Evolution of Andra's R&D for the Cigéo Project: Short and Long-Term Challenges

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Andra

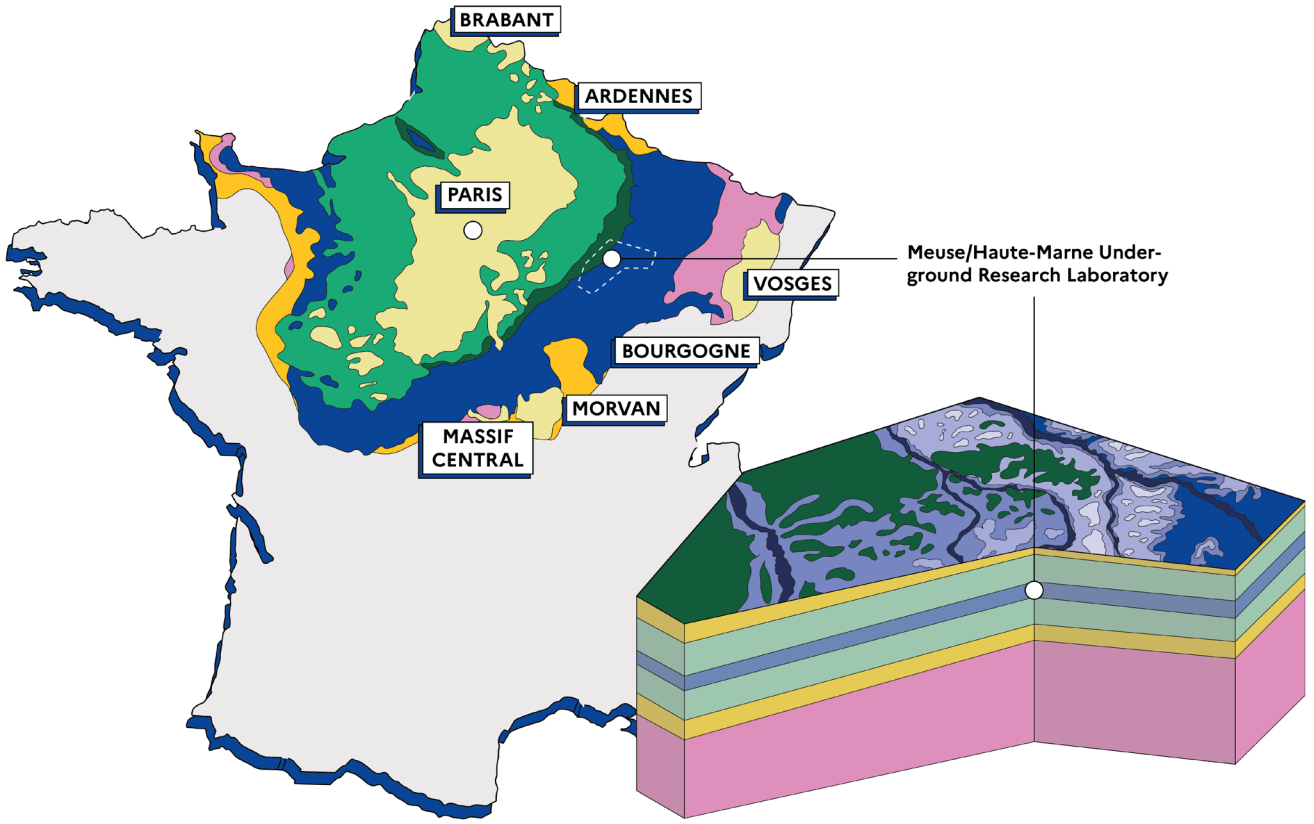
Description of Cigéo (1/2)

East of the Paris sedimentary basin

- Meuse/Haute-Marne district (Northeast France) near Bure
- Mesozoic sedimentary pile approximatively 2 km thick
- Low seismic activity without major tectonic faults
- Study area covering 250 km²

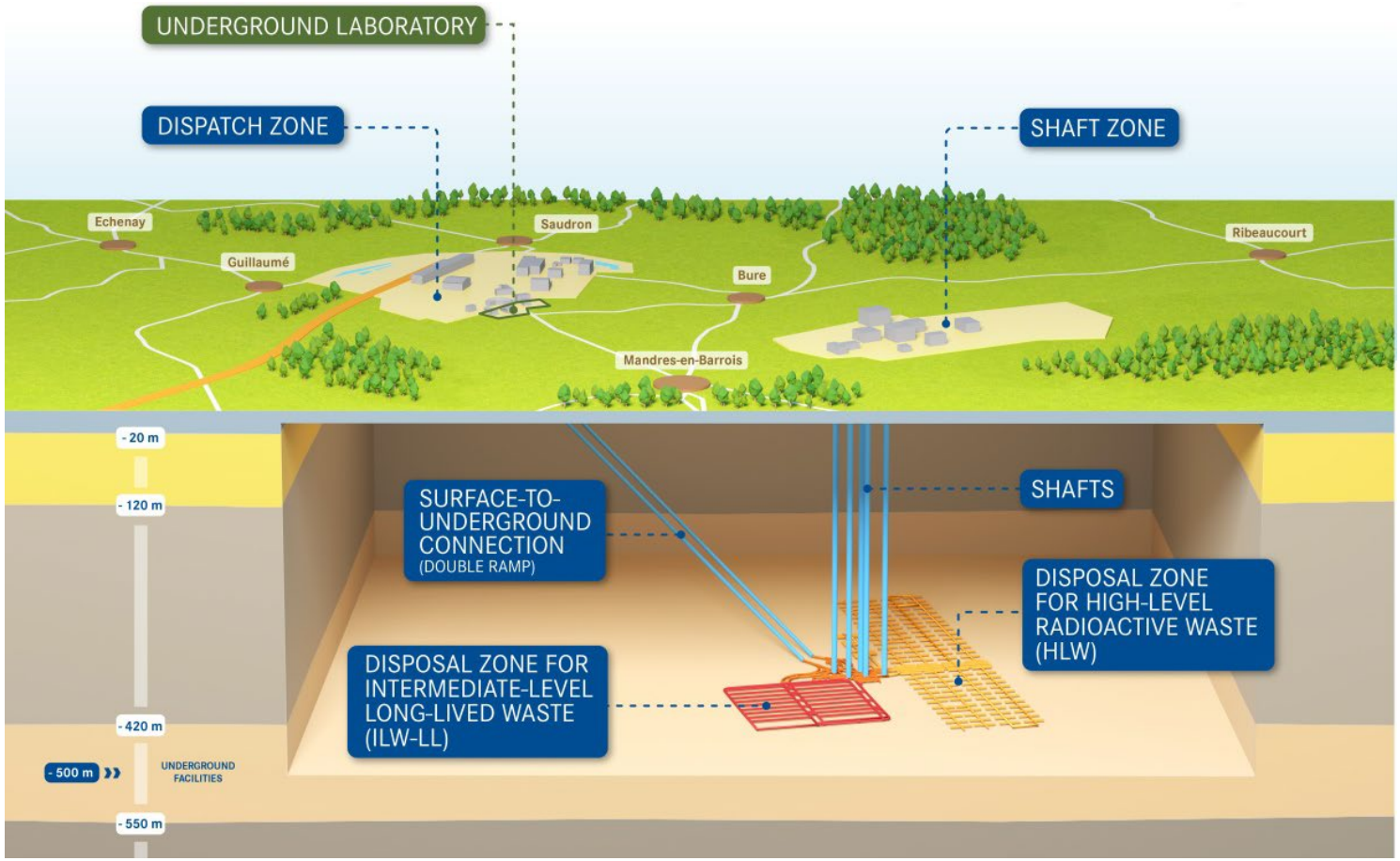
The Callovo-Oxfordian (**COx**) formation as a host-rock

- Mudstones (*"Bure argillite"*)
- Age: 160 Millions years
- Thickness : 130 to 170 m and depth: 420 to 580 m
- Surrounded by 2 calcareous aquifers
- Favorable properties for confining and limiting the migration of radionuclides
- Pillar of long-term safety (with seals of access)

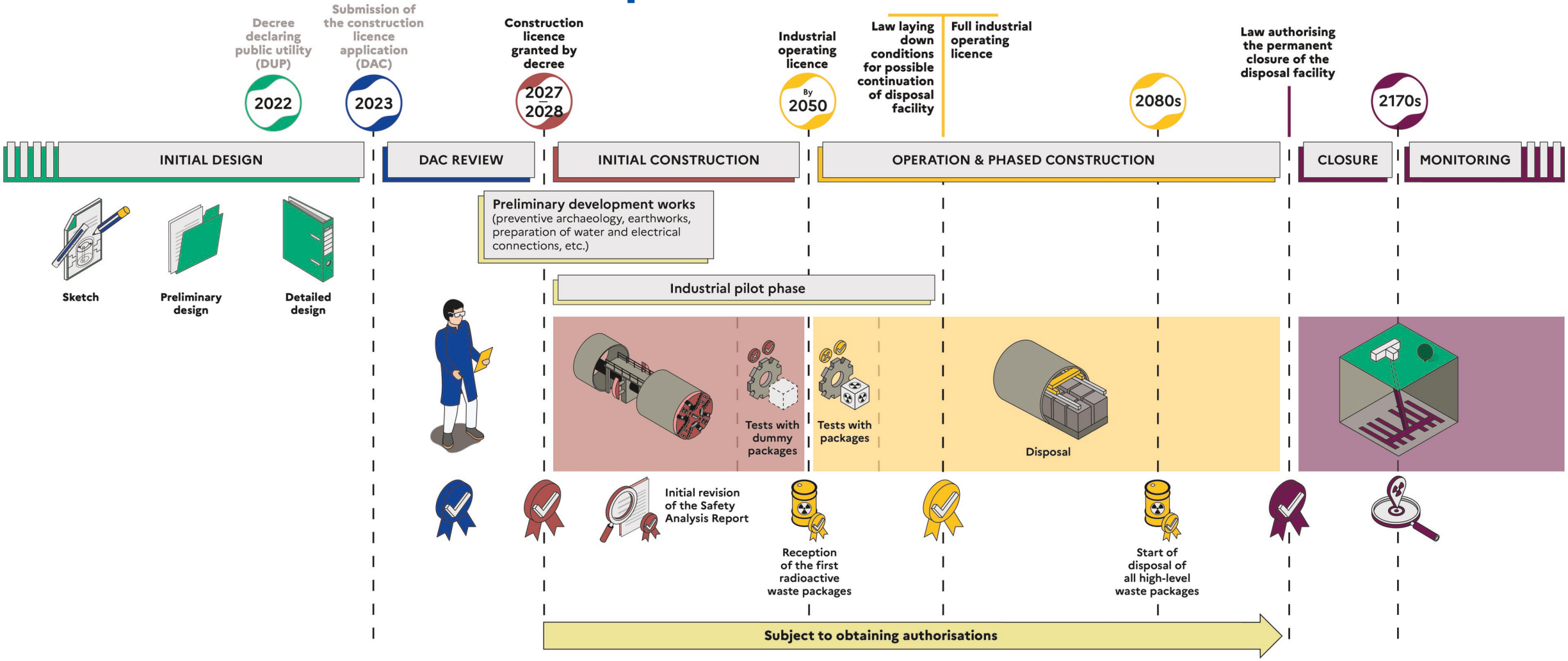


Description of Cigéo (2/2)

- 85000 m³ of waste
- 15 km² underground footprint
- 270 km of galleries
- 10 Mm³ of excavated materials
- 4 Mm³ of concrete
- 320000 t of steel
- 120 years of operation
- 26 to 37 billion euros



Current status and next steps



Evolution of Andra's R&D for the Cigéo Project

The transition from the design phase to the implementation preparation phase does not mean that R&D is no longer necessary: it means the R&D must be different

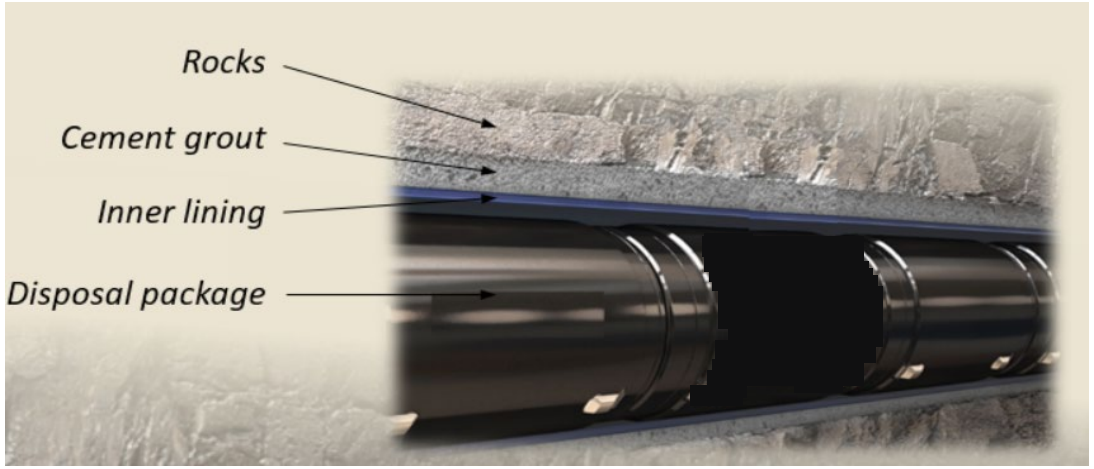
- Short-term R&D needs (until the end of the pilot industrial phase)
    1. Provide scientific and technical input addressing Andra's commitments made during the review process
    2. Support the industrialization of the first phase of Cigéo including optimizations
    3. Support the pilot industrial phase
- Long-term R&D needs
    4. Conduct forward-looking and adaptative R&D to prepare for futures phases of Cigéo including continuous optimizations
    5. Maintain robust scientific and technological monitoring
    6. Maintain and develop core expertise while capitalizing on accumulated knowledge

Short-term R&D needs: addressing Andra's commitments

HLW disposal cell

- **Corrosion of carbon steel lining in the vicinity of the cementitious backfill material**
  - Influence of the backfill material formulation (alkalinity, alkaline reserve, sulfide content), temperature, oxygen, chlorides, heterogeneities, irradiation…
  - Consequences of the geochemical evolution of the cementitious backfill material over time

HL vitrified waste disposal cell



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- **Risk of explosion due to gas exchange between the disposal cell and the gallery, as well as corrosion of metallic components**
  - Improved design of the head of the disposal cells
  - Monitoring and modeling of the internal atmosphere of the disposal cell
  - Development and qualification of a purge device

Full-scale mockup of the carbon steel lining designed to test inerting processes

Mapping of H_2/O_2 concentration using Lidar

Short-term R&D needs: addressing Andra's commitments

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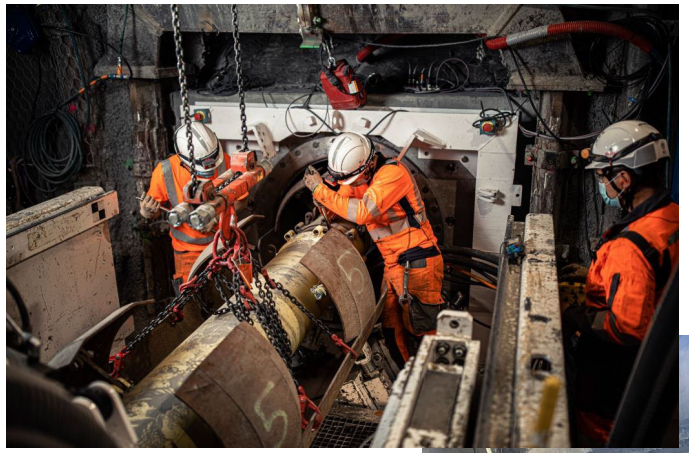
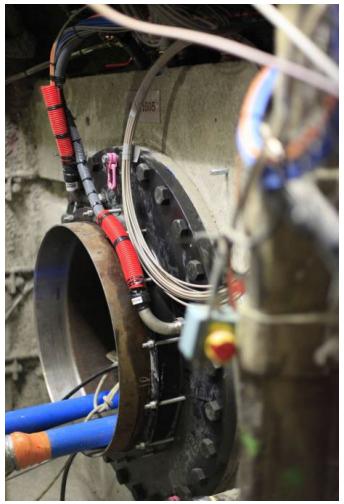
  - Improved design of the head of the disposal cells
  - Monitoring and modeling of the internal atmosphere of the disposal cell
  - Development and qualification of a purge device
- **HLW disposal cells demonstrator program**
  - In-situ full-scale demonstrators (functional part and cell head), head optimizations, heating test, backfill material, gas exchange monitoring, and inerting tests





Short-term R&D needs: support the industrialization of the first phase

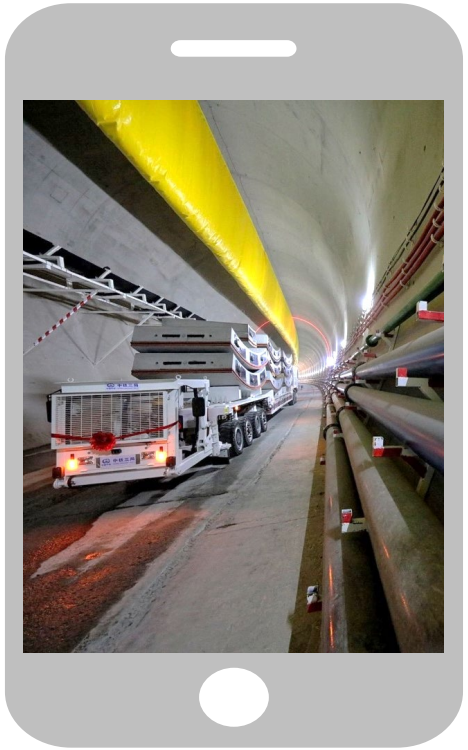
ILW disposal cells, galleries and intersections

Objectives of the program

- Supporting contractualization for the request for proposal (RFP) on underground infrastructure (end 2026)
    - More than 10 years of work, start of construction ~2035, cost ~ 2,000 M€

18 km
Galeries (TBM)

2,6 km
Shafts (5)



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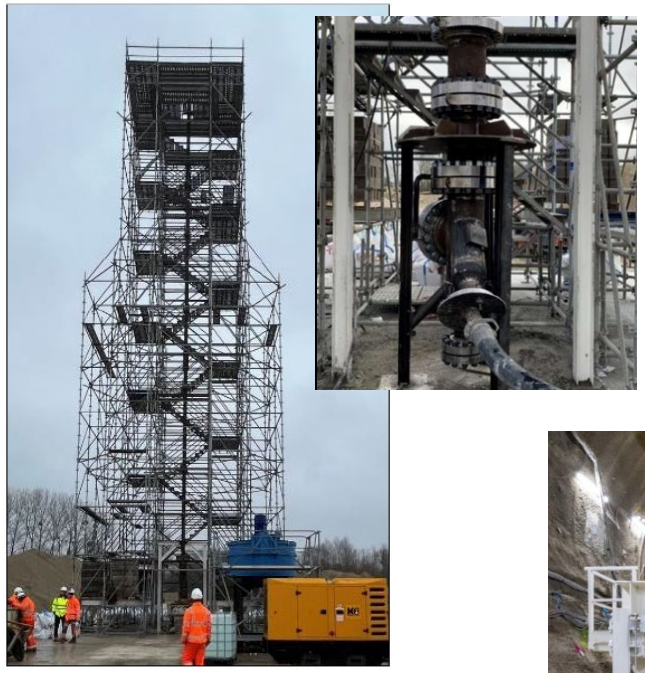
- Optimizing the underground infrastructure
  - Improve construction methods
    - → Optimization of phasing and material flows

Scaled-down tests: pipe of 25 m



URL -490 m test

10 m drift lining casting

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- Optimizing the underground infrastructure
    - Improve construction methods
        - → Optimization of phasing and material flows
        - → Demonstration of the removal of concrete segments at an intersection

        …

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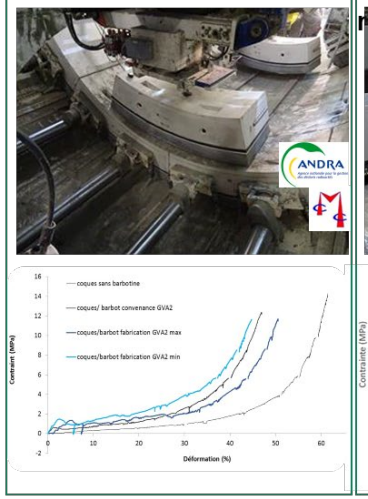
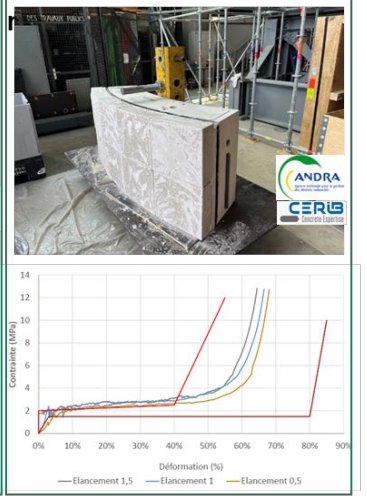
  - Improve construction methods
  - Improve compressible materials solutions (for TBM and conventional methods)

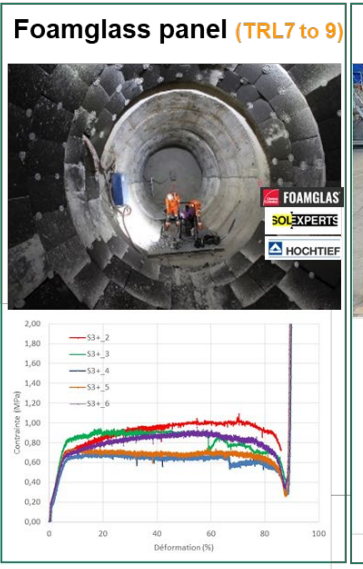
VMC segment (TRL9)



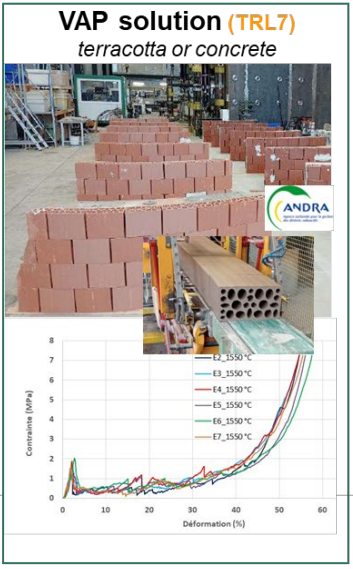
Foam concrete (TRL7)



Foamglass panel (TRL7 to 9)



VAP solution (TRL7)
terracotta or concrete



Short-term R&D needs: support the industrialization of the first phase

ILW disposal cells, galleries and intersections

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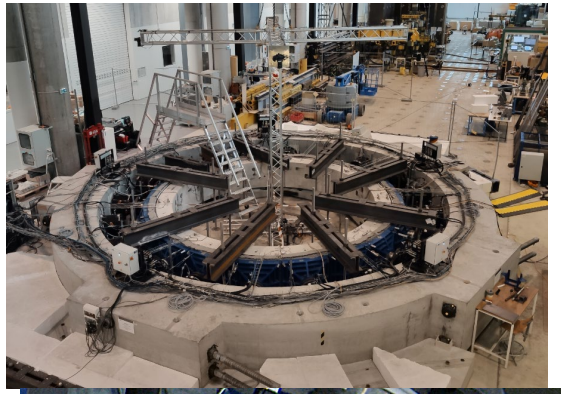
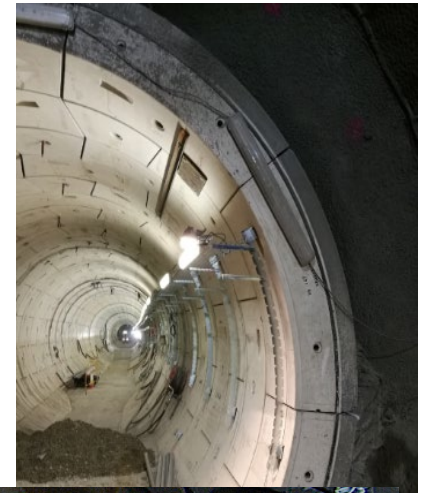
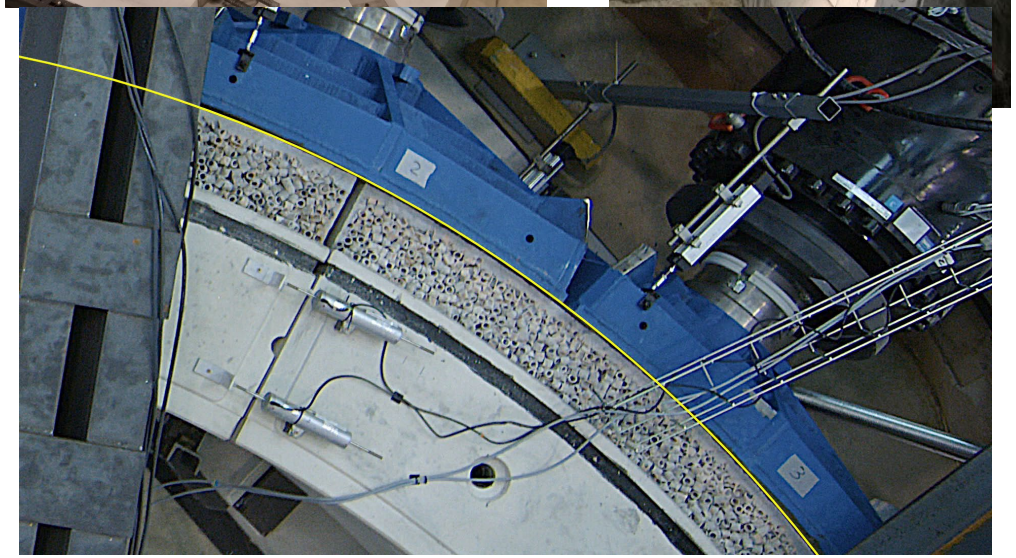
- Optimizing the underground infrastructure
    - Improve construction methods
    - Improve compressible materials solutions (for TBM and conventional methods)
        - Multi-scale design and qualification approach (materials/integration method)

        → Developing innovative methods of integration at intersections
            - Additive manufacturing…

        → Developing technical and economic analyses that take into account the entire process







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ILW disposal cells, galleries and intersections

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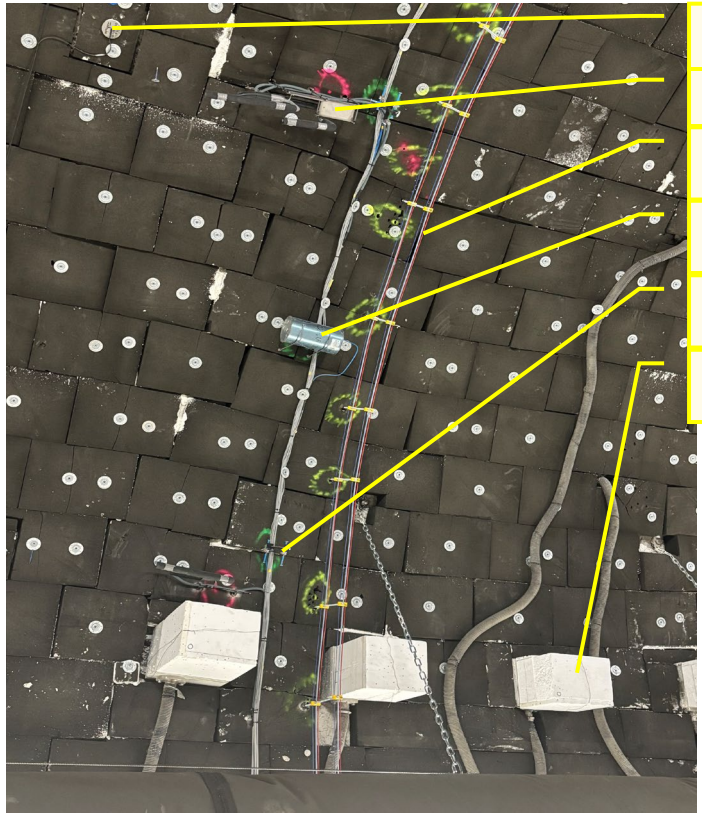
  - More than 10 years of work, start of construction ~2035, cost ~ 2,000 M€
- Optimizing the underground infrastructure
  - Improve construction methods
  - Improve compressible materials solutions (for TBM and conventional methods)
  - Optimize the dimensioning taking into account compressible materials
    - → Confirm the behavior over time of the Callovo-Oxfordian formation
      - → Convergences, induced fractured zone, lining loadings…
    - → Improving THM-C models, benchmarking
    - → Full-face excavation of a large diameter gallery (10.6 m)
    - → First *in situ* intersections with compressible materials (same geometry as Cigéo)
    - → Developing a performance-based approach for concrete durability over 100 years



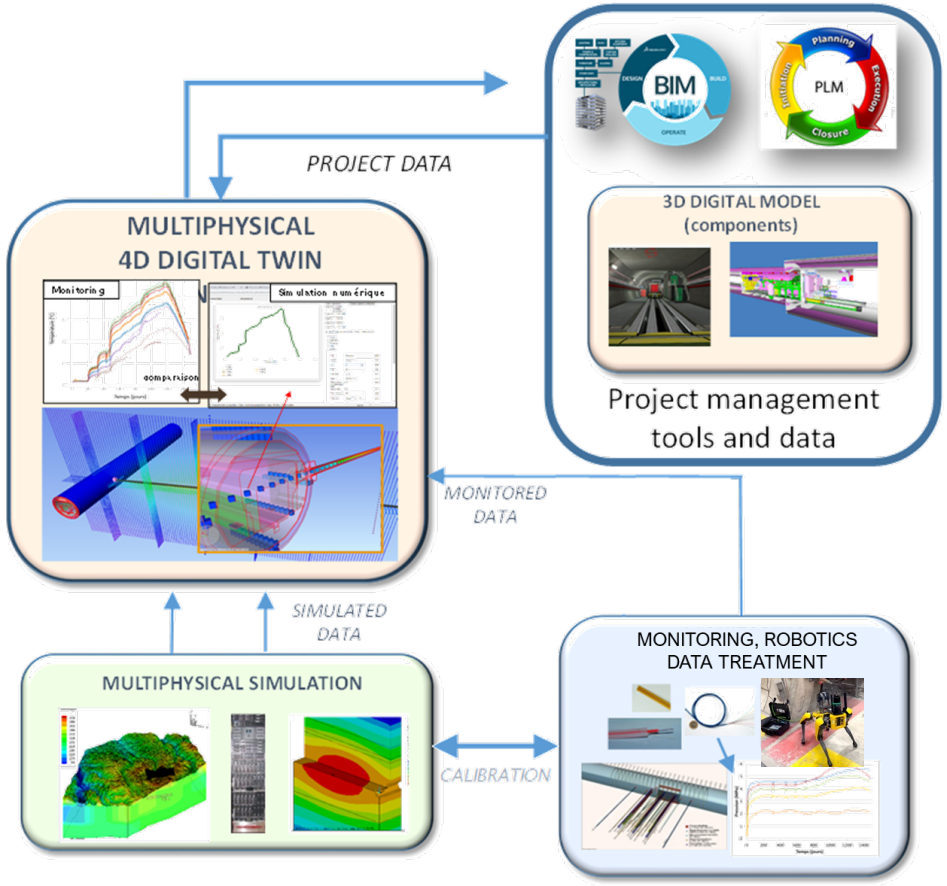
Monitoring a ILW disposal cell with compressible éléments before setting the concrete lining

Short-term R&D needs: support the pilot industrial phase

Development of surveillance tools

Main objectives of the pilot industrial phase:

- Reinforce the overall view of phenomenological functioning and long-term predictions of repository behavior
- Ensure that the observed evolution of the repository is consistent with the safety demonstration



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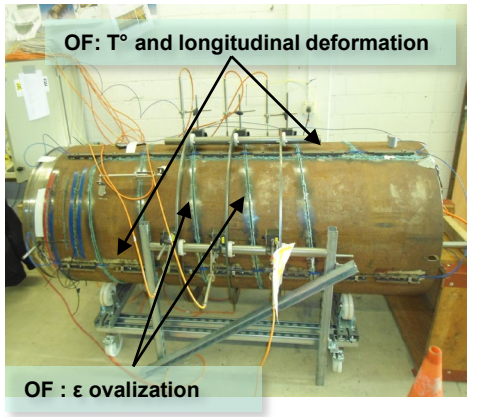
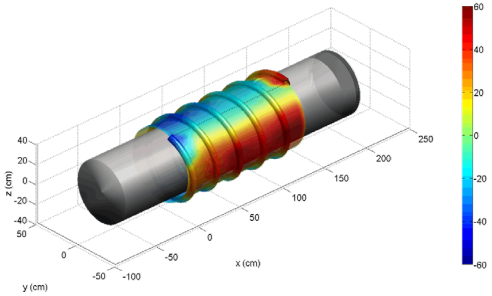
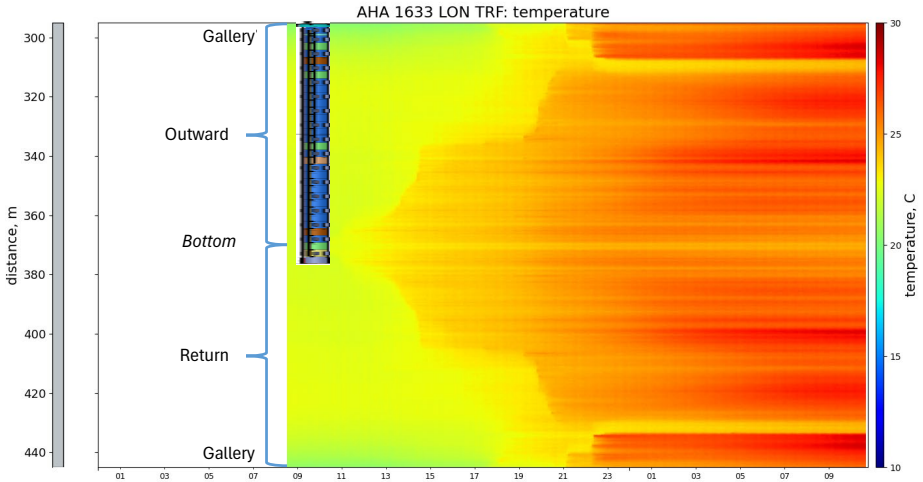
Main areas of R&D:

- Sensor development
  - → **Parameter of interest:** chemistry (pH, dissolved species), corrosion rate, THM processes, gas
  - → **Sensor of interest:** optical fiber, lidar, non-intrusive sensors, distributed measurement
  - → **Field of studies:** durability/reliability, calibration, signal processing, data transmission, energy source…







Evolution over time of the filling of the void between the lining and the host-rock with cementitious backfill material

Short-term R&D needs: support the pilot industrial phase

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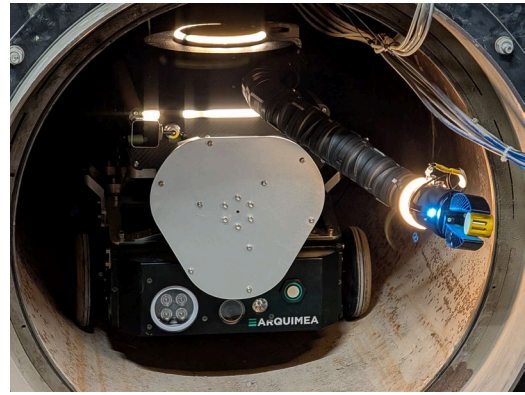

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Main areas of R&D:

- Sensor development
- Robotic

  Complements fixed devices, reduces strain and risks, streamlines intervention costs

  → **R&D challenges:** embedded sensors and tools, AI for autonomous robotics, underground navigation, real-time data processing, energy management

  → **Applications:** scan to BIM, crack detection, convergence measurements, excavation monitoring, removing corrosion sampling in HLW disposal cells

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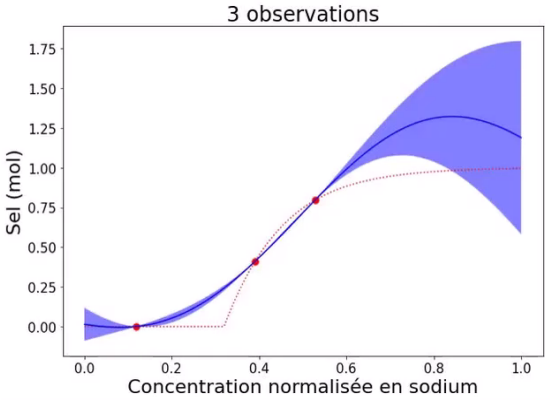
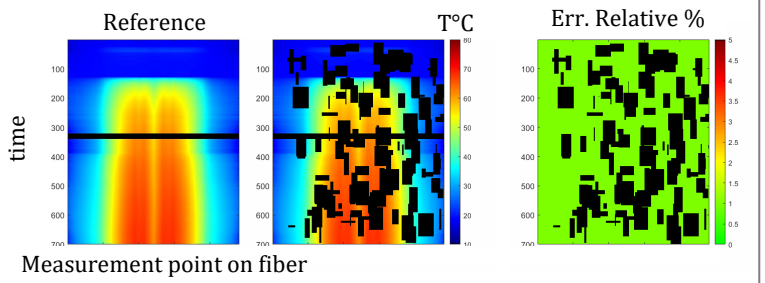
Main areas of R&D:

- Sensor development
- Robotic
- Data processing, Multiphysics simulation and AI
  - → Predict, compare, combine, and reconstruct sensor datasets
    - Sensor drift or failure, replacement or addition of sensor, absence of data
  - → Development of efficient numerical simulation tools and solvers
    - Management of couplings, HPC, HPDA
  - → AI techniques for solving complex systems and reducing computation times
    - Multi-physics representation capabilities (time and space)

Active learning principle :
- Approximation with a few simulation results
- Estimate uncertainty
- Run a simulation for the highest uncertainty
- iterate



RPCA tests (we define aleatory missing data) (Candès *et al.*, 2009)



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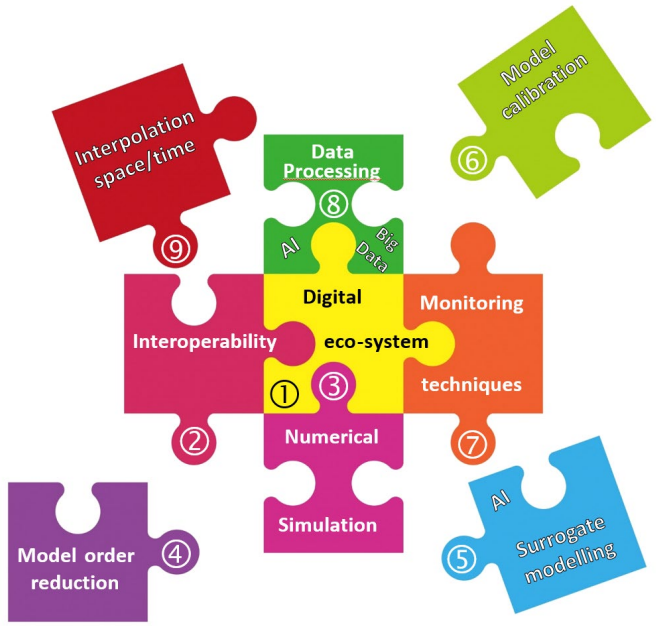
- Robotic
- Data processing, Multiphysics simulation and AI
- Development of phenomenological digital twins
  - → Support the operator in monitoring surface and underground facilities during the Pilot Industrial Phase
    - Check that the facility and its geological environment remain within the phenomenological operating range defined within the framework of the safety assessments and the commissioning authorization
    - Contribute to verifying operational safety and provide a decision-making tool in the eventuality that the repository does not operate in accordance with expectations
    - Capitalize multi-physical knowledge (time/space) in a single environment



Technological bricks

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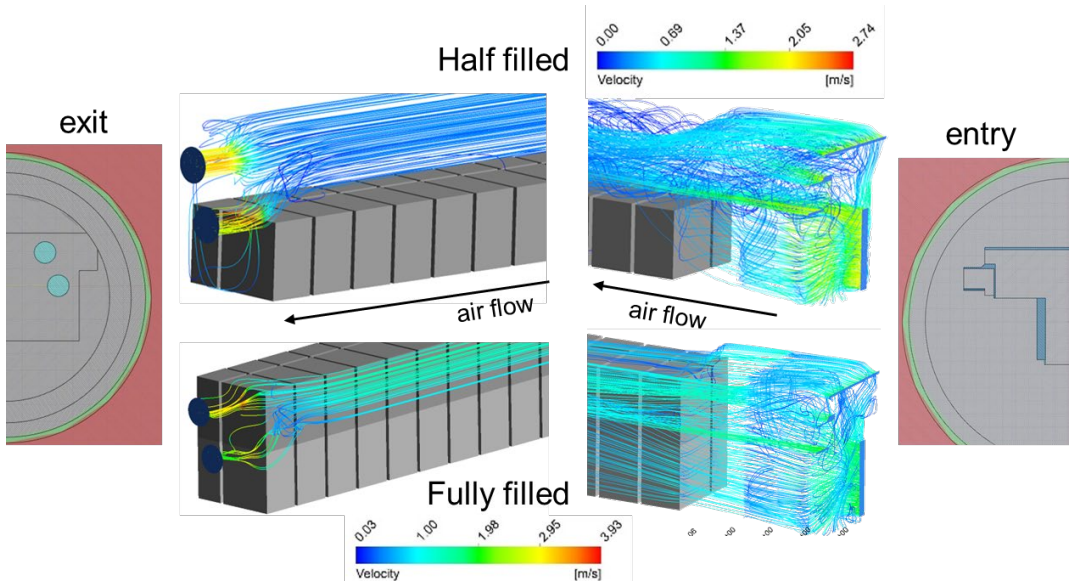


Thermo-aeraulic evolution of ILW disposal cell (half-filled and fully filled)

Long-term R&D needs: conduct forward-looking and adaptative R&D

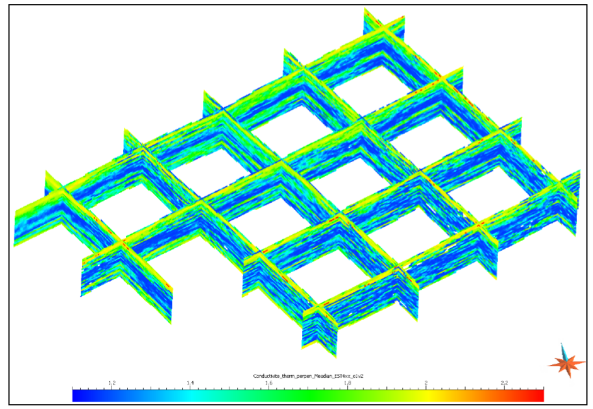
Disposal architecture optimization (THM)

Objective of the program: optimize the disposal footprint and therefore its cost

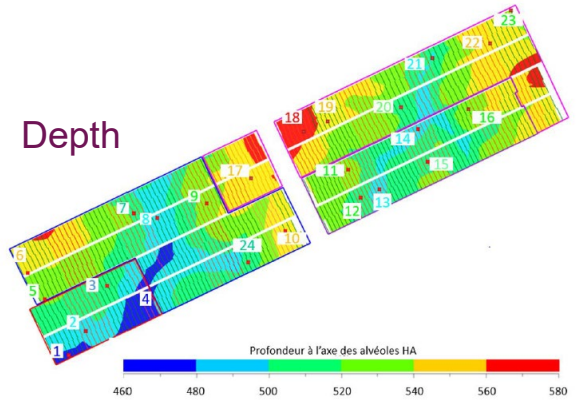
R&D levers for optimization:

- Changing the dimensioning criteria
  - Need to keep Terzaghi's effective stress criteria, no change in maximum temperature
  - Study the criteria for initiation and propagation of fracturing

Parameters derived from 3D seismic data



Depth



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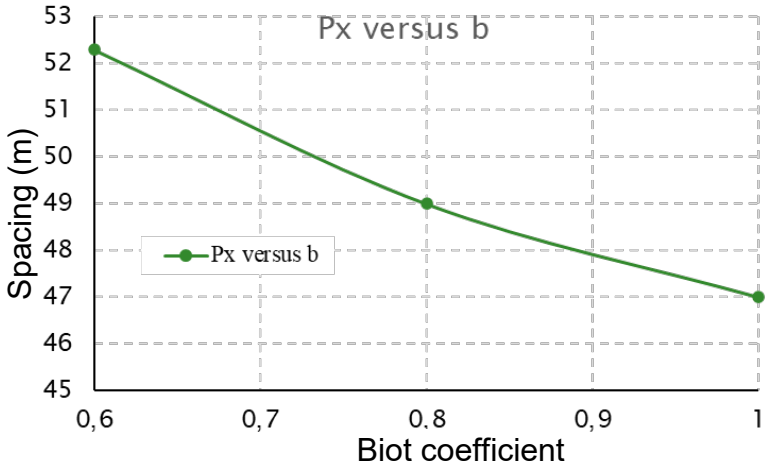
  - Integrate the pre-peak non-linearity
  - Precise the evolution of parameters with temperature and damage



Example of the evolution of the spacing between two adjacent cells as a function of the Biot coefficient (2D calculation)

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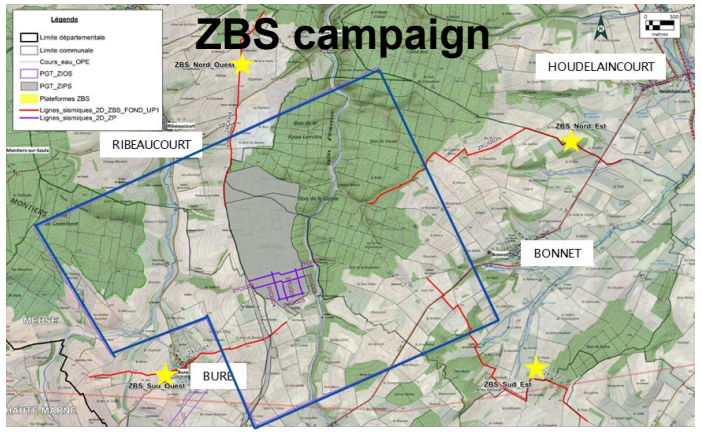
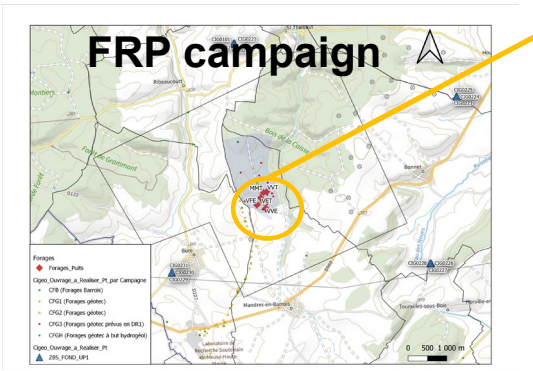
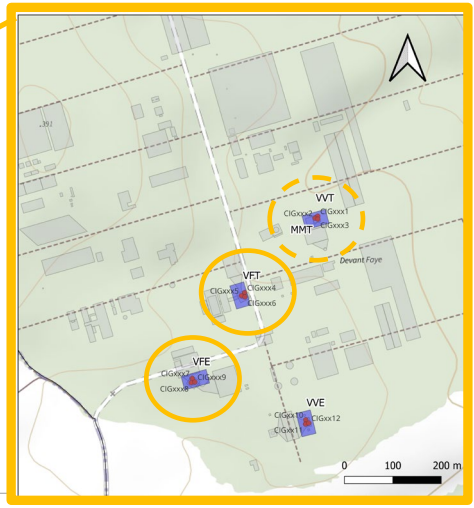
- Reducing uncertainties in thermo-hydro-mechanical parameters
  - Improve experimental protocols
  - Acquisition of new THM data to better assess their spatial variability
    - → Deep drilling Campaign ZBS (2026-2027) and FRP (2028-2029)
    - → Acquisition of THM parameter during construction



Four platforms located on the edge of ZIOS, enabling the characterization of the Oxfordian, Callovo-Oxfordian, and Dogger formations.





Two or three platforms located along the axis of the shafts, enabling characterization of the Oxfordian and Callovo-Oxfordian formations

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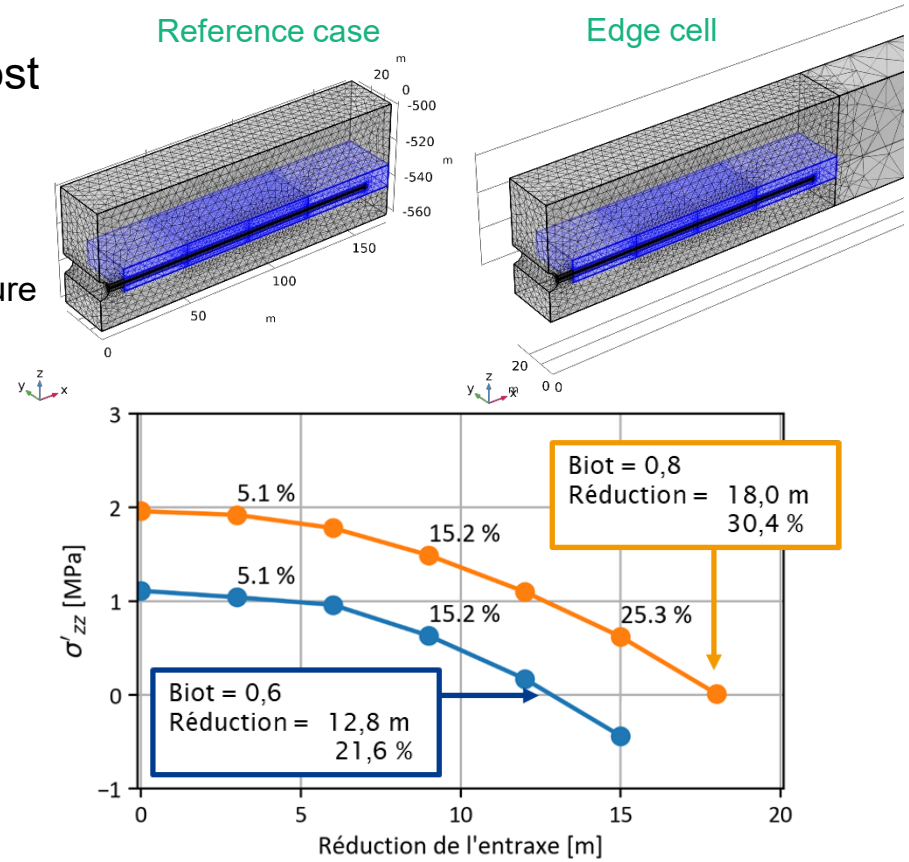
    - → Deep drilling Campaign ZBS (2026-2027) and FRP (2028-2029)
    - → Acquisition of THM parameter during construction
- Improving the conceptualization of the simulation
  - More realistic geometry (edge cells…), boundary conditions



Example of reduction in center-to-center distance for neighborhood edge cells