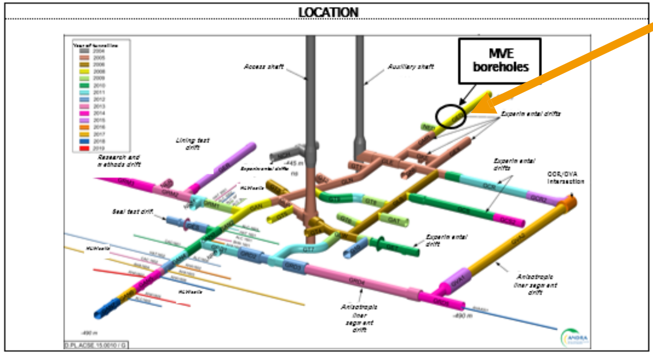
MVE (Glass alteration) Experiment of Andra in Bure URL

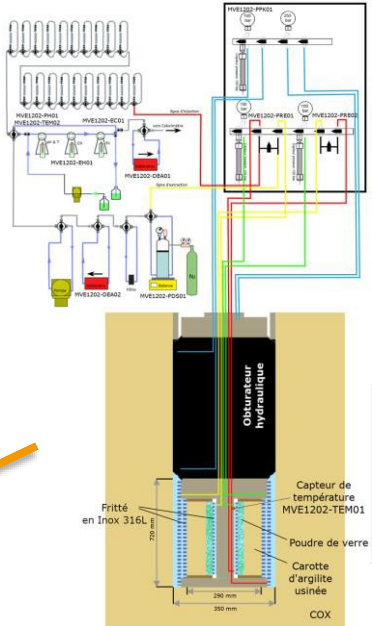
Context

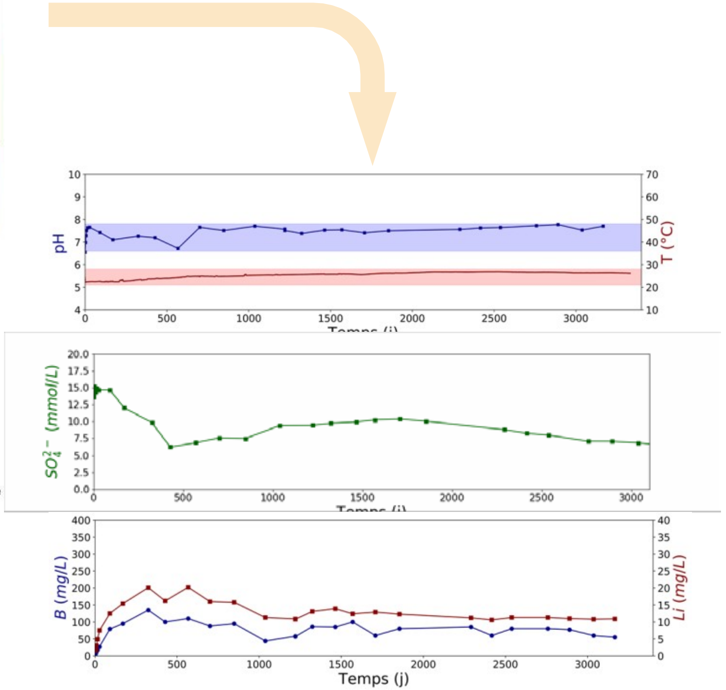
The alteration of glass in disposal conditions involves three alteration regimes: initial rate, rate drop and residual rate.

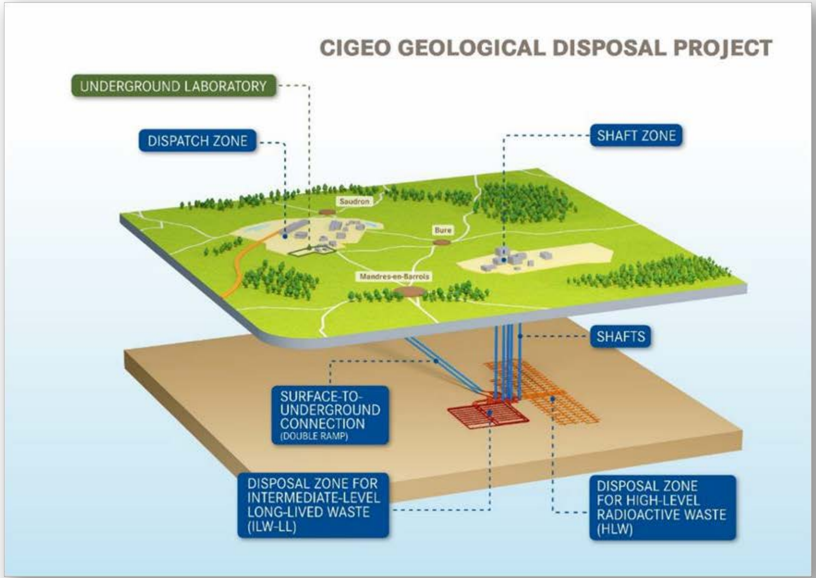
Four series of URL experiments were launched to back up surface laboratory studies in order to address the alteration regimes taking into account specific characteristics of the environment such as site water chemistry

- MVE – "Long Term" focusing on the residual rate
- MVE – "Rate Drop" described in the slide focusing on the glass "rate drop" alteration regime
- MOO – "Dormant Tests" (multi-decade tests) to study long-term glass/iron and glass/clay rock interactions with various types of glass
- MAV – which brings together developments in the HLW cell concept with the introduction of a filling material in the annulus between the exterior of the sleeve and the rock



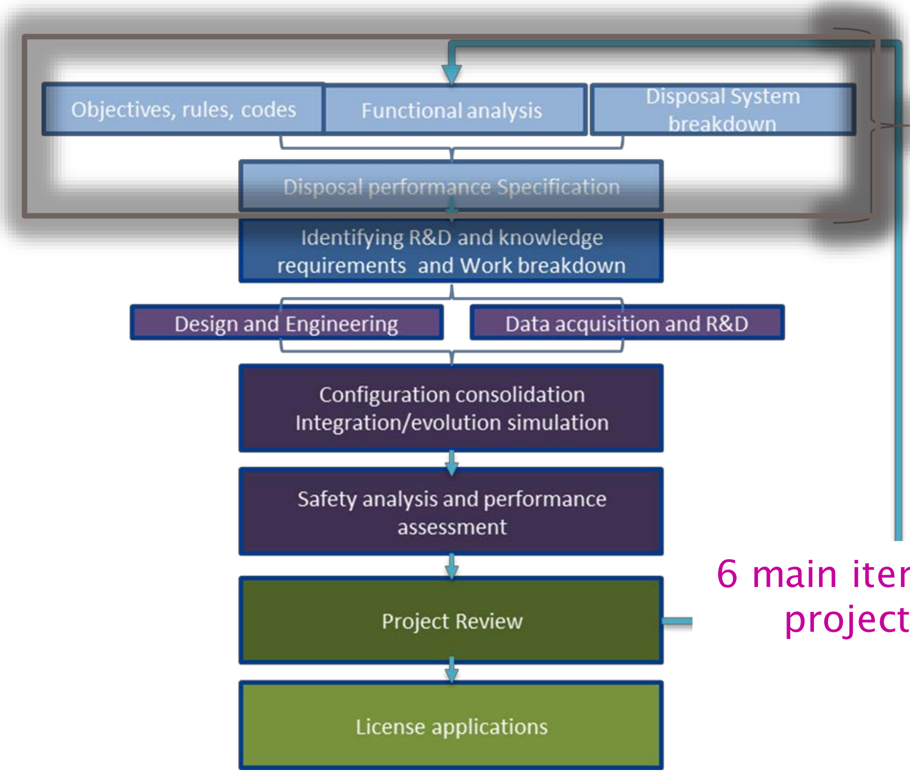


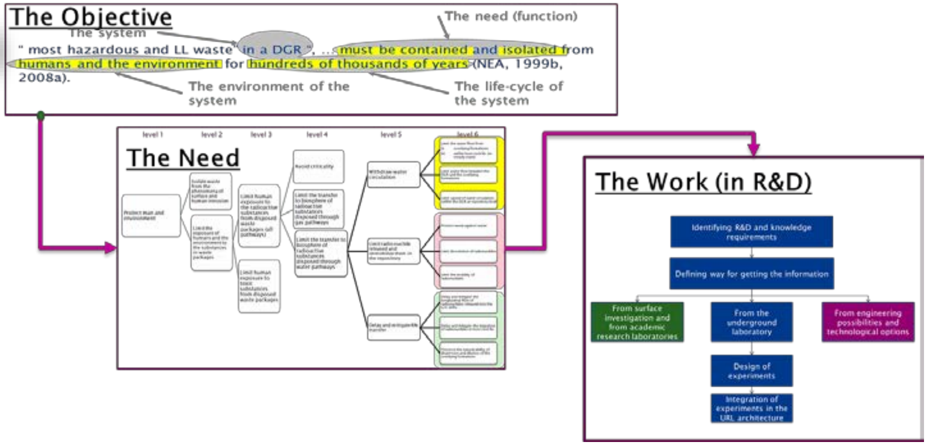



CIGEO GEOLOGICAL DISPOSAL PROJECT
UNDERGROUND LABORATORY
DISPATCH ZONE
SHAFT ZONE
Saudron
Bure
Mandres-en-Barrois
SHAFTS
SURFACE-TO-UNDERGROUND CONNECTION (DOUBLE RAMP)
DISPOSAL ZONE FOR INTERMEDIATE-LEVEL LONG-LIVED WASTE (ILW-LL)
DISPOSAL ZONE FOR HIGH-LEVEL RADIOACTIVE WASTE (HLW)

Conclusion

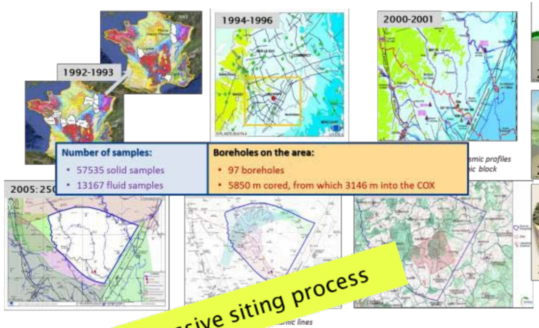
R&D to progressively assess Cigéo performances, in brief



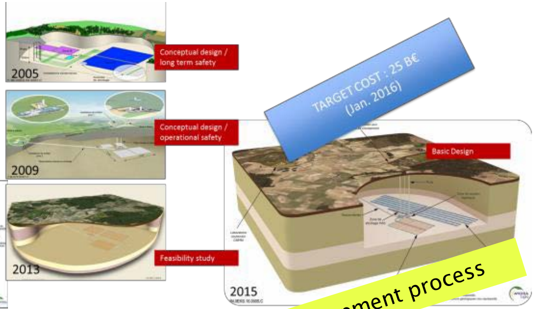


6 main iterations of Cigéo project since 1991

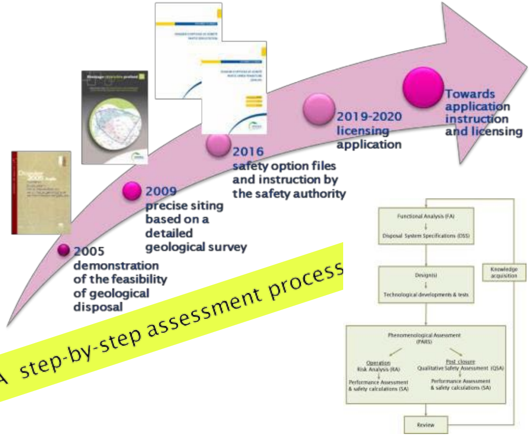
A step by step progress since 1991



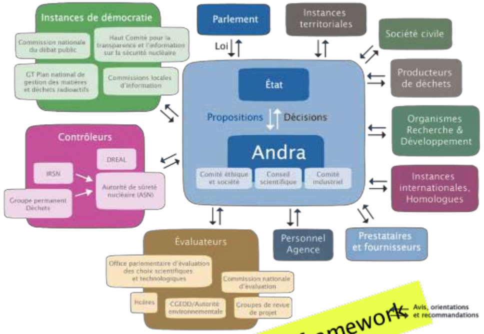
A progressive siting process



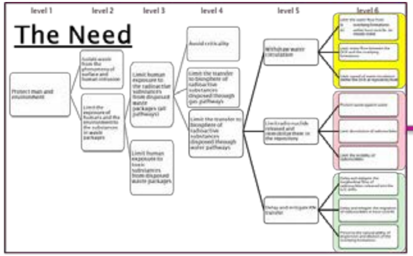
A gradual development process

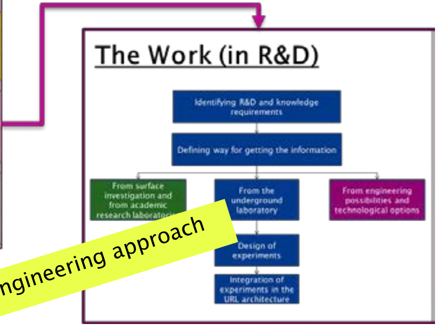


A step-by-step assessment process



A mature governance framework





A robust systems engineering approach

Bure URL plays a major role in the completion of Cigéo license application

- To justify that our design choices fulfill the safety requirements assigned to Deep Geological Repositories
  - ➔ Isolate the waste from man & environment (short and long terms)
  - ➔ Contain radionuclides in the disposal system
- To demonstrate the Technology Readiness of Cigéo
  - ➔ Constructability of drifts and disposal cells (excavation technology, supports and linings…)
  - ➔ Feasibility of seals and plugs (EDZ, bentonite, concrete…)
- To consolidate our phenomenological understanding of the disposal
  - ➔ Assess the perturbation of the hosting geology due to the disposal
  - ➔ Develop and calibrate numerical models to simulate the disposal over thousands of years
- To consolidate the Surveillance and Monitoring plan of Cigéo
  - ➔ Characterize the degradation process of the Engineered components of the repository
  - ➔ Develop, test and qualify probes and monitoring tool
- To gain stakeholders trust
  - ➔ Show the project, share the challenges and…success
  - ➔ Involve a large community (scientists, engineers, sociologists,… to local residents)

ANDRA

THANK YOU FOR YOUR ATTENTION

More info on https://international.andra.fr/