Concrete for Cigéo: How to design the civil engineering for long-term geological disposal of radioactive waste?

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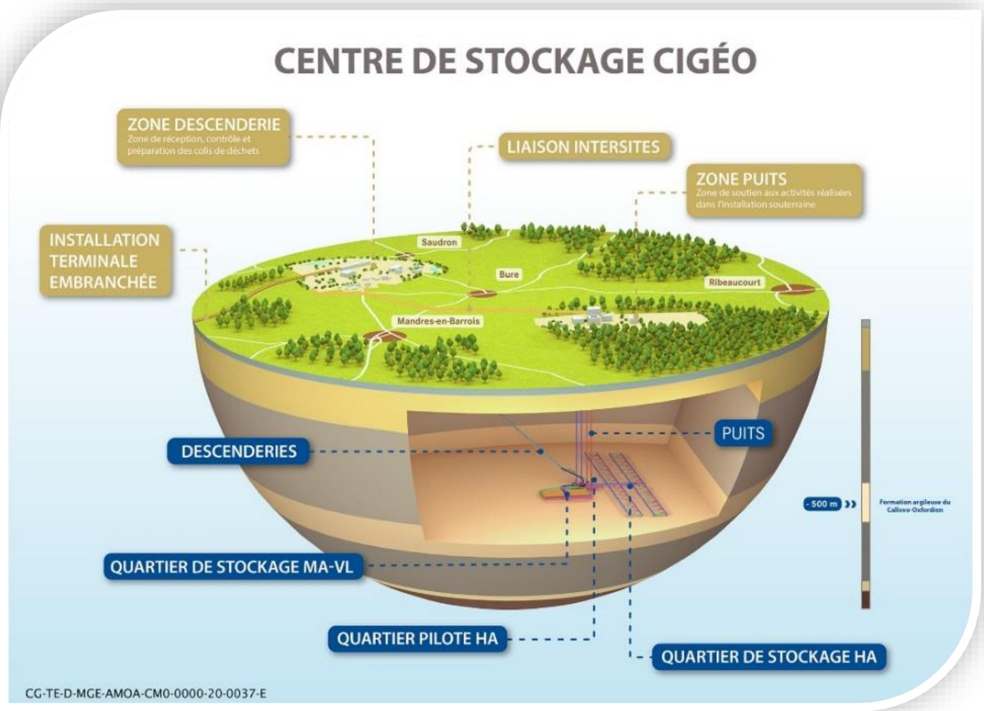
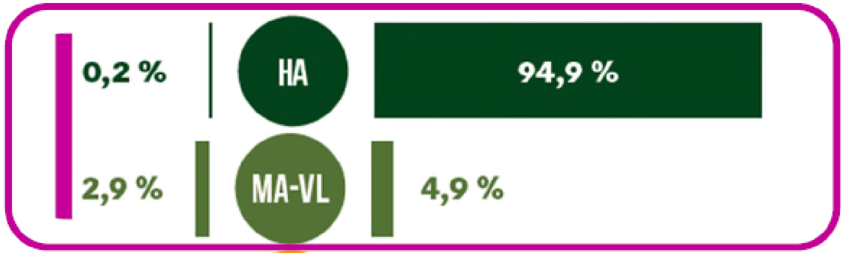
Fundamental Objective of Cigeo Project: Protect Human Being and Environnement from Radioactivity

The purpose of an underground repository is to provide **post closure long term safety functions**:

- Isolate the waste from surface phenomena and human intrusions ;
- Oppose water flow ;
- Limit the release of radionuclides and immobilize them inside the repository ;
- Delay and soften the migration of radionuclides



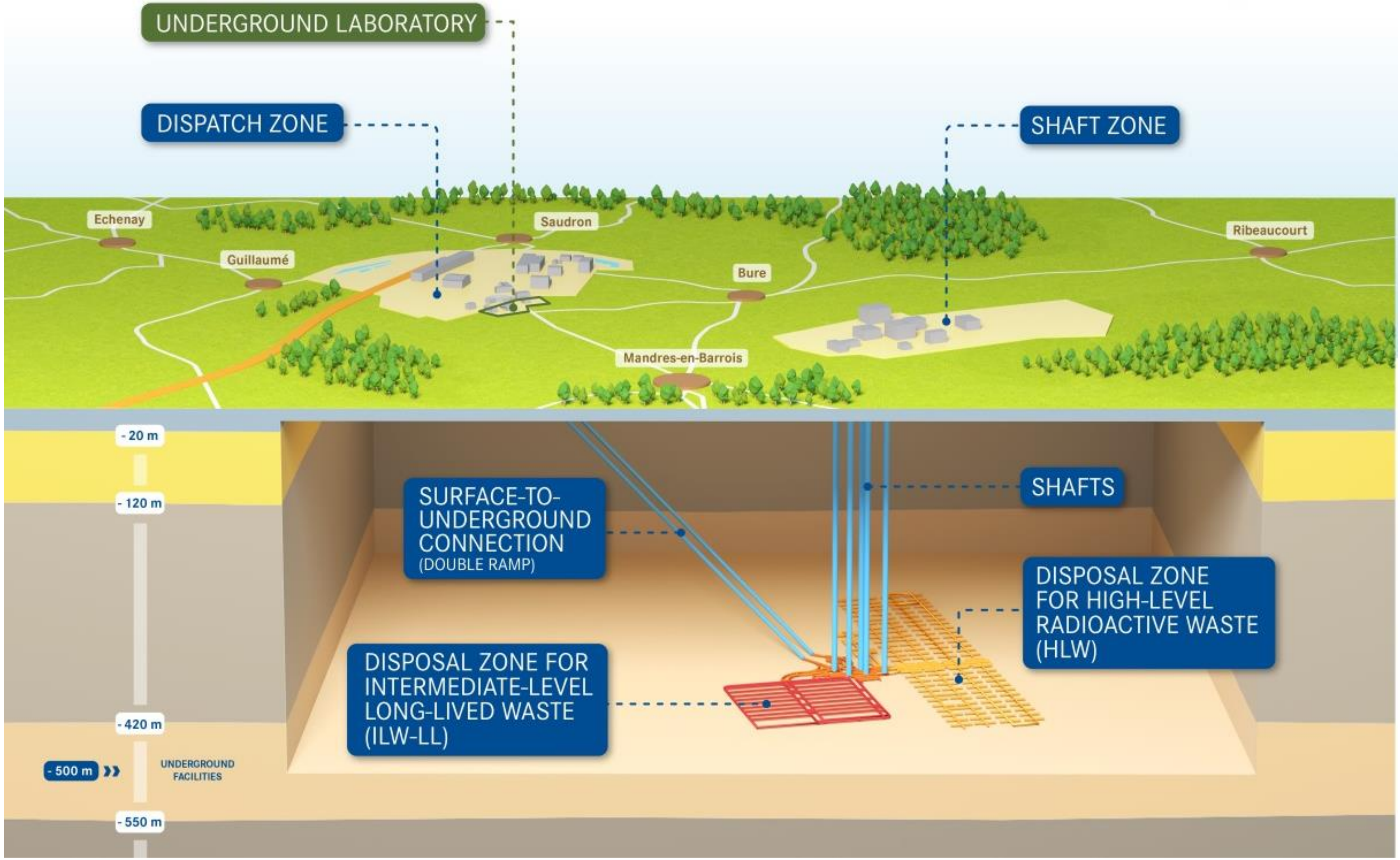
The geological repository meets the need to offer a confinement capacity in correspondence with the lifetime and danger of the HLW an ILW-LL, which represent, in the French case, 2.1% of the global waste volume and 99.8% of their overall radioactivity



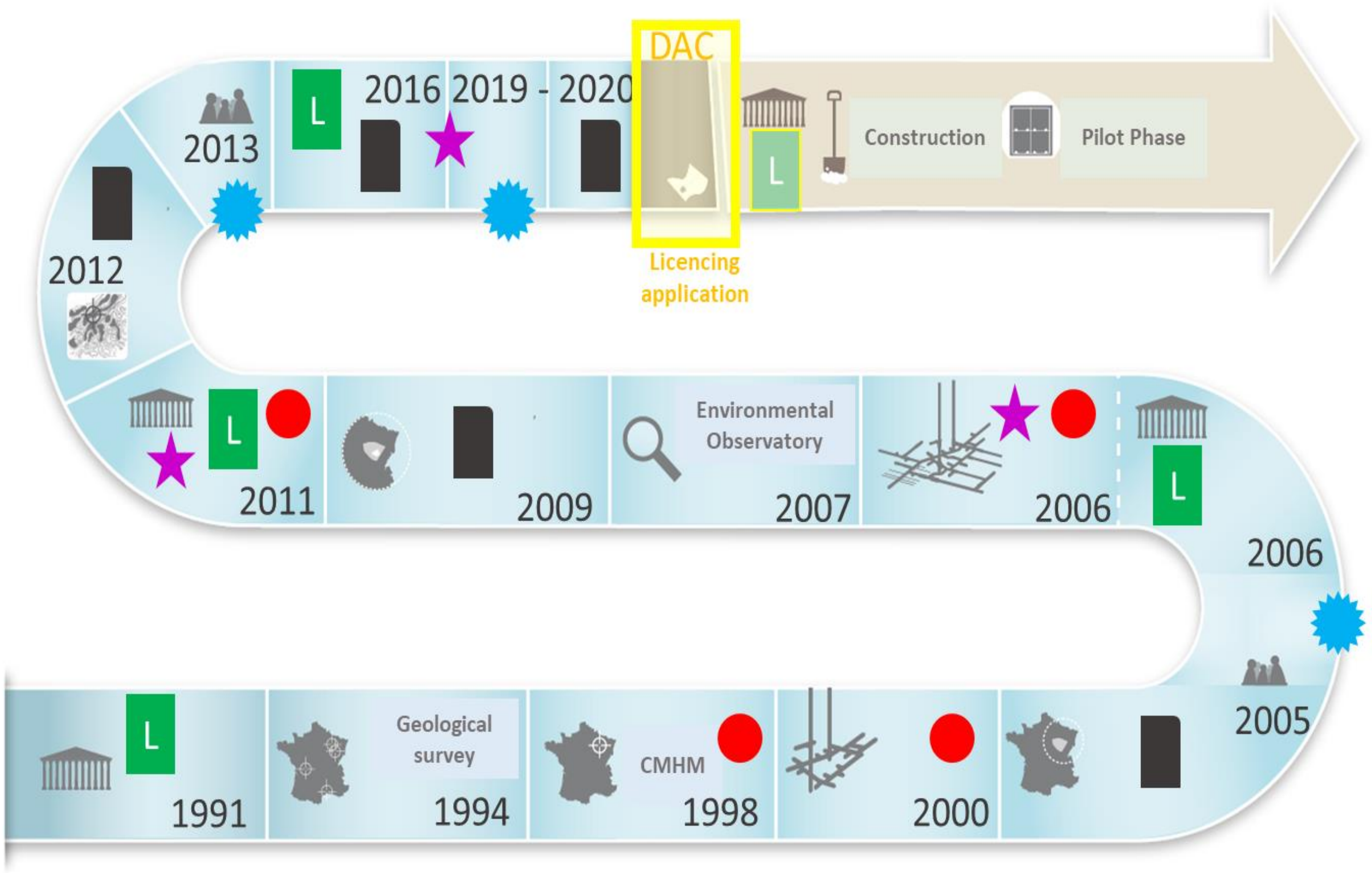
Some Key Figures of Cigeo Underground Disposal Project

https://www.andra.fr/cigeo

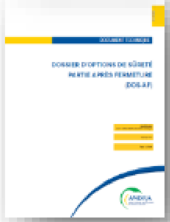
- 500 m deep
- 15 km² footprint
- 270 km of galleries
- 85000 m3 of waste
- 120 y operating
- 26 to 37 G€



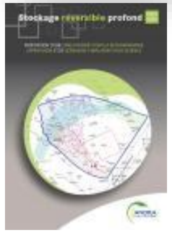
30 years of progressive development and key milestones



2023 | Submission of the Construction License Application (DAC)



2016 | Dossier of Safety Options (DOS)

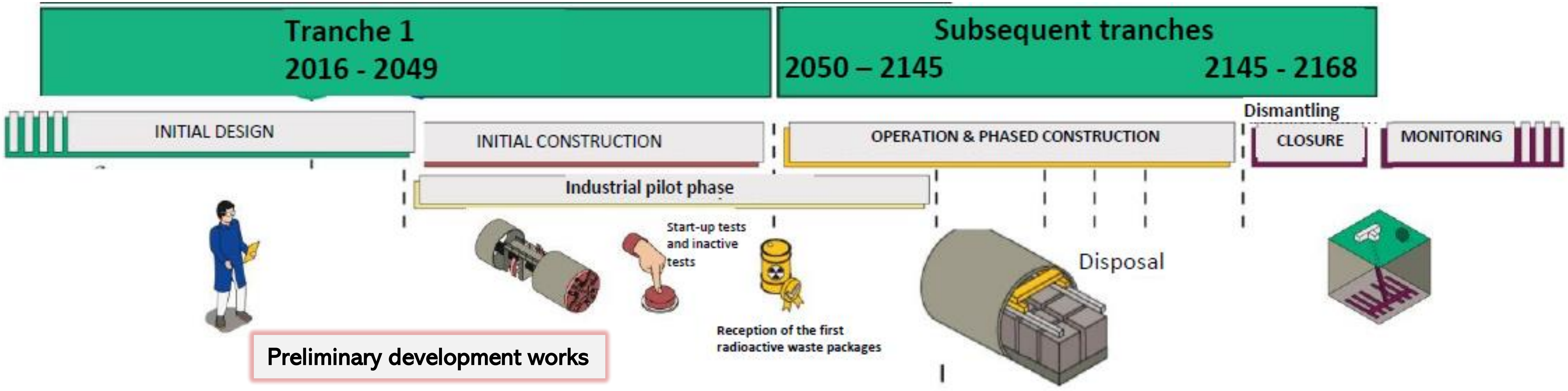


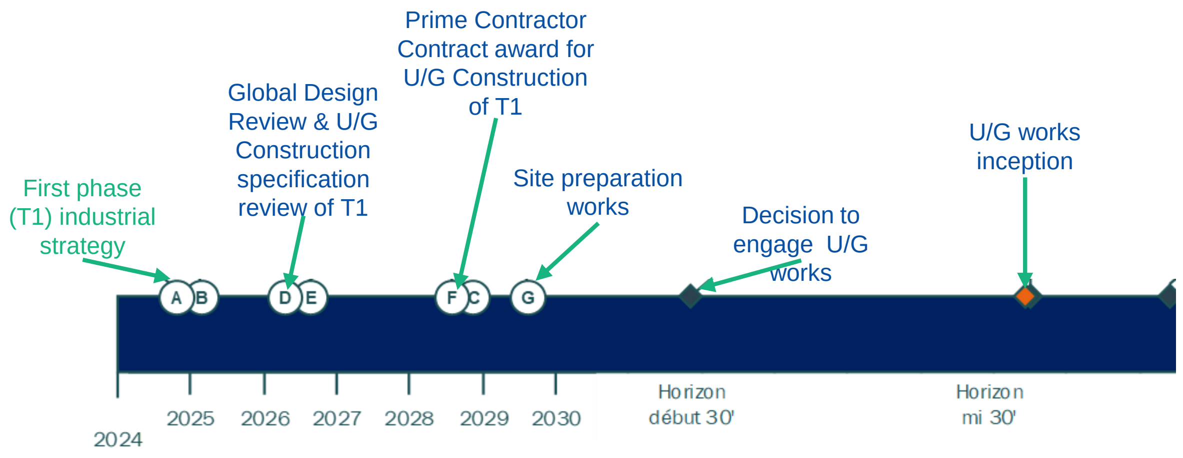
2009 | Preliminary Design and Siting

2005 | Dossier of Scientific Feasibility

https://international.andra.fr/submission-application-authorization-create-cigeo

Construction and exploitation of Cigéo: next steps





The Scope of Cigeo Phase 1

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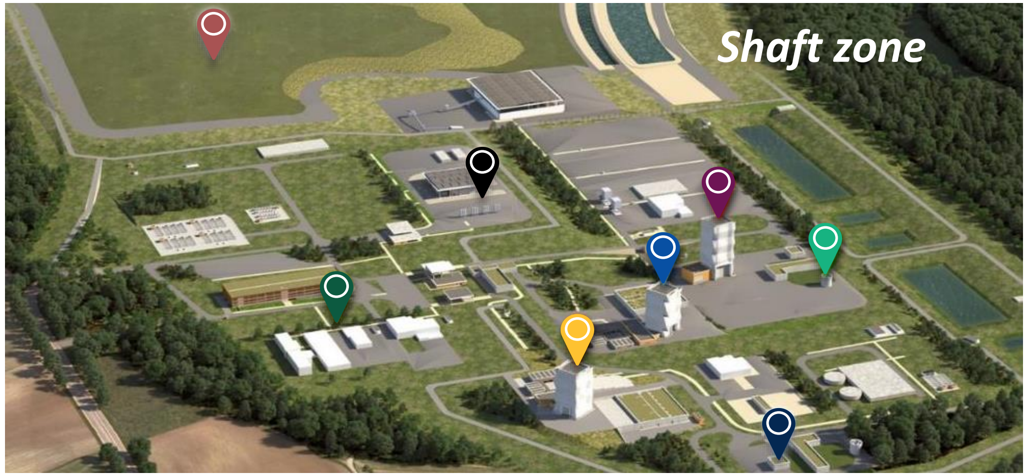
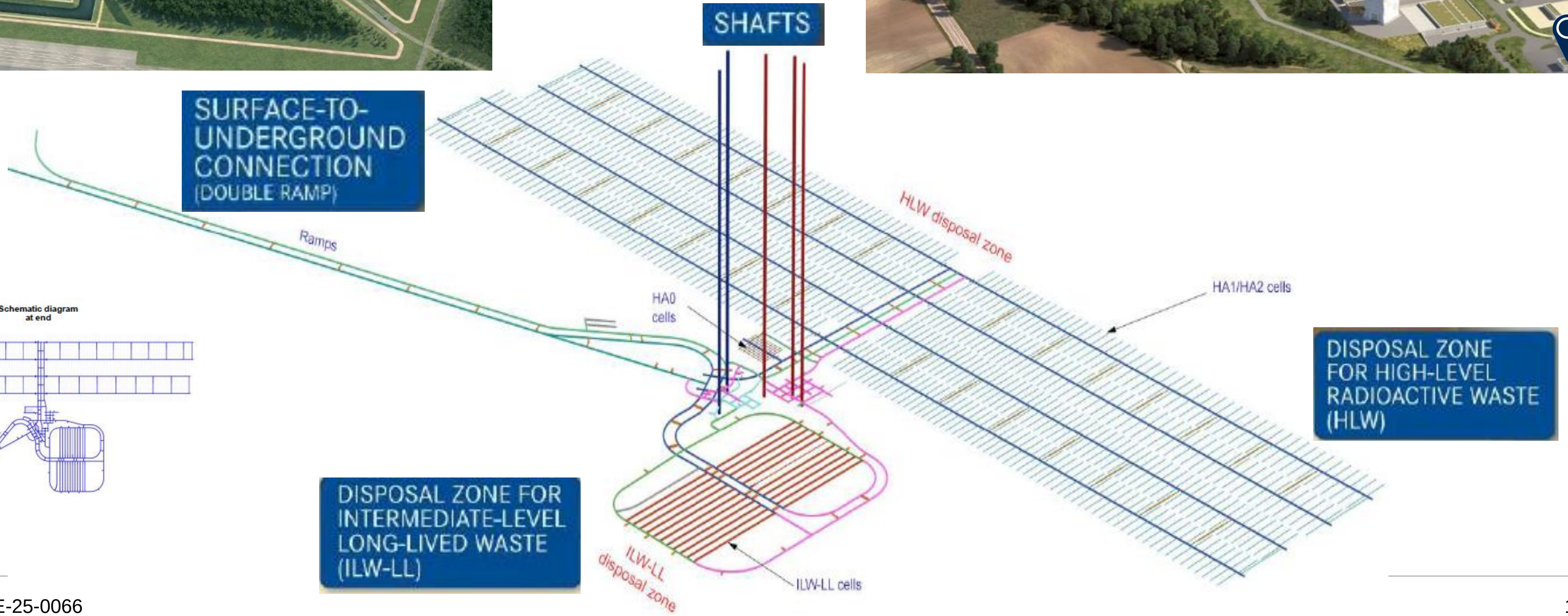
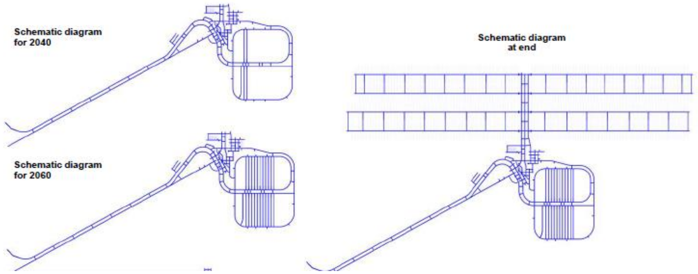
- Service ramp
- Package inspection, preparation, and conditioning buildings
- Package ramp head
- Nuclear rail terminal

- Construction shaft Equipment / Materials
- Operations shaft Personnel + Fresh air ventilation
- Construction shaft Personnel + Fresh air ventilation
- Operations shaft Stale air ventilation
- Construction shaft Stale air ventilation







The Scope of Cigeo Phase 1

Service ramp

Package inspection, preparation, and conditioning buildings

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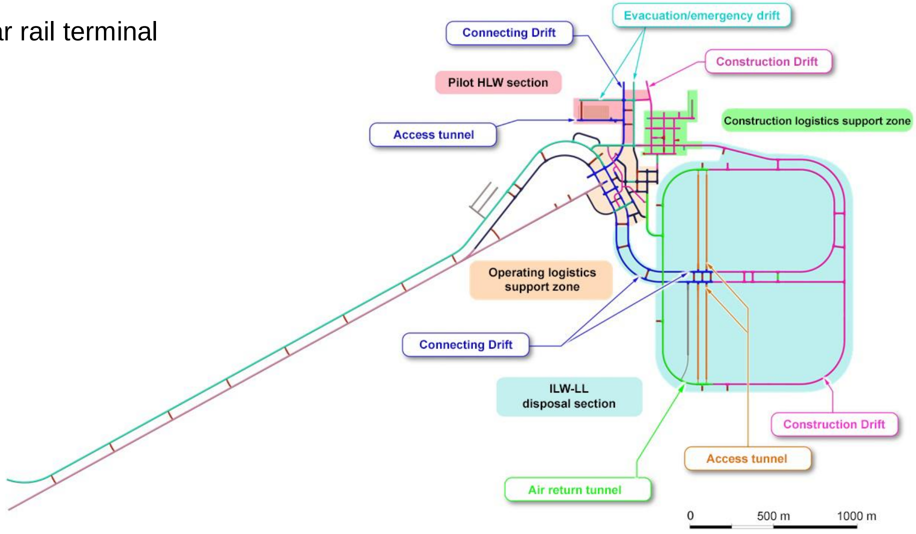
Nuclear rail terminal



First construction

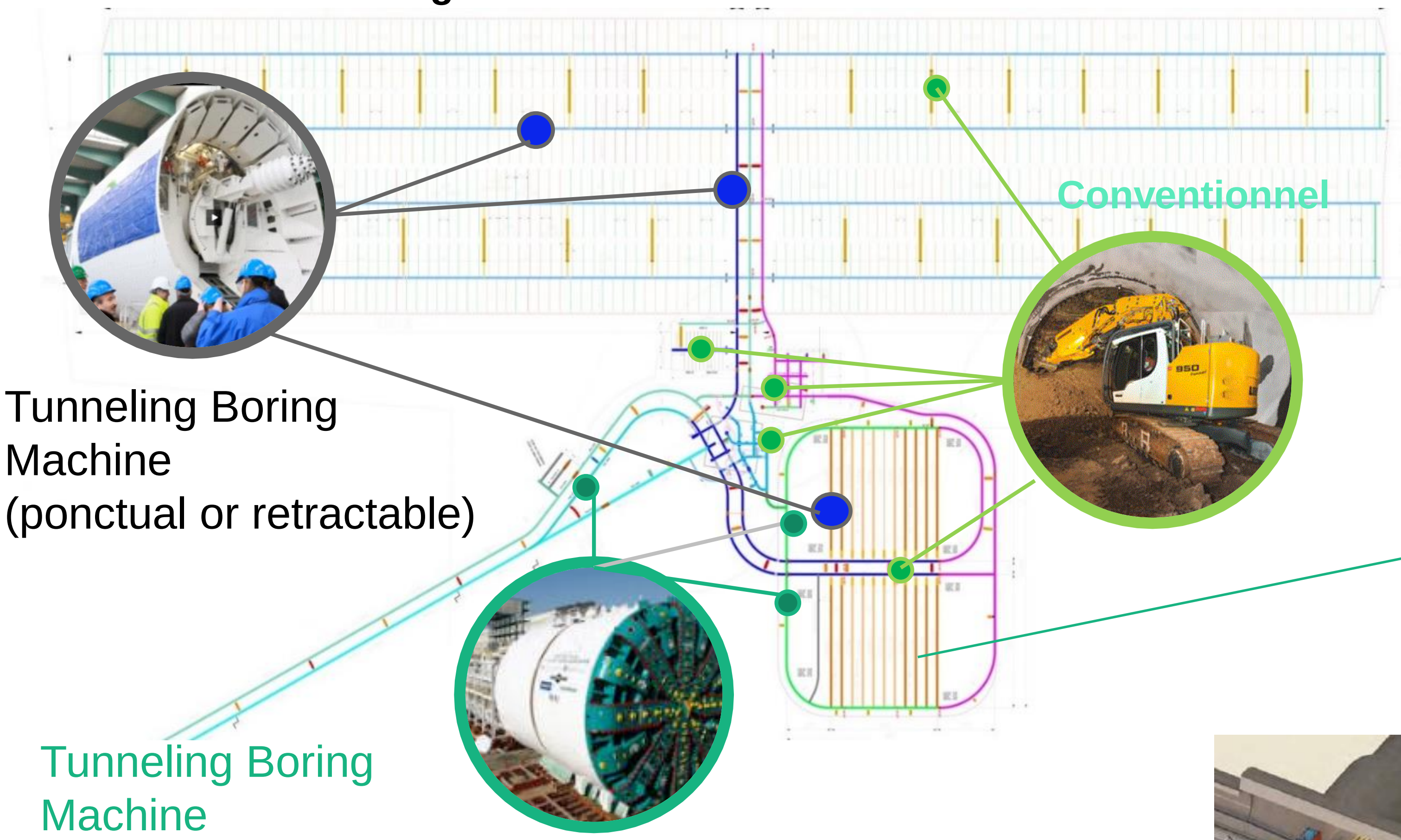
- Shafts (x5)
- Ramps (x2)
- Underground connecting galleries and logistics zones

allowing the exploitation of the first ILW-LL cells (x4) and HLW cells (x18)

Investment # **7 Md€**

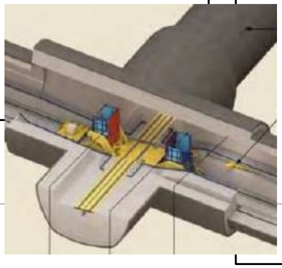
Underground structures of Cigeo
Construction methods and dimensioning

Intersections and linings

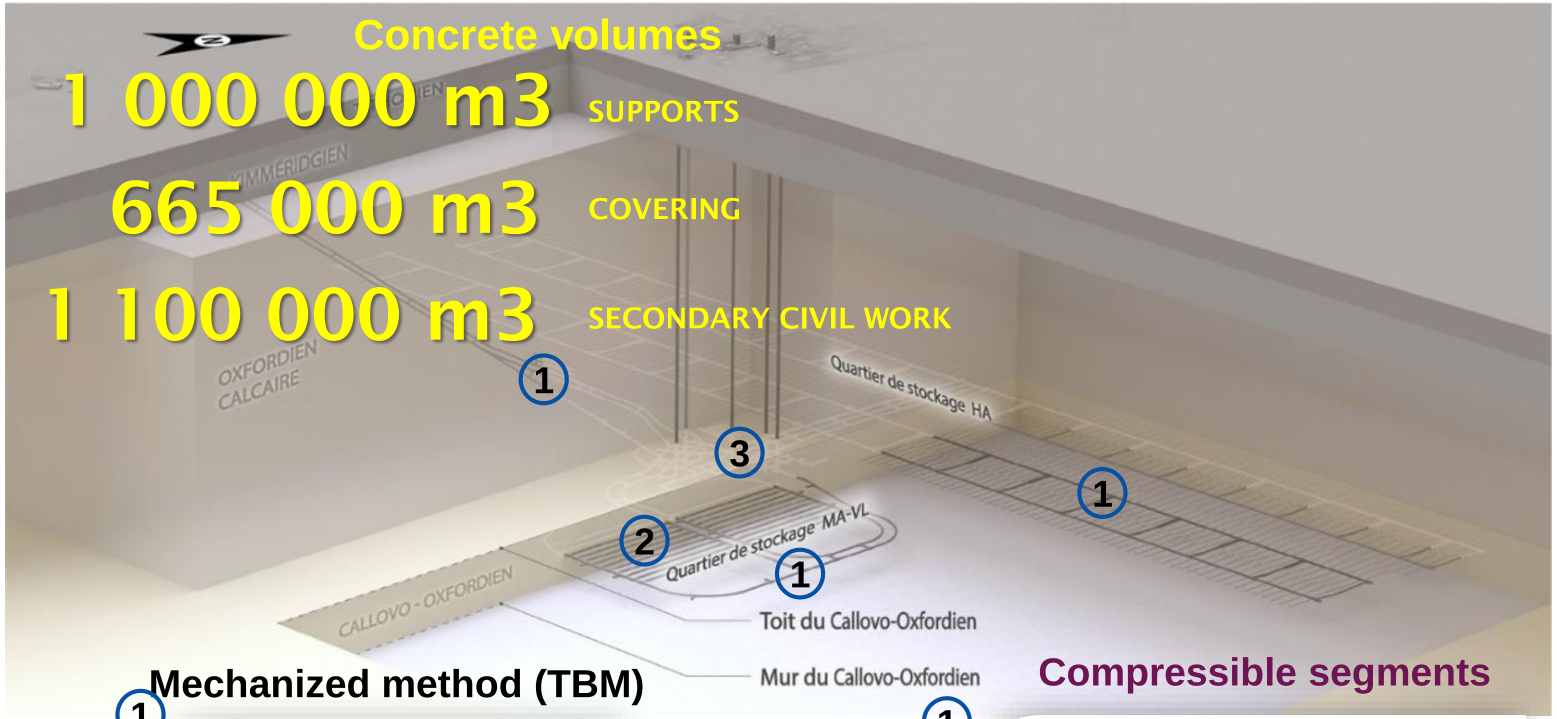


Robust dimensioning by use of a compressible material absorbing the convergence of the rock

- Use of a compressible material showing a large plastic deformation at low threshold level
- Segments: reinforced concrete C60/75 50cm + 20 cm of compressible material
- Intersection : reinforced concrete C60/75 de 130 cm + 20 cm of compressible material

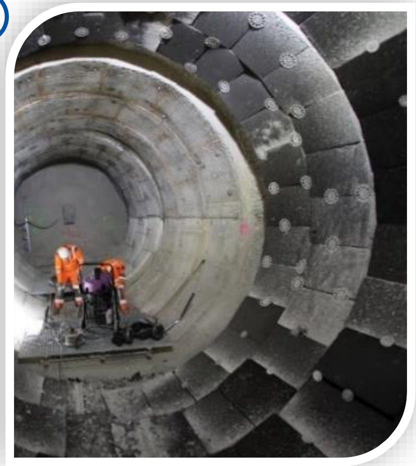


A secular lifetime underground installation thanks to specially developed and tested concrete components



Integration of a compressible layer in traditional digging method

3



Concrete ILW-LL containers

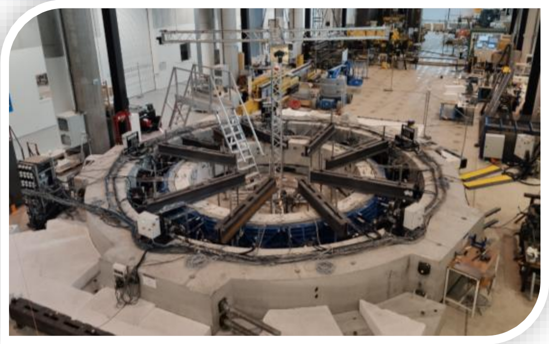
2

Mechanized method (TBM)

1

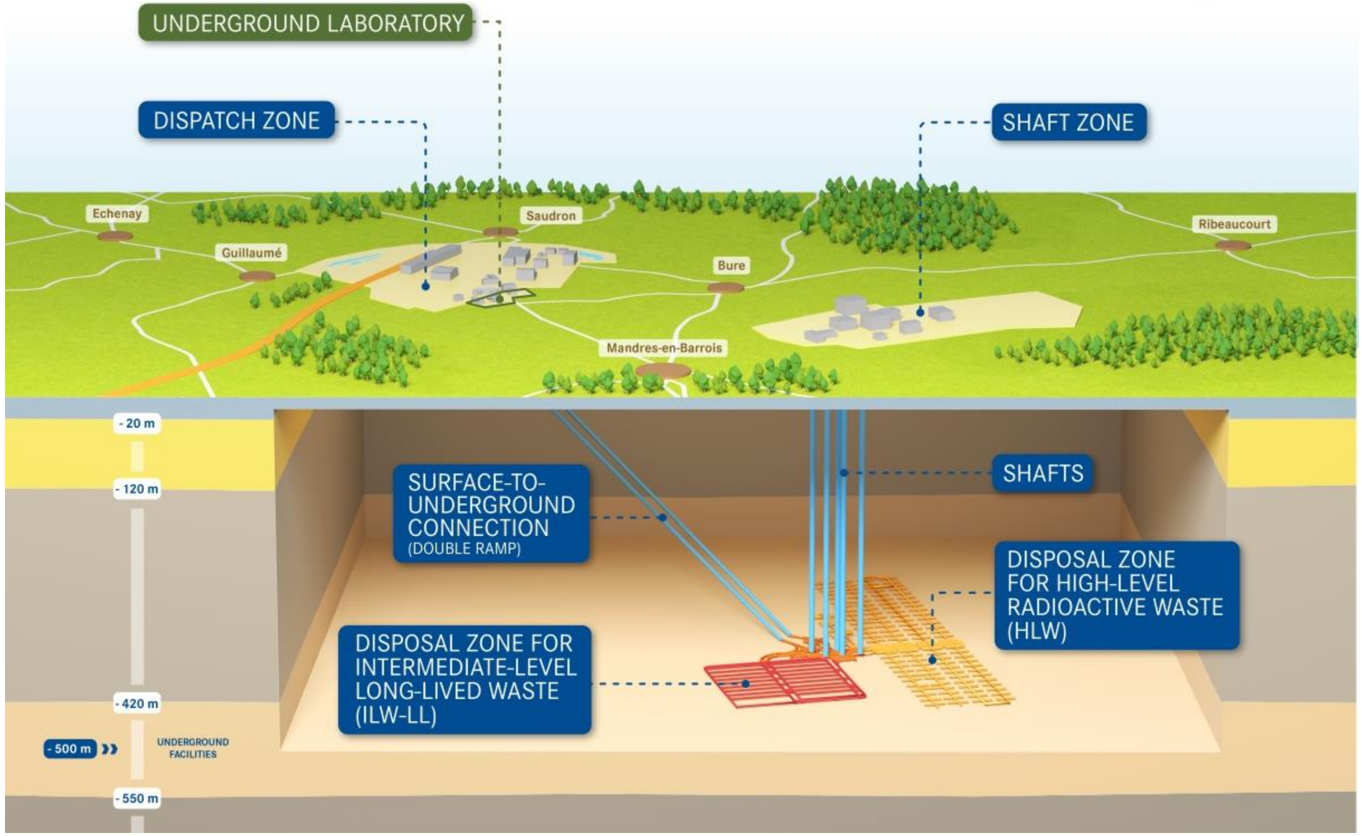
Compressible segments

1



Specific features of Cigéo and related R&D challenges

- Mega project
- Underground facility
- Nuclear Facility
- Very long operating life
- Reversibility
    - Retrievability
    - Flexibility (flexible operation)
- Long-term safety



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Conception principles

Objective: operational and post-closure safety

- Constructability, safety and industrial performances over the operating period
- « Reversibility: retrievability / flexibility » requirement
- Preservation of the host-rock favorable properties

Host Rock: mechanical behavior

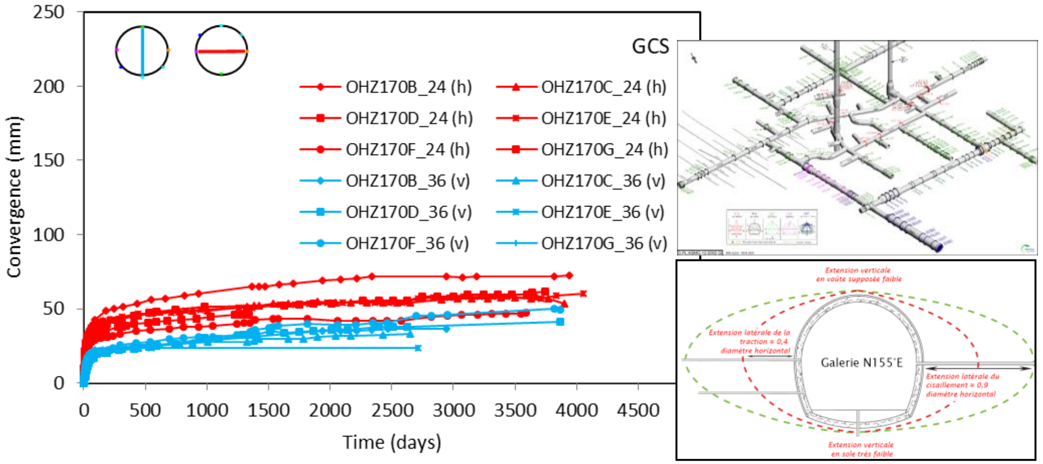
- Continuous differed behavior
- Anisotropic behavior
- Induced damage zone vs. excavation directions

Concept: design & construction method

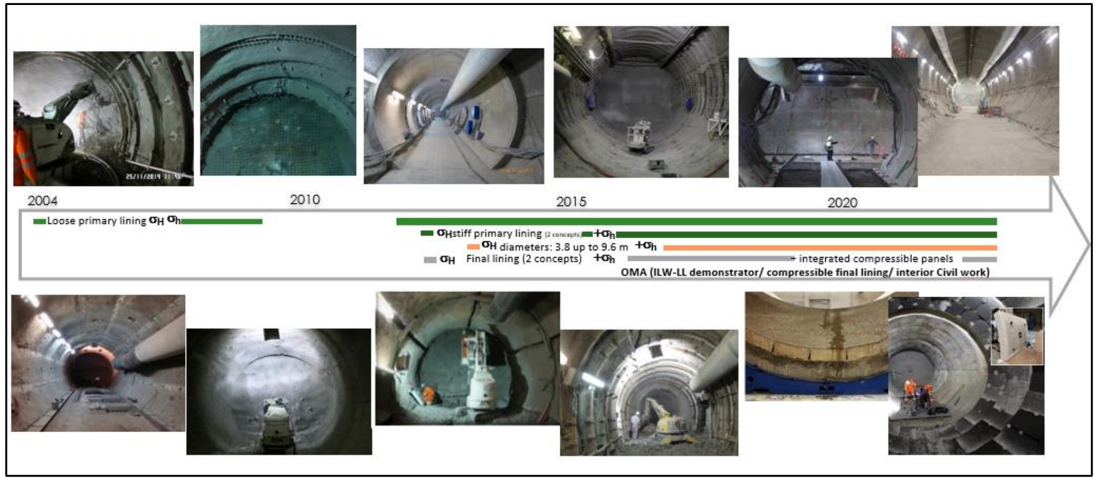
- **Design**
  - Rock/structure interaction & evolution over time
  - Accidental/incidental scenarios
- **Method**
  - Hydro-mechanical impact (EDZ), robustness, technical-economic impact, adequacy of materials

Structure: linings & intersections

- Integration of compressible elements
- Optimization of dimensioning (reduce margins)
- Towards a performance-based approach for concrete structures
- Additional levers to improve the durability
- Improvement of the method (quality of execution)
- Inspection/rejuvenation feedback & strategy



URL Feedback: Drift parallel to the horizontal major stress



URL: Conventional exavation method examples

Hydromechanical behavior of host-rock/structures over a century

A joint program combining engineering design methods and phenomenological simulations

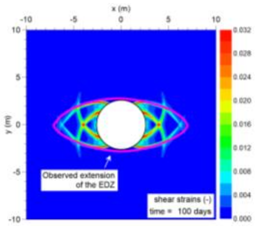
Host Rock

Feedback from URL: improve the different design approaches

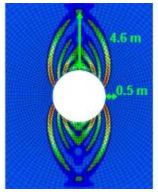
- Convergences, induced fractured zone, lining loadings…

Three types of approaches

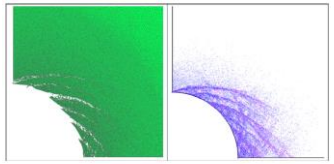
- Empirical approach: *Sulem/Panet semi-empirical method*
- « Simplified » approach for engineering design: *integration of two materials with an explicit modeling of the fractured zone*
- Phenomenological approach: *anisotropic elastoviscoplastic model, damage model (phase-field), micro-macro approach…*



(UPC Model)

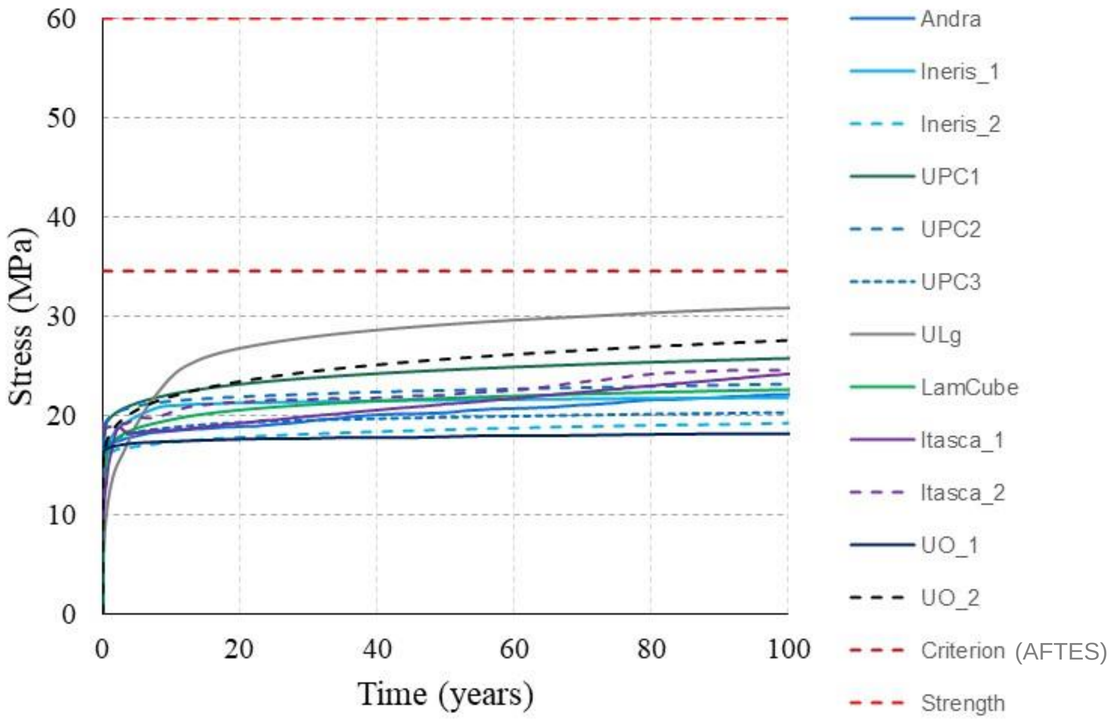


(Ulg Model)



(LamCube discrete model)

Structure: linings & intersections



Example: prefabricated lining orthoradial stress comparative studies

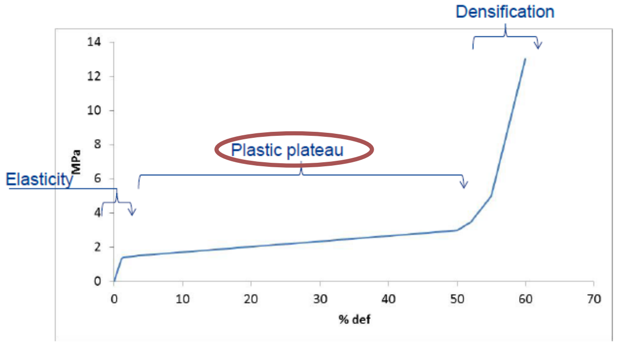
Compressible linings: an asset for long term durability

A robust multi-scale technical and economic demonstration program

Takes into account:

- Product behavior
- Integration process
- Mechanical behavior of the support

Both for conventional and mechanized excavation methods



- Elastic behavior : guarantees the integrity of the layer fabrication till erection
- Compressible behavior : caps the transmitted stress while maintaining a minimum confinement of the host rock

Mechanized methods (TBM): integration on the precast lining

VMC

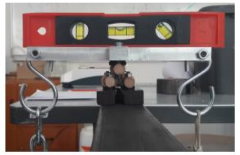
Foam concrete

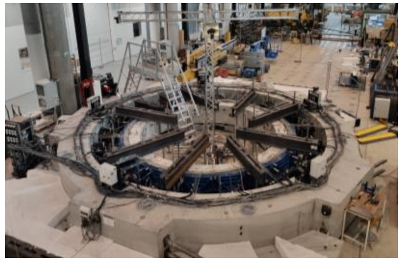
Hollow clay block

Conventional tunnel

Example: panel between primary and final lining

Multi-scale approach: example of VMC segments





A design process integrating incidental/accidental case studies

A joint program combining lining stability and impact on the host rock

Fire design for linings

Methodology

- Definition of the fire scenarios (construction, operation…)
- Establishment of the fire curves (standard, Andra's reference, or calculated)
- Engineering design of the lining
  - Conservative approach (Eurocode)
- Phenomenological approach
  - Effects on the thickness of the undisturbed host rock

R&D program

- Hydromechanical evaluation of the influence of temperature
  - on Callovo-Oxfordian samples
  - on compressible materials
- Improving the assessment of fire effects on concrete lining (spalling, properties modification…)

Full-scale test on disposal package

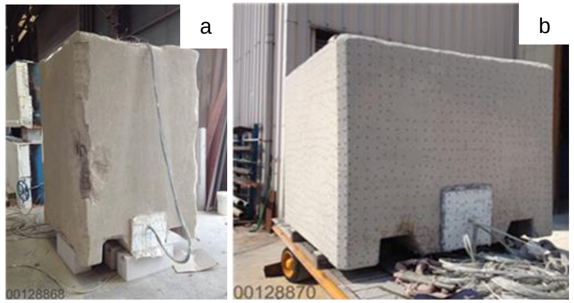
Experimental conditions: ISO 834-1/A1

- Temperature rise between 800 °C and 1 000 °C over 10 min
- Temperature held around 1 000 °C for 50 min

Full-scale demonstrator during fire test

Main results

- Disposal package can be handled after fire
- Less damage with polypropylene fibers
- Protection of primary packages confirmed, with respect of thermal criteria (100 °C for bituminous waste)



Containers made of non-fiber (a) and PP fiber (b) concrete after fire resistance tests

Example of method improvement

Concrete placement through a 490-meter borehole

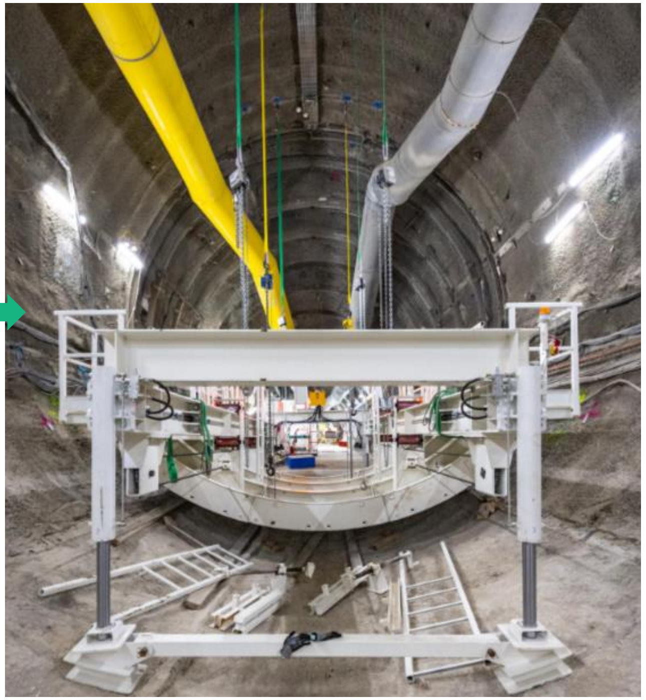
Scaled-down tests: pipe of 25 m

Dry cementitious materials

Concrete

URL -490 m test

10 m drift lining casting



Durability of concrete over a century

Over 30 years of R&D on concrete alteration in disposal conditions

- Carbonation, sulfate attacks, leaching in different environments, impact of radiation, reinforcement corrosion, coupling between these processes and with thermal and mechanical behavior…
- This knowledge is used to define requirements and acceptance criteria for concrete used for disposal packages and structural components

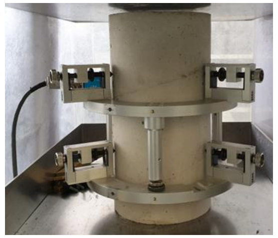
Ongoing work to consolidate the assessment of the durability of concrete over the operating period to quantify margins to

- Apply technical and economic optimizations
- Extend the durability of performance for more than 100 years

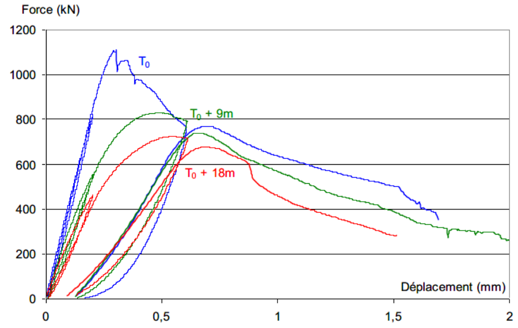
Application of performance-based approach and long-term behavior studies to

- Qualify the agreement of this approach with Andra's specifications
- Define criteria to extend the durability of the structural components according to operating period duration

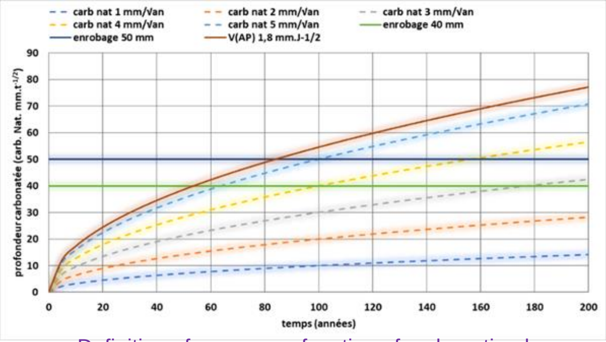
Carbonation test



Compression test



Compression tests after 9 and 18 months of leaching

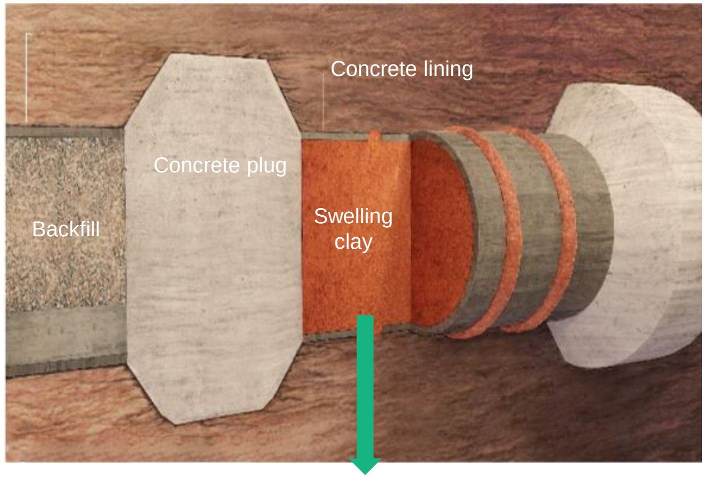


Definition of cover as a function of carbonation by performance-based approach

Geochemical evolution and migration of species (RN / toxic chemicals)

Geochemical evolution of cementitious materials

- Concrete/host rock interface: thickness of the undisturbed host-rock
- Concrete/seals (bentonite/sand) interface: influence on the swelling pressure
  - ➢ must be taken into account in the design
- Concrete/waste interface: influence on vitrified glass alteration, activated metallic waste corrosion…



Radionuclides and toxic chemicals migration

Play a significant role in safety assessments (notably for surface repositories) :
low permeability, high retention properties…

- Potential perturbations generated by waste altering the behavior of RN/TC
  - Influence of organic compounds generated by the waste degradation
  - Influence of soluble salts (nitrates, sulfates ammonium…)
- Evolution of the environmental regulatory framework
  - The behavior of « new TC » (PFAS, phthalates) needs to be studied to support environmental impact assessments

Reduction of steel quantity: use on non-metallic reinforcement

Concrete structure will be designed with a significant amount of metallic reinforcement which will

- Have an impact on the durability of the concrete through corrosion development
- Generate H_2 by corrosion in anoxic condition over a long period, which must be managed to limit the increase in pressure and the risk of damage to the geological medium (long-term safety issue)

Studies on the use of non-metallic bars or fibers

- Incorporation rate and homogeneous spreading for fibers
- Adhesion to concrete and mechanical behavior of the structure
- Durability in alkaline environments, e.g. composite rebars made of glass or carbon fibers in vinylester matrix
- Preliminary large-scale tests for a slab in the URL this summer

Need to define a certification process for non-standardized solutions

Glass or carbon rebars, with vinylesther matrix, high-adherence or sandblasted surface

Carbon fibers

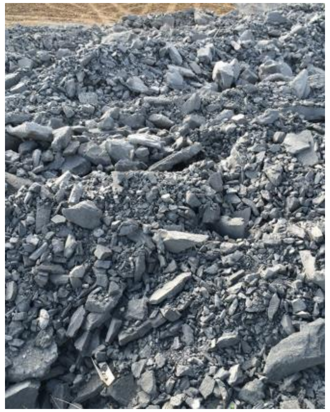
Reuse of excavated materials

Over 12 millions m^3 of excavated clay

- 40 % will be used as backfill material in the galleries at the closure of the disposal facility
- 60 % will remain available for reuse

Solutions under study

- As unprocessed material: quarry backfill, road fill, raw earth
- As processed material
  - Alkali-activated materials (geopolymer) by calcination (650 - 800 °C)
    - Incorporation rate from 33 % to 100 %
  - Terracotta (800 - 1 000 °C) for bricks or tiles
  - Cement by clinkerization (1 450 °C)
    - Incorporation rate up to 25 % (incorporation tests at small scale with different percentages of clay)
    - Representative-scale tests for processing large volumes (up to 500 tons)



Need to sort the clay from the materials used to secure the excavations (shotcrete, fiberglass bolt) depending on the excavation techniques

The move towards low-carbon concrete

Portland and blended cements as a reference for Cigeo's components and for long-term behavior R&D

Ongoing evolutions

- Adaptation to regulations and standards evolutions towards low-carbon concrete
- Decrease of the availability of several raw materials (fly ash, slags…)

→ *Development and characterization of long-term behavior of low-carbon concrete*

Main goals

- Verification of compliance with the requirements applicable to Cigeo components
- Adaptation and validation of multi-coupling simulation models of THMC behavior to support the demonstration of performance over time

Start of a 10-year program with waste producers focusing on

- Use of cements not dependent on by-products from other industries (fly ash, slags)
  - CEM II/B-M, CEM II/C-M, CEM IV/A with calcinated clay, natural pozzolana and limestone
- Study of long-term evolution in disposal environment (leaching, carbonation, corrosion, radionuclides migration…)

→ *Same level of knowledge as the current reference is required for low-carbon concrete*

Thank you for your attention