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OPTIMISATION OF THERMAL DIMENSIONING OF THE CIGEO PROJECT: OPERATIONAL GOALS AND SCIENTIFIC ISSUES

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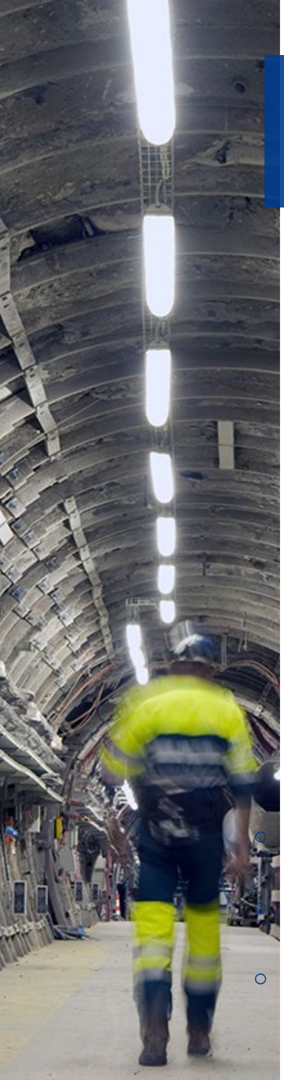
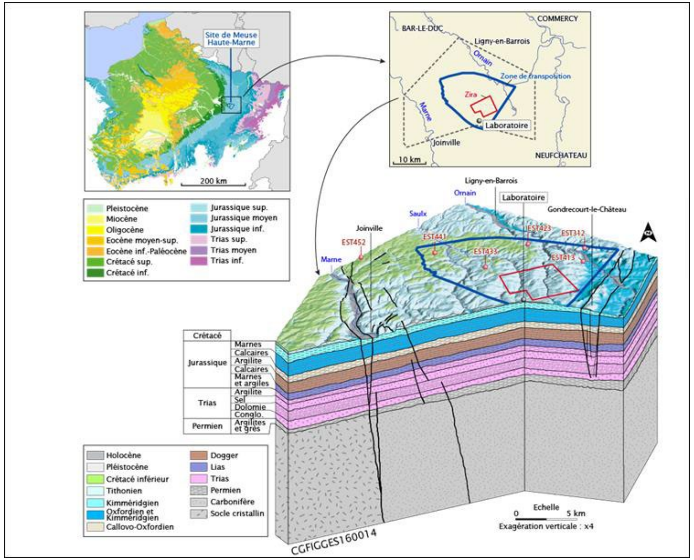
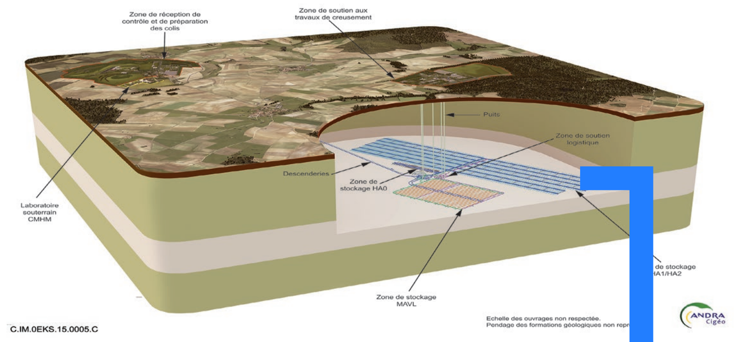
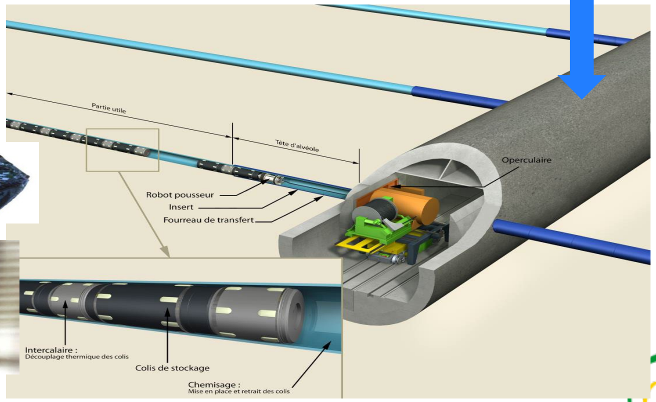


Introduction

Cigéo Project scheme (current development)







- Disposal located in the ZIRA at the middle of the Callovo Oxfordian claystone layer (some -500m depth)
- HLW packages emplaced in series of parallel micro-tunnels (horizontal disposal cells) drilled (excavated) from access drifts
- Micro-tunnels cased with steel liner for emplacement and retrievability

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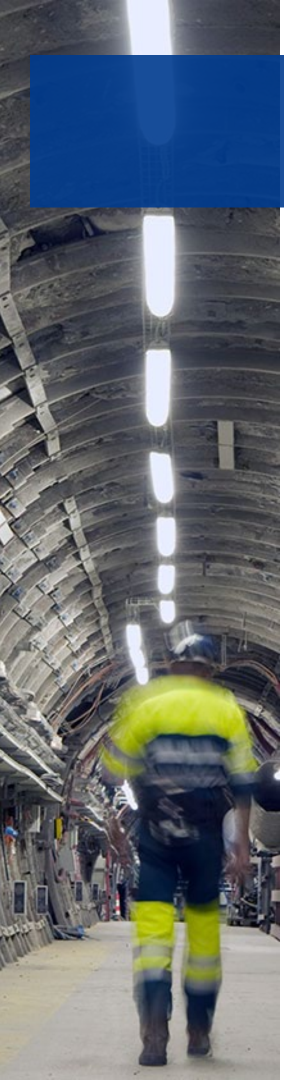

Objectives at large

Technical (economical) objectives :

- Reducing the disposal underground footprint
  - Reducing the cumulated length of disposal cell access drifts
    - Reducing the spacing between HLW disposal cells

Scientific (long term safety) objectives :

- Preventing host rock fracking induced by thermal loading (generated by the thermal power of the HLW packages)
  - Improving geotechnical knowledge and host rock behaviour under thermal loading
    - Planning in vitro and in situ tests at various scales of time and space

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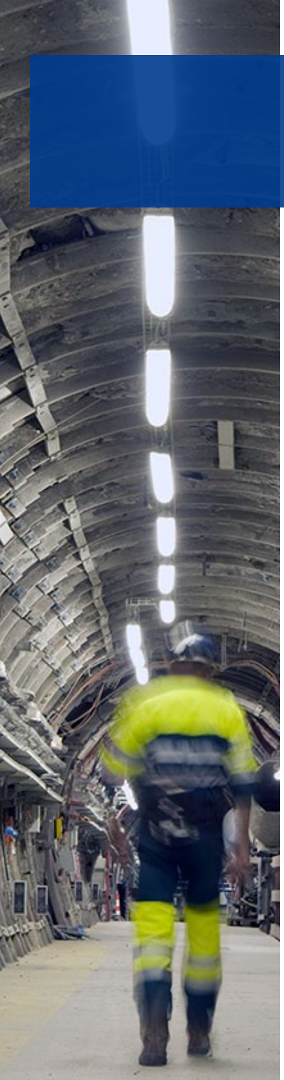


High Level Waste (HLW) repository
Design criteria

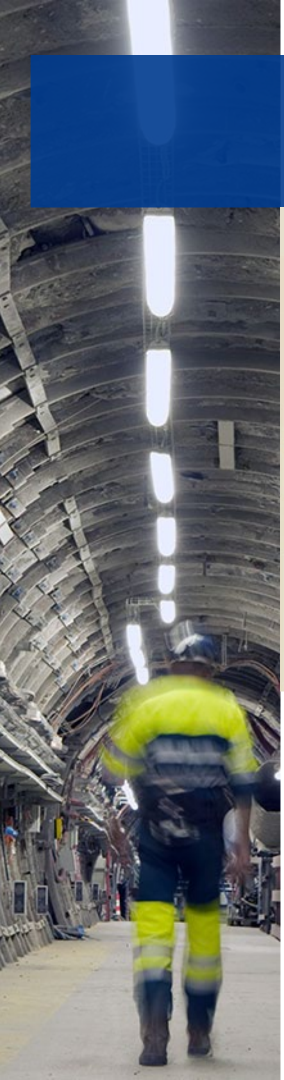
HLW disposal packages will be emplaced in a network of parallel dead end micro-tunnels excavated from access drifts

Heat emitted by HLW will generate in the Callovo-Oxfordian claystone

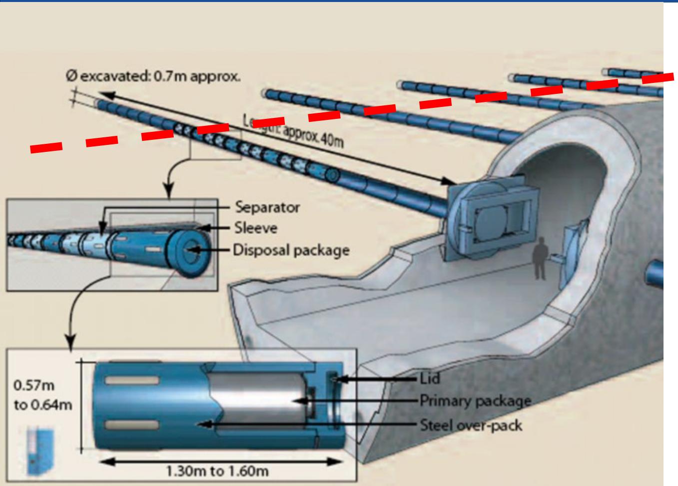
- Transient temperature increase
- Transient pore pressure build-up
  - Due to the differential thermal expansion of the Callovo-Oxfordian skeleton and pore water
  - Generation of transient mechanical field that can lead to fracturing (extension, shear) at multiscale

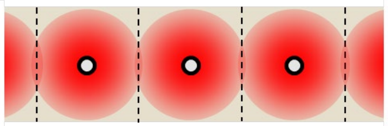
Design criteria/long term safety requirements are defined to preserve “favorable properties of the Callovo-Oxfordian formation”

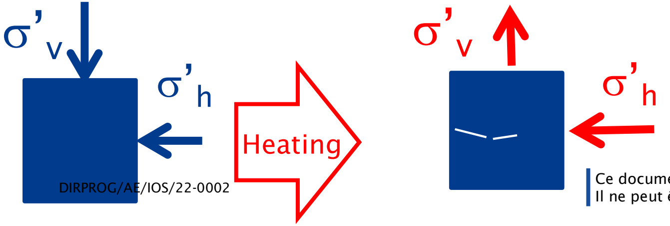
- Maximum temperature in (at contact) the host rock limited at 90°C
- Prevent damage/fracture initiation in the rock (TH**M** criterion)



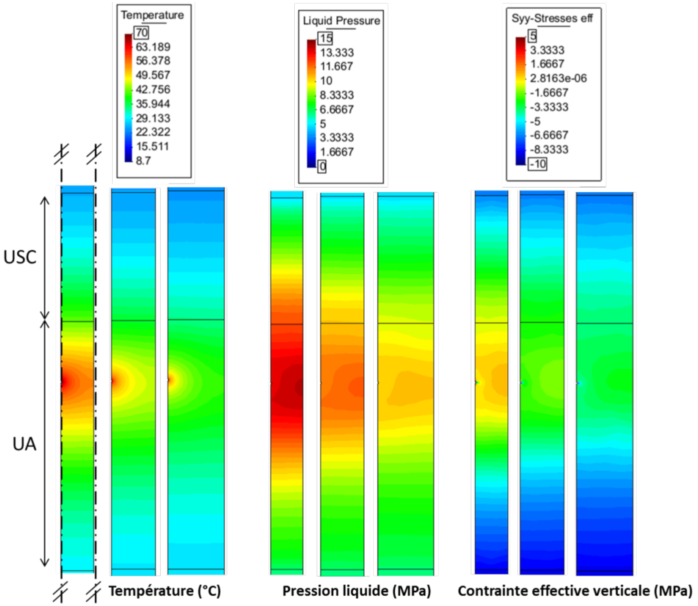
THM behavior of the COx claystone under thermal load
Interaction between parallel HWL disposal cells



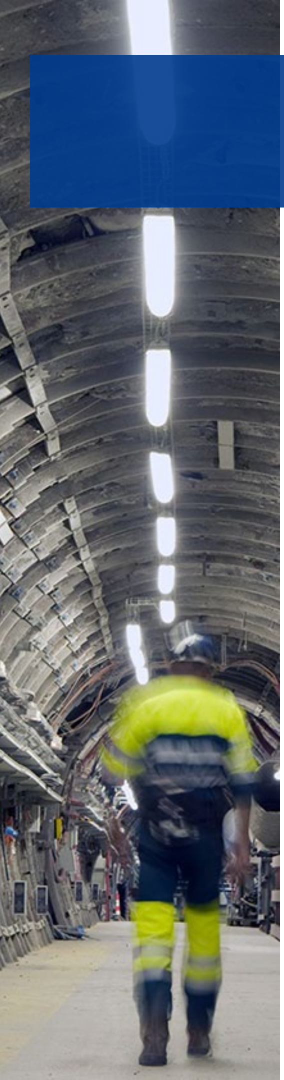




2D calculations at the middle of the cells



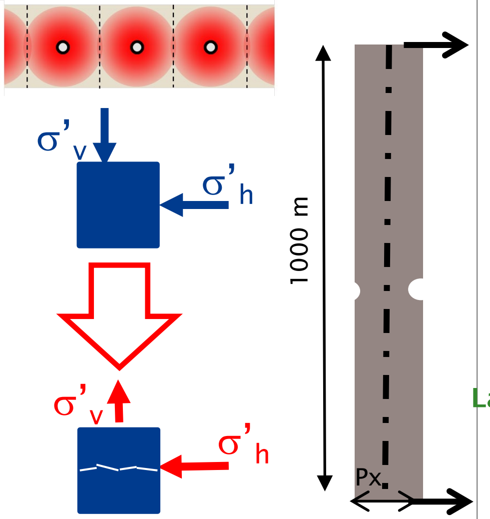
Depending on the spacing between cells σ'_v could reach the unixial tensile strength of the rock inducing sub horizontal damage/cracking

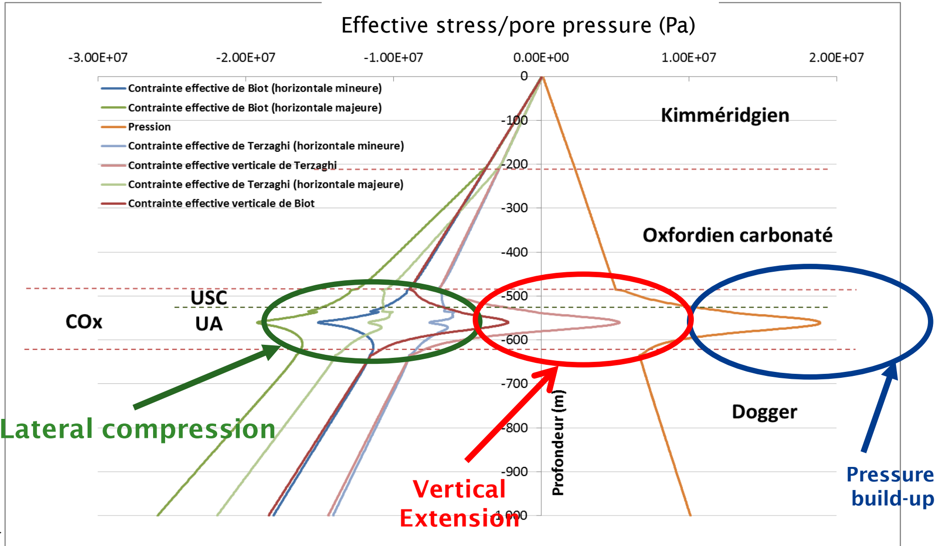


Modeling THM behavior of the COx claystone under thermal load

Schematic THM behaviour

- Example of the evolution of the effective stresses and pore pressure at the distance between two cells





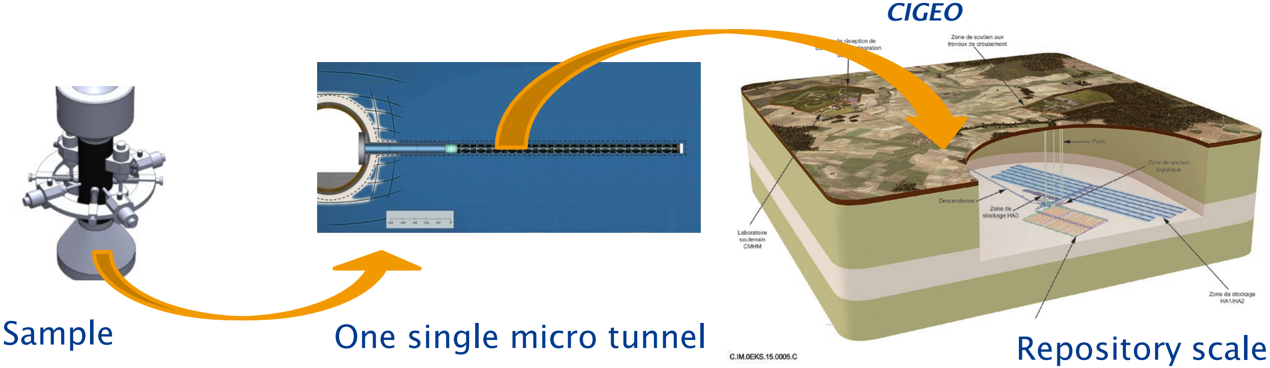
Example HA0 (120 W) – Spacing between micro-tunnels 12.7 m

Pressure Build up → Vertical extension : Tensile effective stresses may be reached
Lateral compression + vertical extension : Deviatoric stress increase

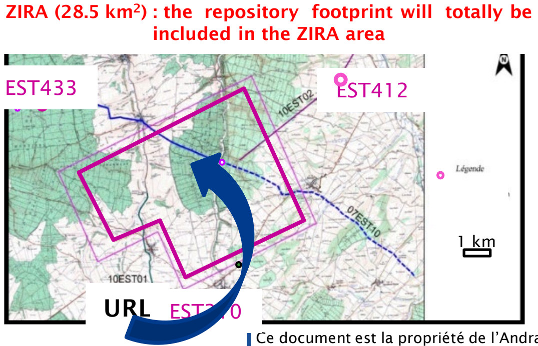
THM behavior of the COx claystone under thermal load

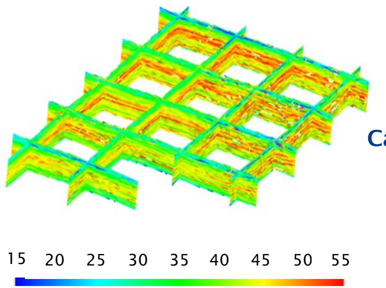
A step wise approach : Upscaling from sample to repository scale

- How to go from sample to a demonstrator (metric scale) in a URL to the scale of a repository ?

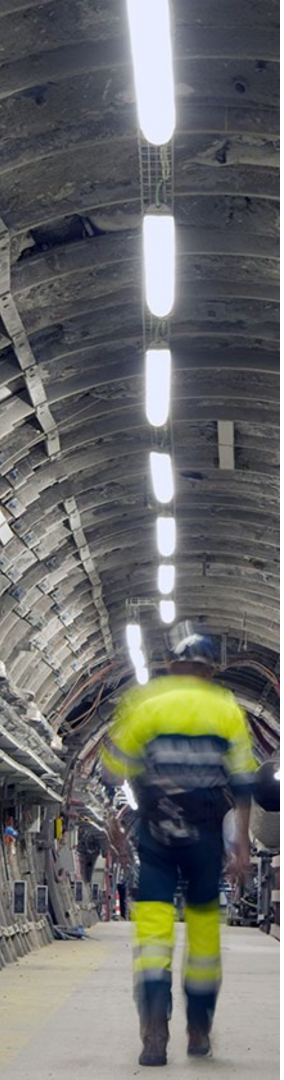


- How to extrapolate data from URL (size of 0.1 km²) to a repository footprint of about 8.5 km²? How to take into account geological variability ?



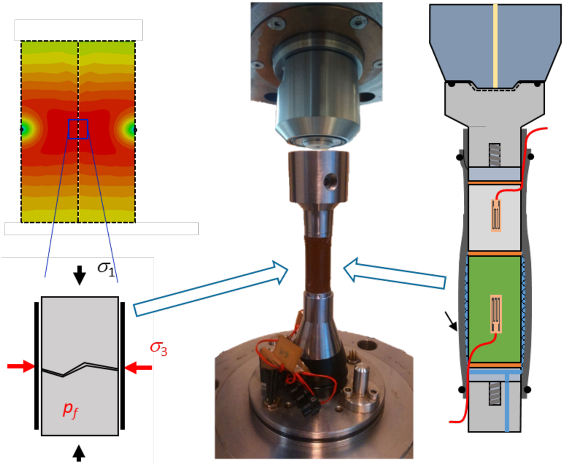


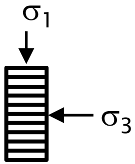
Calcite content of COX claystone (from 3D seismic measurement)



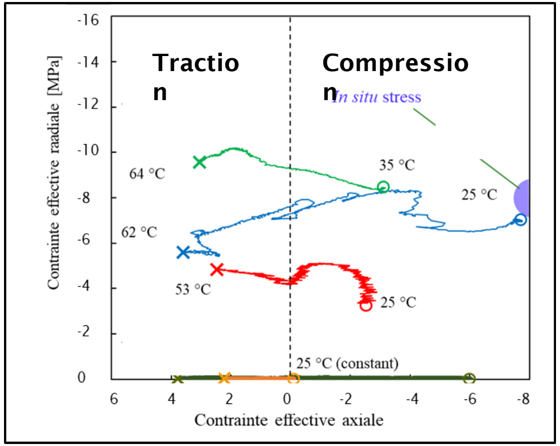
THM tests carried out on Callovo-Oxfordian samples
Results obtained at sample scale

- Thermal pressurization tests on Callovo-Oxfordian samples (cored perpendicularly to sub horizontal stratification orientation)
  - Stress path conducts to the apparition of one horizontal fracture
  - Effective tensile stresses between 0,5 et 4 MPa
    - Coherent with those obtained by traction tests



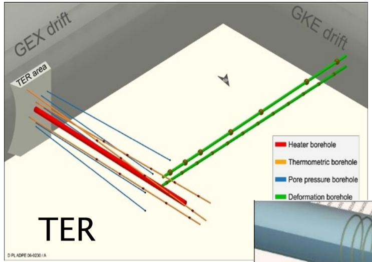


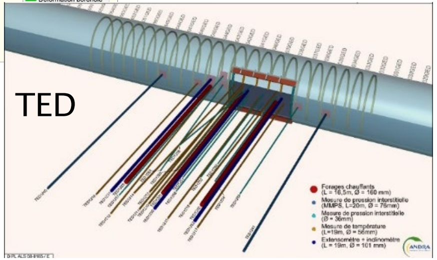
Braun, 2019

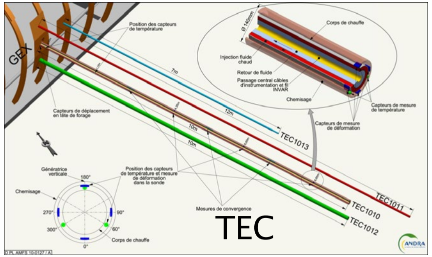


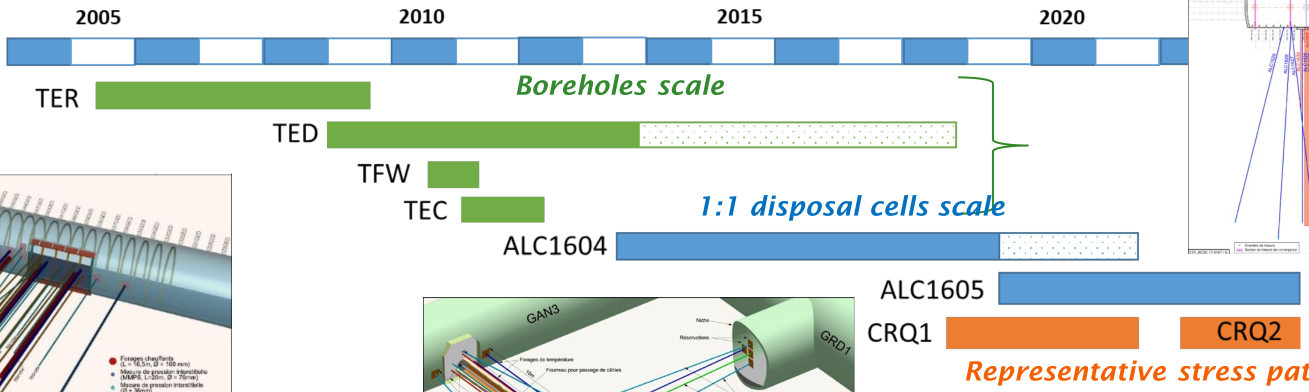
THM in situ tests carried out at the Meuse/Haute-Marne URL
From borehole scale to 1:1 cell scale : Overview

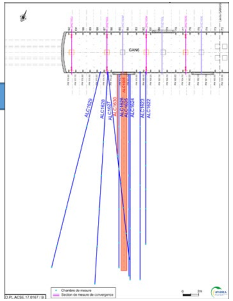
A good understanding of the THM behaviour of the COx

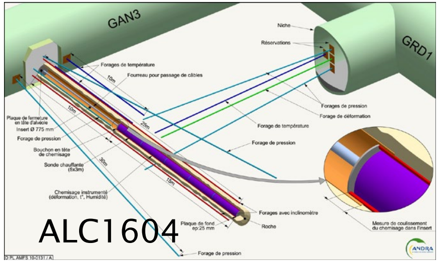


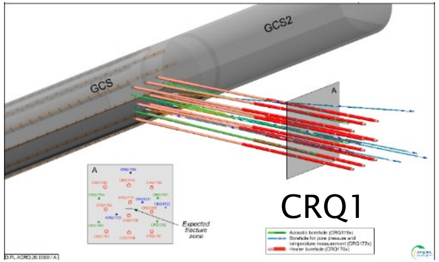






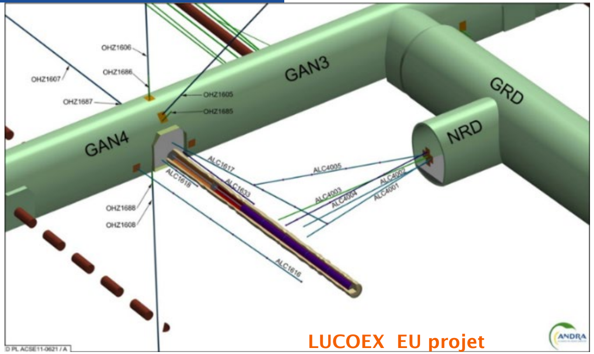


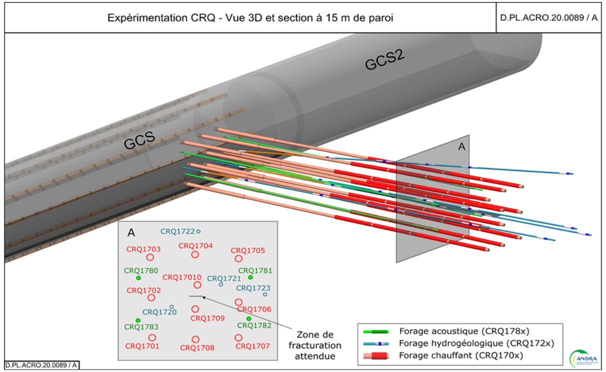




THM in situ tests carried out at the Meuse/Haute-Marne URL
Objectives and results

- Disposal cell experiment
  - Demonstration test to build a full scale micro-tunnel
  - In situ test enabling to increase knowledge on THM behavior and verify accuracy of numerical models at full scale
  - Results:
    - Pressurization coefficient (ΔP/ΔT) similar the one measured at small scale test
    - A good reproduction of the pressure increase within a poro-elastic approach
- CRQ experiment :
  - Evaluate the host rock THM behaviour under thermal loading as it could be generated in Cigéo at mid-space between two disposal cells
  - Pursue the thermal loading until rupture of rock
  - Results :
    - Volumetric deformation and fracking observed
    - Need of a second test to confirm results (values obtained) and observations made





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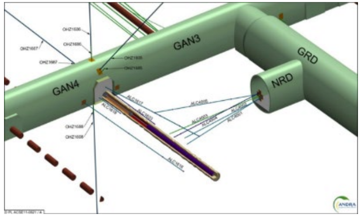
Mastering the THM behaviour of the Callovo-Oxfordian
Thermo-poro-elasticity : a robust approach

- Thermo-poro elasticity model allows a good prediction of the THM behaviour at the borehole and the disposal cell scale
  - Benchmark exercise DECOCALEX2019



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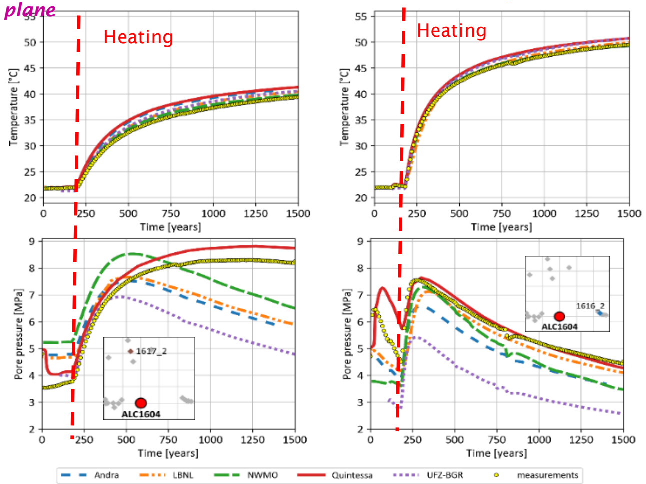
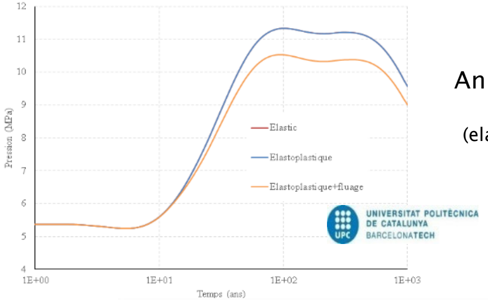
Perpendiclular to the beding plane

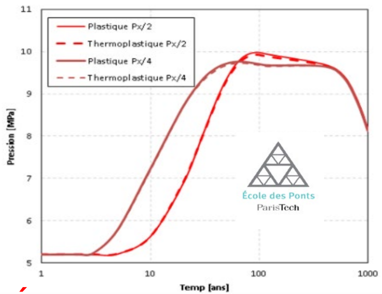
In the beding plane



- Calculation at the repository scale
  - The thermo-poro-elastic approach overestimates the effective stresses compared to the other models

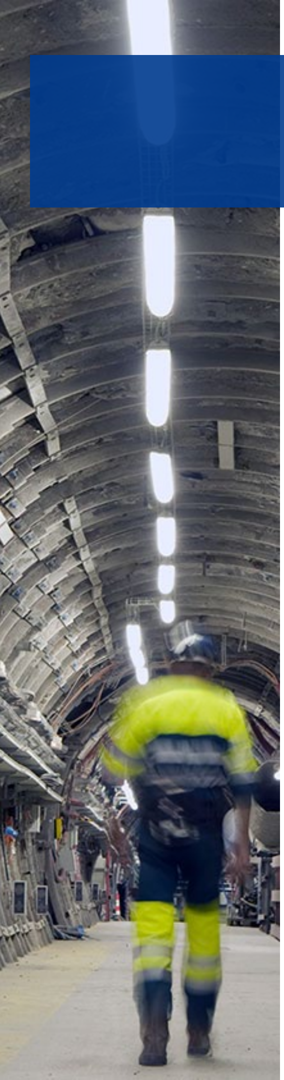


Anisotropic thermo-elasto-viscoplastic model (elastic and strength anisotropy)



Elastoplastic model (based on CamClay) and thermo-plasticity

The thermo-poro-elastic approach is robust for the design of Cigéo

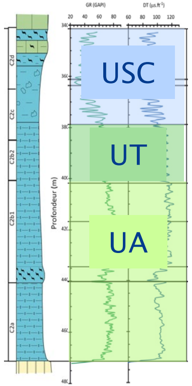


THM behavior of the COx claystone under thermal load
Spatial variability of the THM parameters

Use of multiscale investigations

- Laboratory measurements on the samples
- Geophysical measurements on the boreholes (Well logging)
- Wave propagation investigation at the site scale (3D high-resolution impedance $I_P=\rho V_P$, $I_S=\rho V_S$)

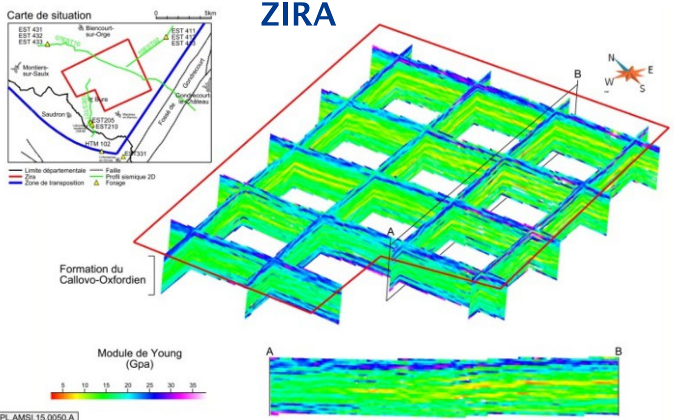
HTM102



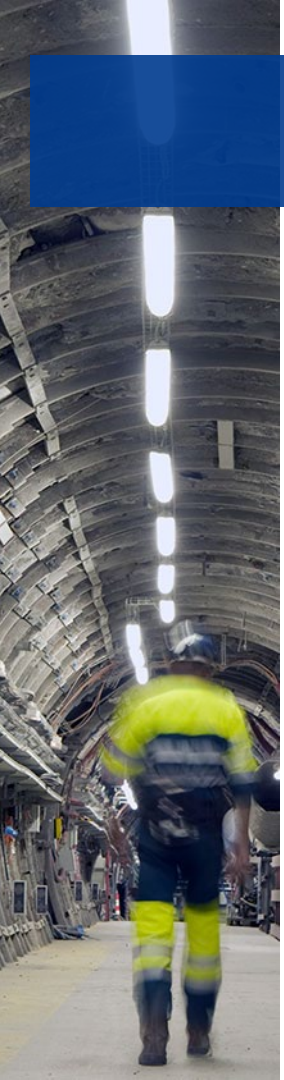
Spatial variability determined from 3D impedance

- Correlation of TM parameters as a function of I_P and I_S
- 3D spatial distribution of TM parameters on ZIRA and uncertainty estimation (Young modulus and thermal conductivity)
- No correlation with permeability

Young modulus on ZIRA



Data and uncertainties have been considered for the current design



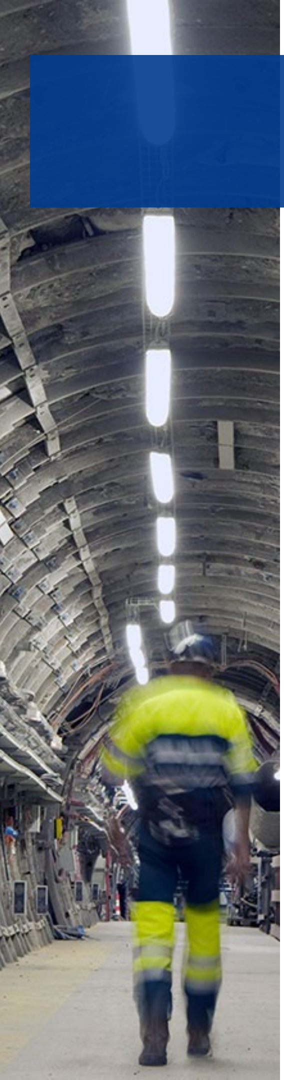
Concluding remarks
Main THM phenomena and key parameters

Pore pressure increase due to
- Difference between thermal expansion of pore water and solid skeleton
- Relative high rigidity of the Callovo-Oxfordian formation
- Low permeability of the Callovo-Oxfordian formation
- Periodic boundary conditions in link with HLW disposal cell network

Thermal damage
- Diffuse thermomechanical damage due to differential thermal expansion of the Callovo-Oxfordian mineralogical components
  - Non significant at the range of the applied temperatures
- Possible localised damage (fracking) induced due to excessive pore pressure increase
  - High values of pore pressure can be reached due to thermo-hydromechanical pressurization and boundary conditions

Most influent parameters
- Rock stiffness (Young modulus)
- Water permeability
- Thermal conductivity

Model for the THM behaviour
- Thermo-poro-elasticity is an accurate model for the design

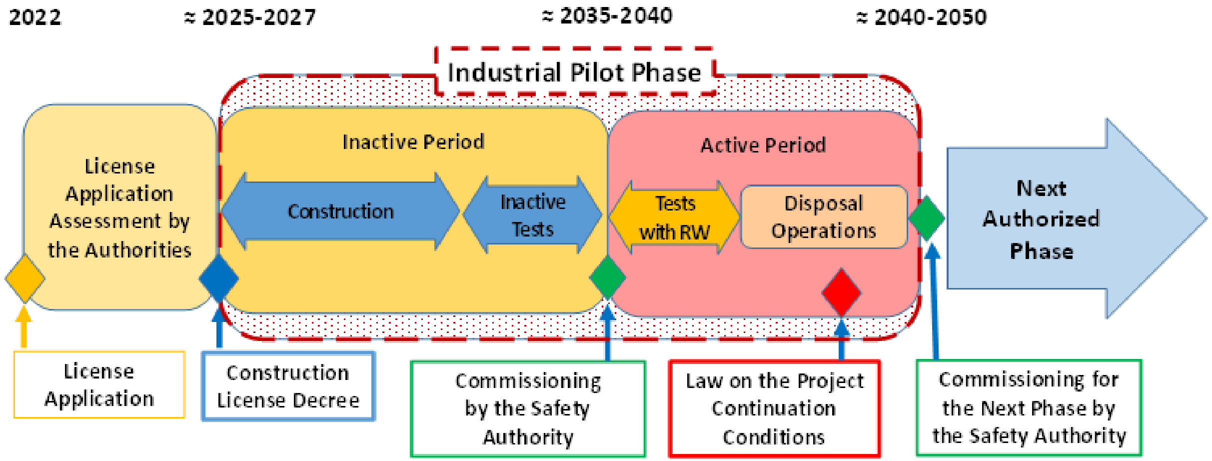


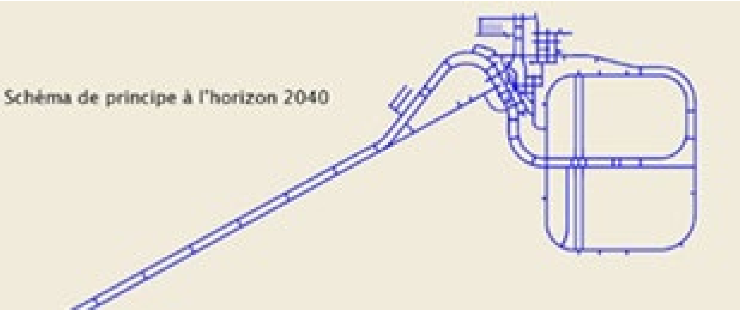
Concluding remarks
Ongoing work

Need to consolidate data and to reduce remaining uncertainties, even if for Cigéo licensing application, a conservative design approach has been already chosen

- Small scale THM behaviour/processes
  - THM Coupling and parameters
    - Definition of an appropriate effective stress concept
    - Reducing the uncertainty on the key parameters
- Less conservative failure criteria
  - Failure initiation in a confined non-damaged zone due to pore pressure build-up
  - Inherent/induced anisotropy
  - Effective stresses (Biot coefficient,…)
- Upscaling of THM parameters from sample/URL to repository area
- Assessment of consequences of a possible damage
  - Sealing capacity of Callovo-Oxfordian

Optimisation through the Industrial Pilot Phase





The lessons learnt from the first 15-25 years of the industrial pilot phase should yield valuable optimisation opportunities :

- **Design hypothesis (THM behaviour)**
- **Design concepts (HLW pilot zone)**
- **Conduct of construction work activities and nuclear operations**

Thank you for your attention