IN SITU THM TESTING AT HIGH TEMPERATURE

Poorly indurated clays (Boom Clay)

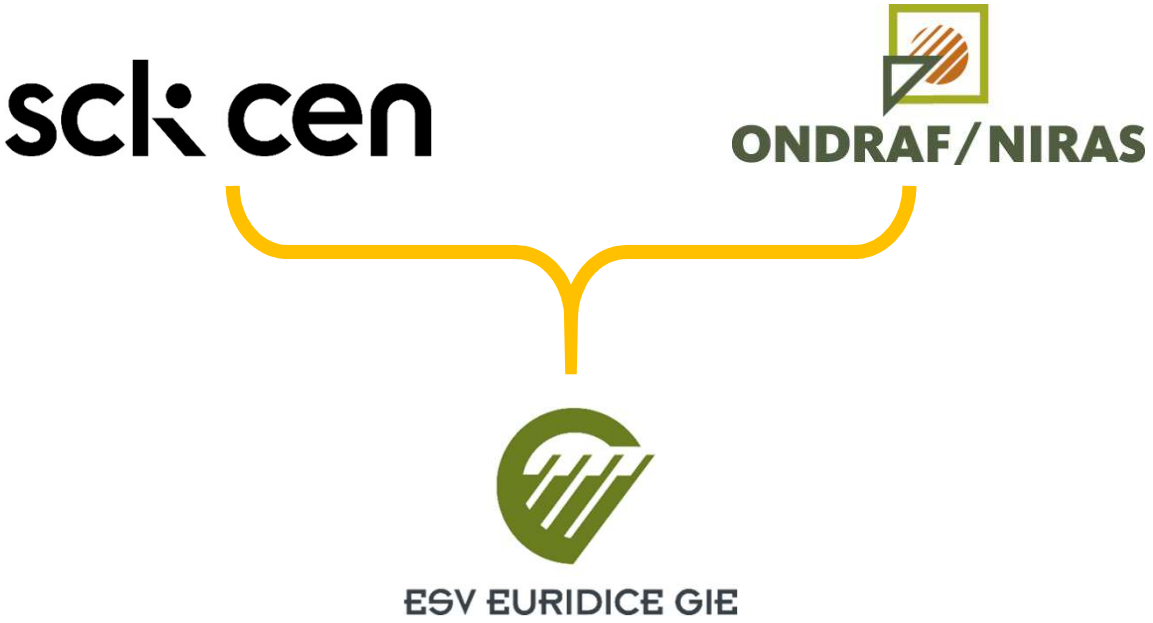
August 31, 2023 • Arnaud Dizier, Jan Verstricht, Temenuga Georgieva, Mieke De Craen, S. Levasseur (O/N) and ESV EURIDICE GIE Technical Team

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 847593.

ESV EURIDICE GIE

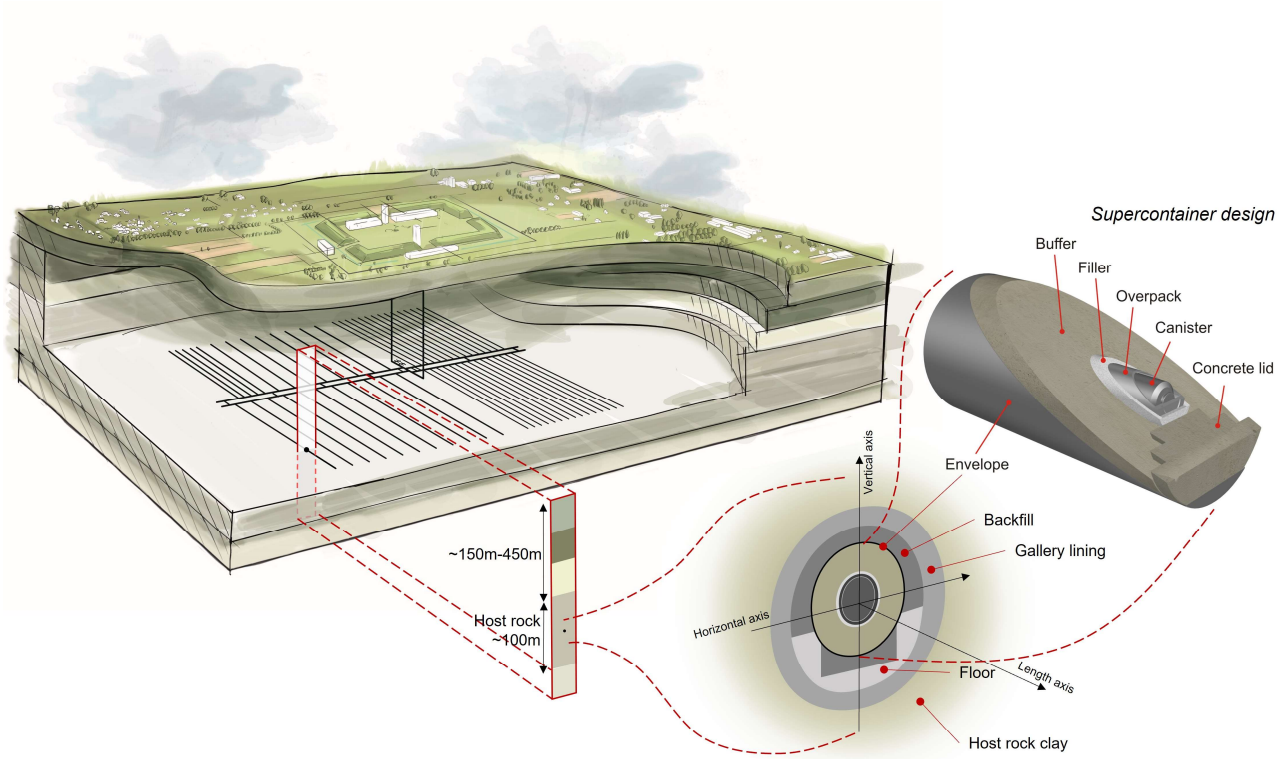
European Underground Research Infrastructure for Disposal of radioactive waste in Clay Environment

ESV EURIDICE GIE



GEOLOGOCAL DISPOSAL OF RADIOACTIVE WASTE IN BELGIUM

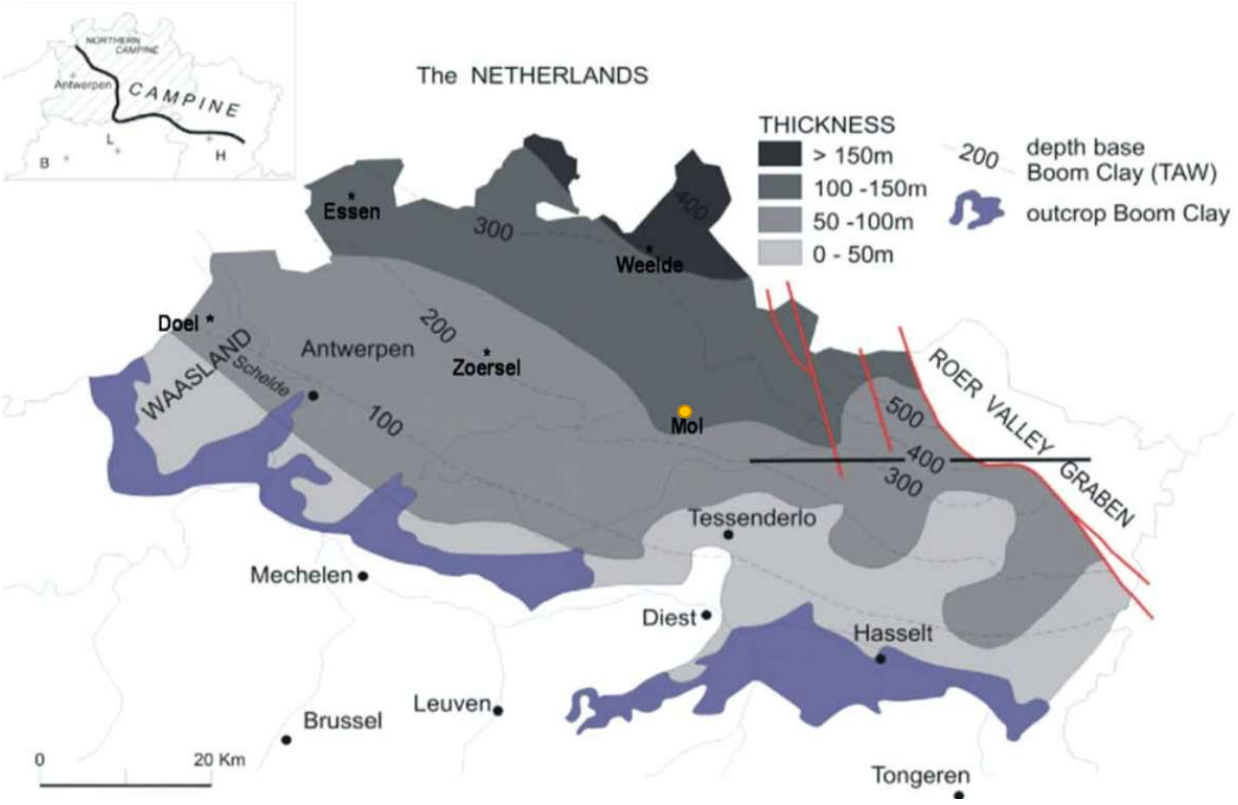
- Disposal in galleries located in low permeable geological layers (poorly indurated clays)
- Engineering Barrier System (EBS) for high level and long-lived radioactive wastes (Belgian concept)



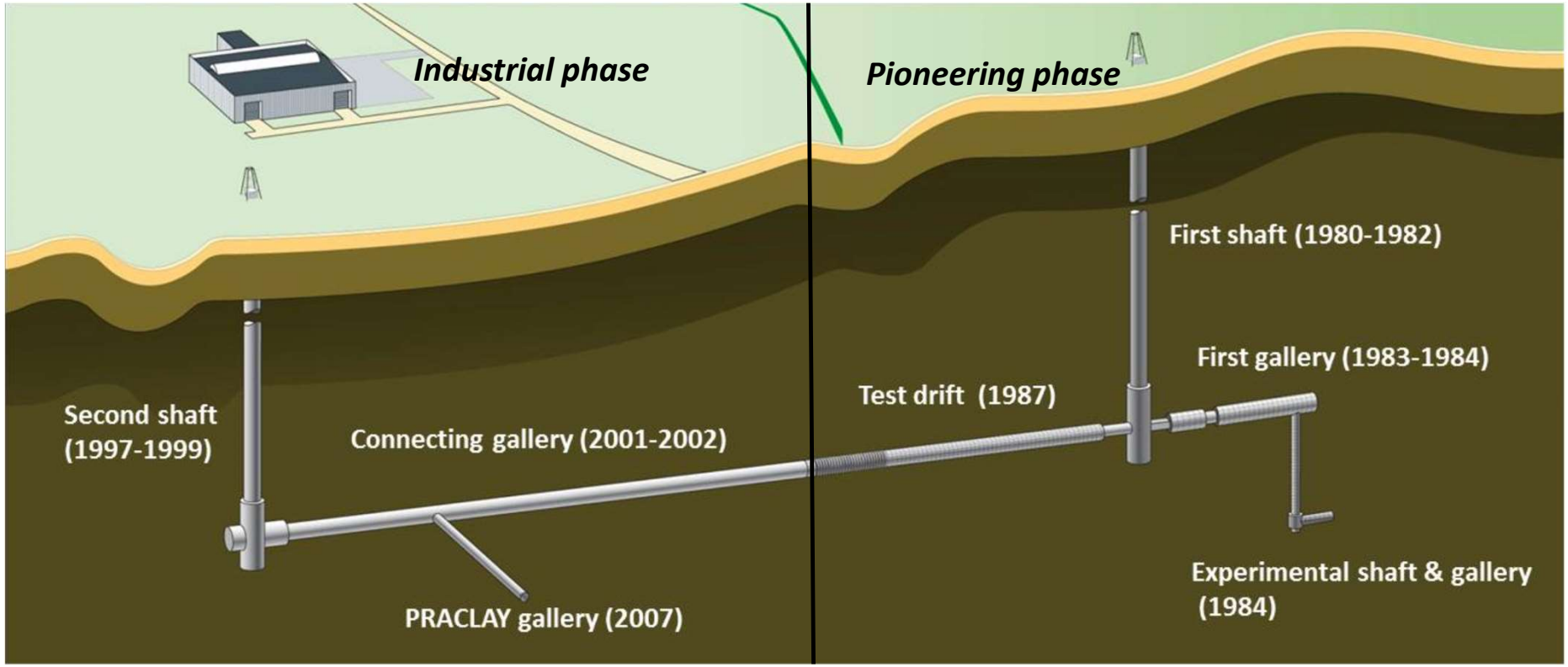
Vertical cross-section of the disposal gallery for C-waste

HADES URL IN POORLY INDURATED BOOM CLAY

- Thickness of ~ 100 m, depth 185 – 287 m
- HADES URL: depth 225 m



HADES – Underground Research Laboratory



HADES – Underground Research Laboratory

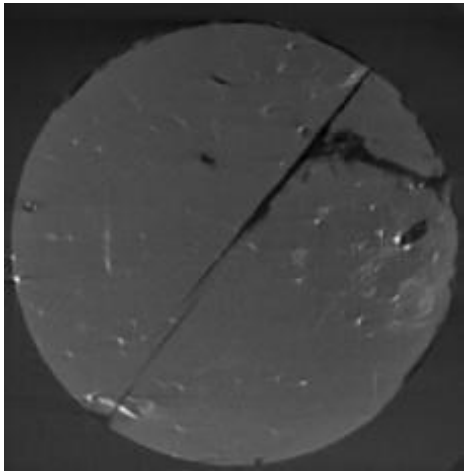
Industrial phase (after 2000)

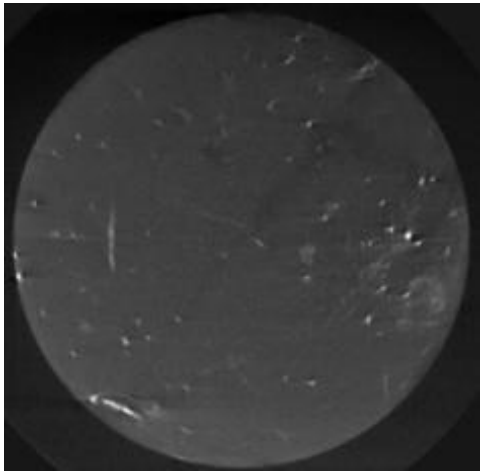
Pioneering phase (1980 – 1990)

BOOM CLAY: POTENTIAL HOST CLAY FORMATION ?

- Geology: low seismic activities, no volcanic activities, limited tectonic activities
- Plastic clay, self-sealing
- Good hydrogeological conditions
- Good geochemical conditions

→ limit and delay the migration of radionuclides





BOOM CLAY: PHYSICAL CHARACTERISATION

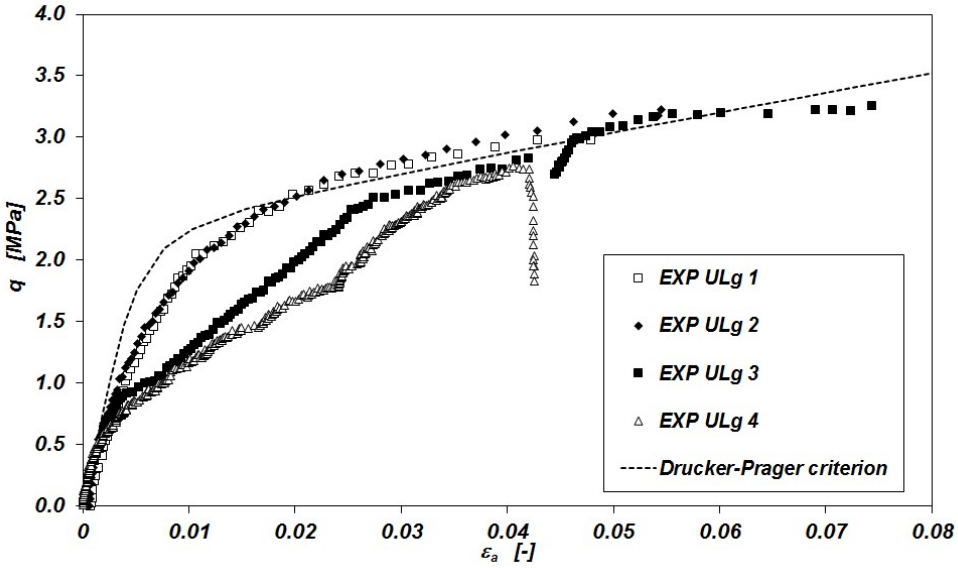
- Geotechnical properties:
  - Porosity : 0.39
  - Soil density : 1900 - 2100 [kg/m³]
  - Plastic limit : 13 – 26.5 %
  - Liquid limit : 55 - 80 %
  - Water content : 20 – 30 wt% (dry weight)

- Hydraulical characteristics:
  - Hydraulic conductivity K = 2 - 4.10^{-12} m/s

- Thermal characteristics:
  - Thermal conductivity λ = ±1.35 W.m^{-1}.K^{-1}

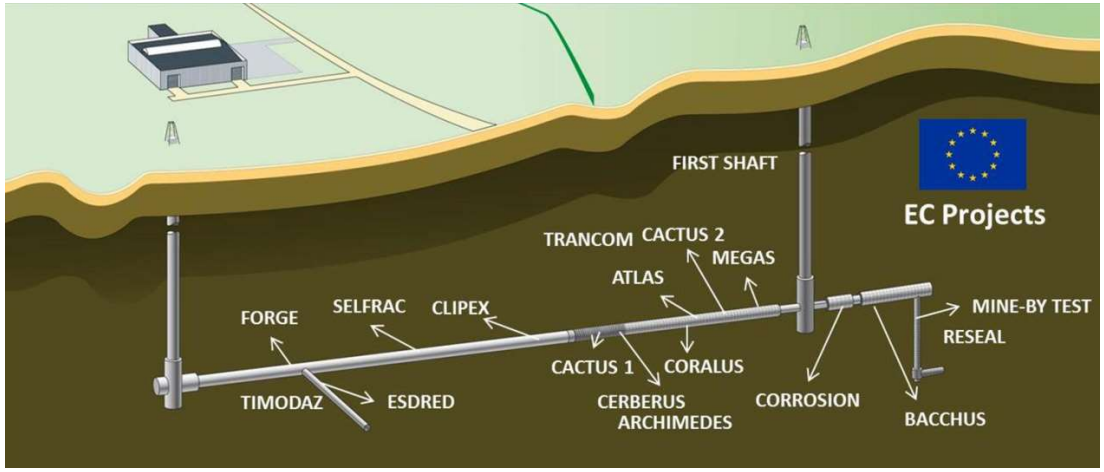
BOOM CLAY: PHYSICAL CHARACTERISATION

- Geotechnical characteristics (Bernier et al., 2007)
  - Poisson's coefficient ν' : 0.125
  - Young Modulus E': 300 MPa
  - Cohesion c': 300 kPa
  - Friction angle ϕ': 18°
  - Dilatancy angle ψ': 0° - 10°



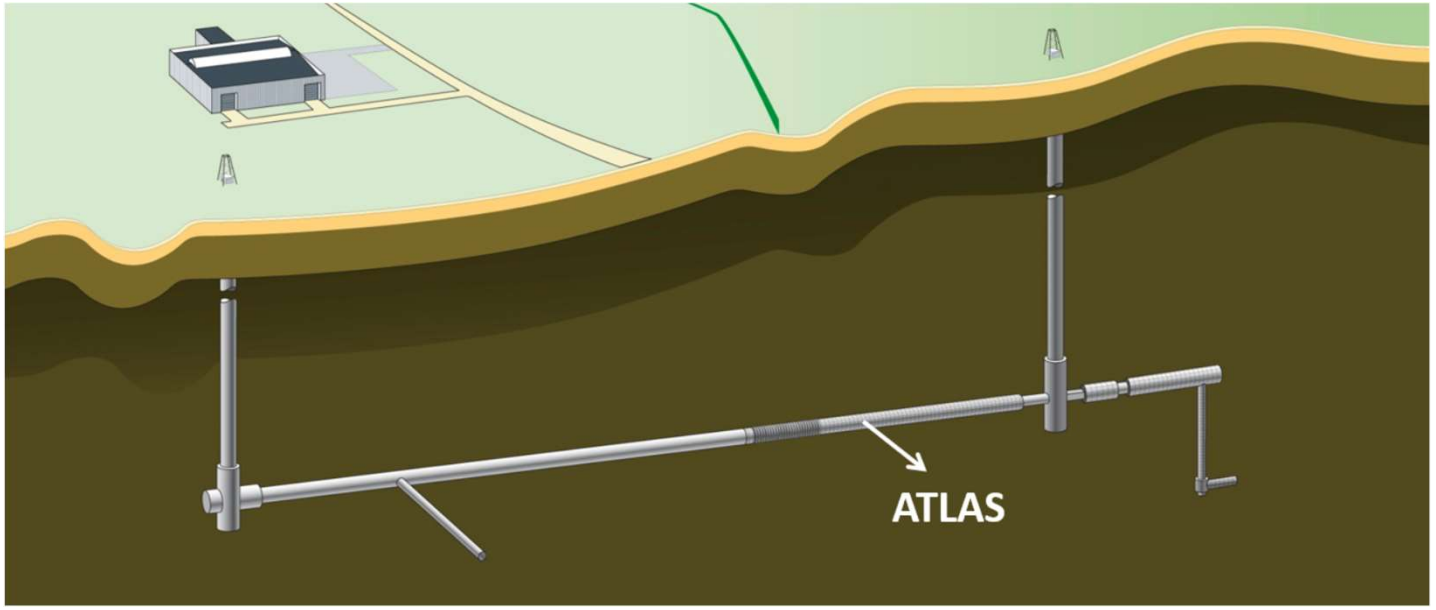
LONG HISTORY OF IN SITU TEMPERATURE TESTING

- First test aiming at simulating a vitrified high level waste canister in a clay quarry in Terhagen before 1980
- In the URL:
  - BACCHUS I, II (1988 - 1995)
  - CERBERUS (1985 - 1999)
  - CACTUS I, II (1990 - 1994)
  - ATLAS I, II, III, IV (1992 -…)
  - PRACLAY (2014-...)

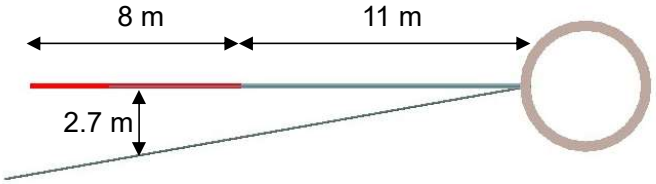


THM EXPERIMENTS IN HADES – ATLAS (1992 - …)

- Small scale heater tests ATLAS I-II, III & IV (*Admissible Thermal Loading for Argillaceous Storage*)
  - Assess/ confirm the thermal properties of Boom Clay
  - T→HM coupling in Boom Clay

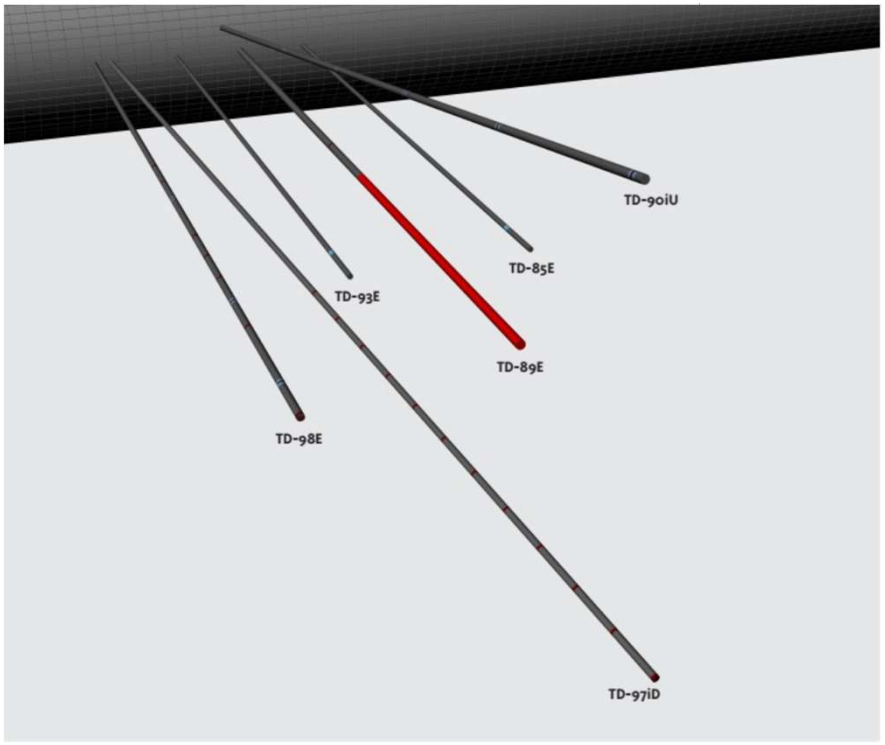


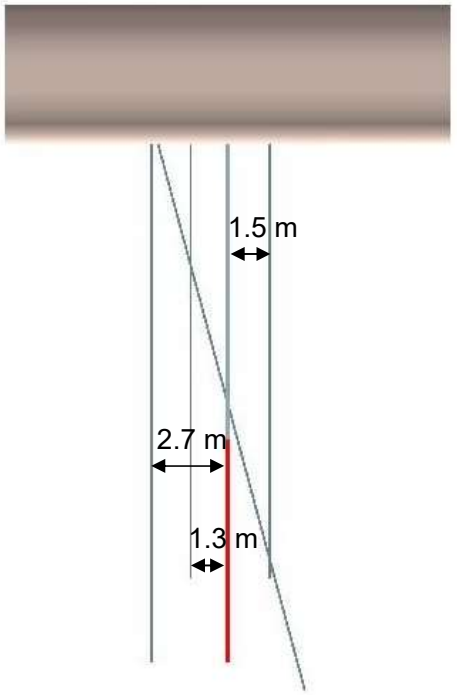
THM EXPERIMENTS IN HADES – ATLAS (1992 - …)



Test drift
Heater
Observation boreholes

Illustration ATLAS III experiment





THM EXPERIMENTS IN HADES – ATLAS (1992 - …)

- ATLAS instrumentation :
  - Kulite pressure sensors on the heating probe
  - Piezometer filter
  - Flat-jacks and biaxial stressmeter

Central borehole with the heating probe

Illustration of a piezometer filter with twin tube connection

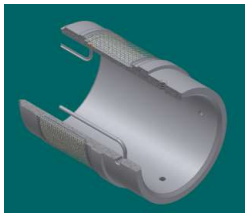
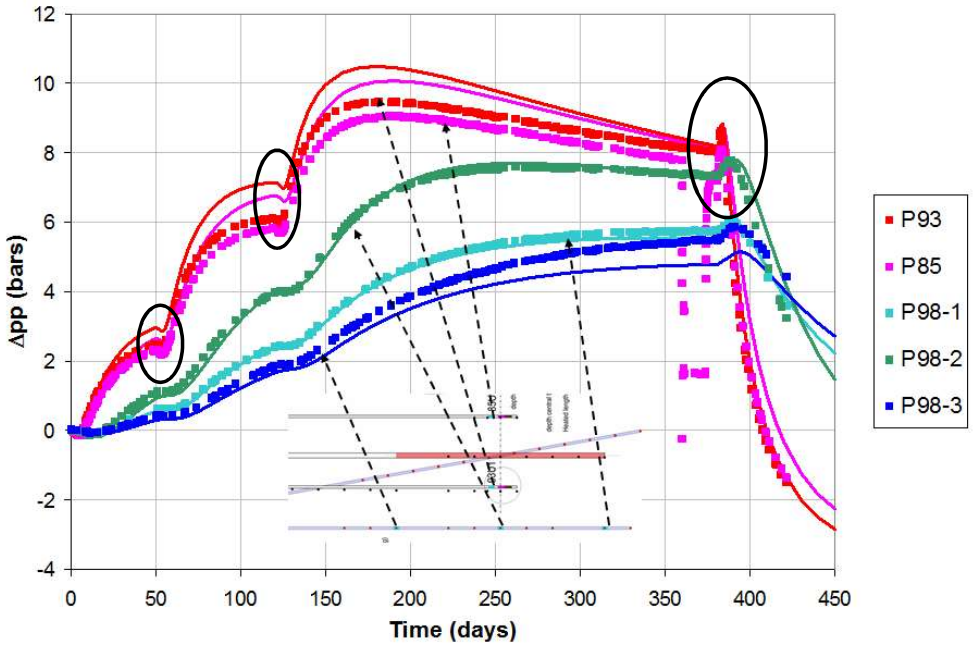
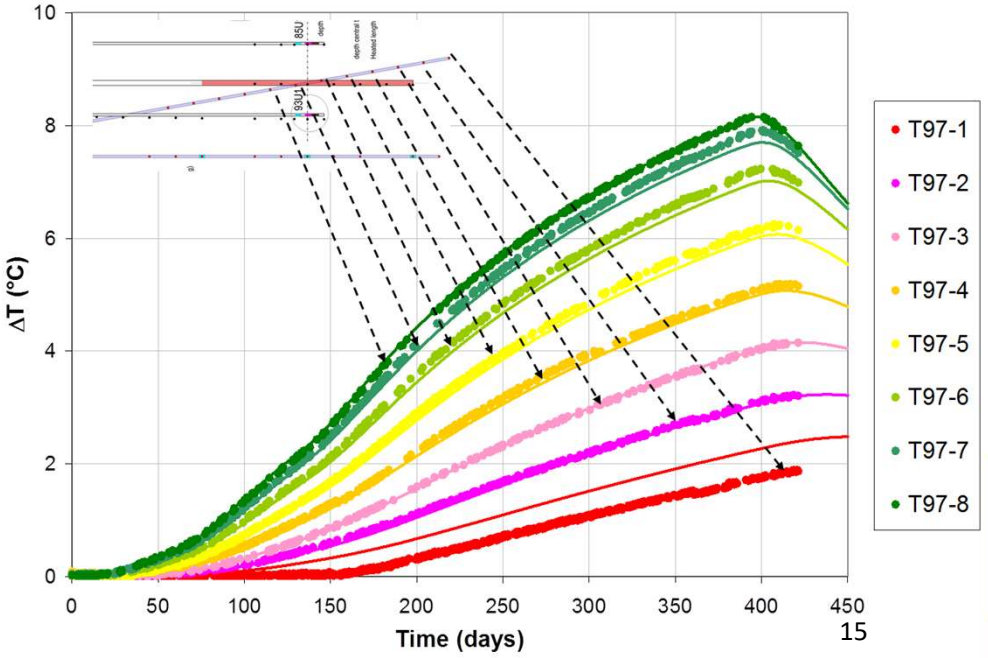


Illustration of an instrumented casing

THM EXPERIMENTS IN HADES – ATLAS III (2007)

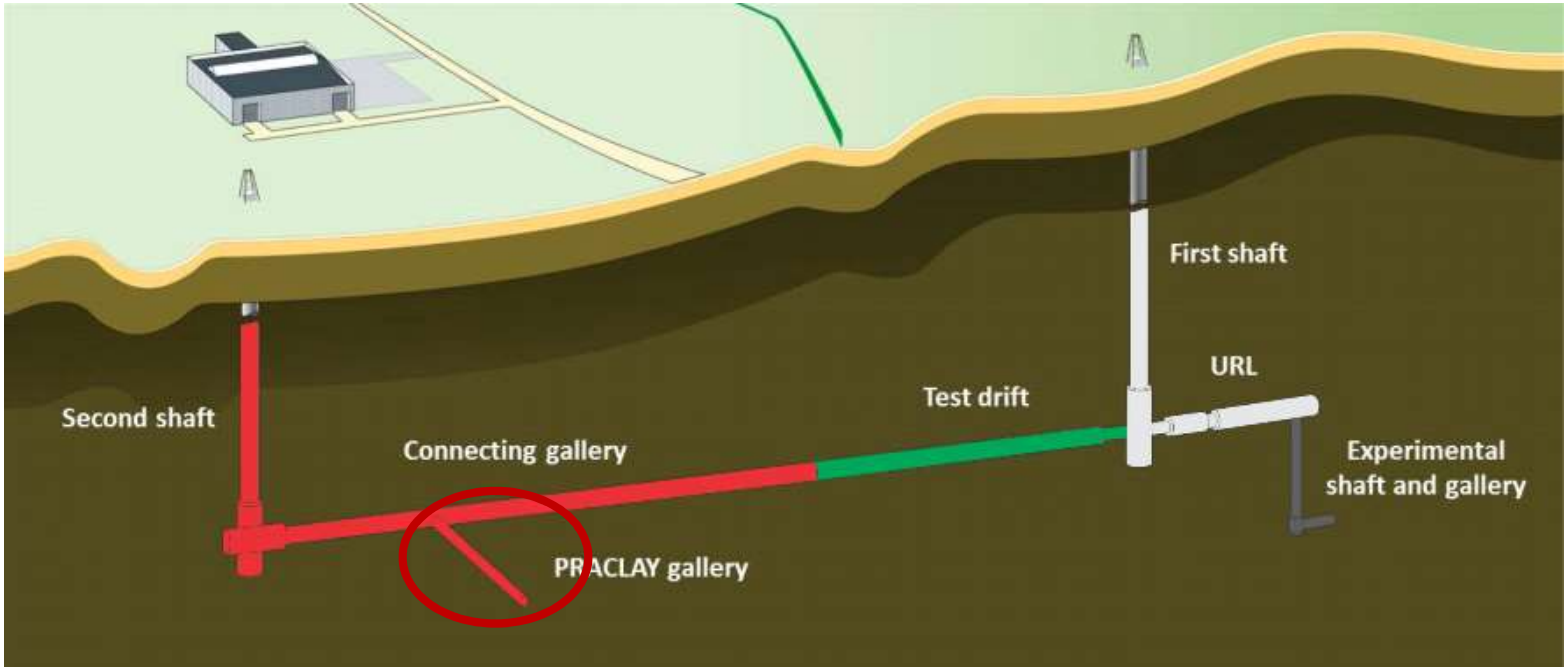
- ATLAS III: Temperature and pore water pressure evolution (exp. + num. results)
  - Anisotropic thermo-hydro-poro-elastic model: transverse isotropic elasticity
  - Heat transport (conduction)
  - Transverse anisotropy of intrinsic permeability $K_h \approx 2 \times K_v$





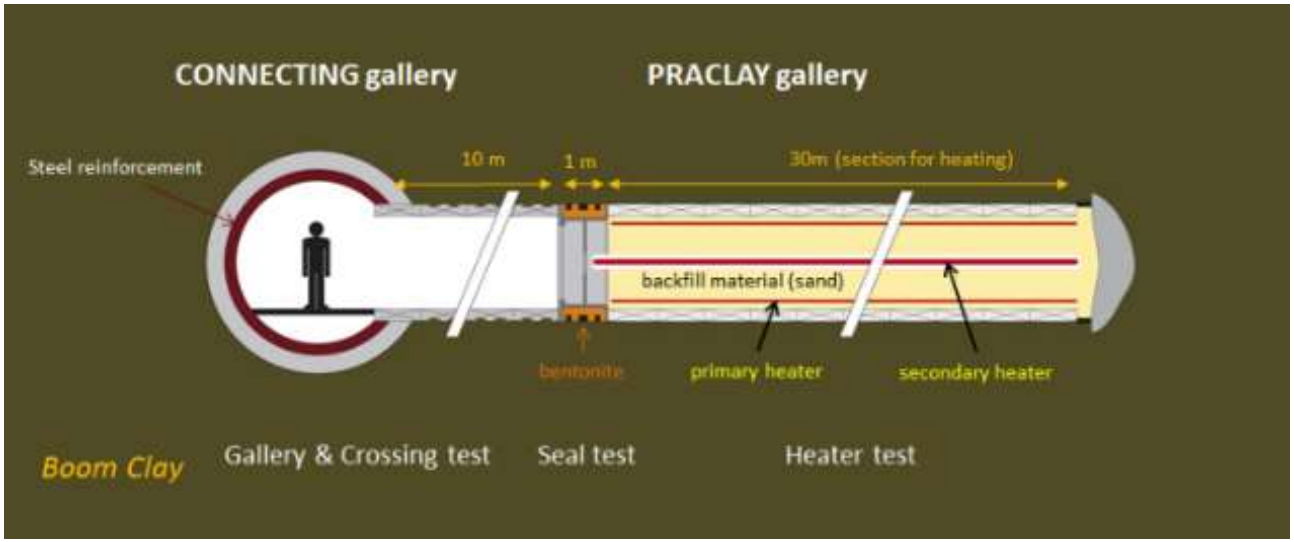
THE LARGE-SCALE PRACLAY HEATER TEST

- Demonstrating the feasibility of geological disposal of high-level radioactive waste in clay formation

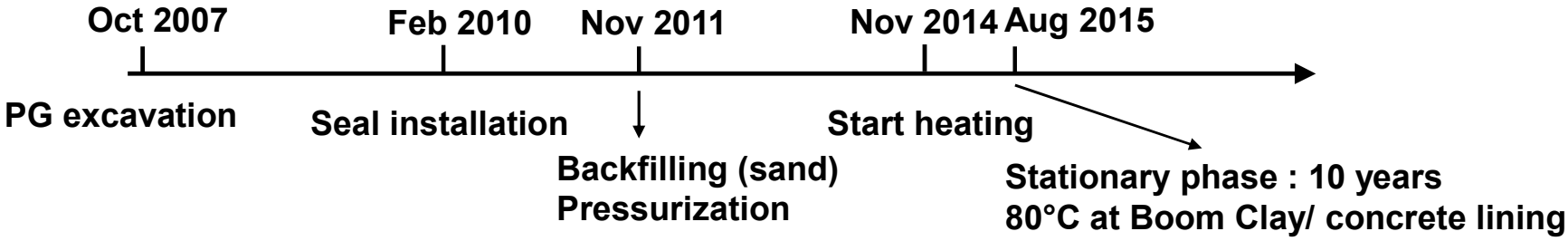


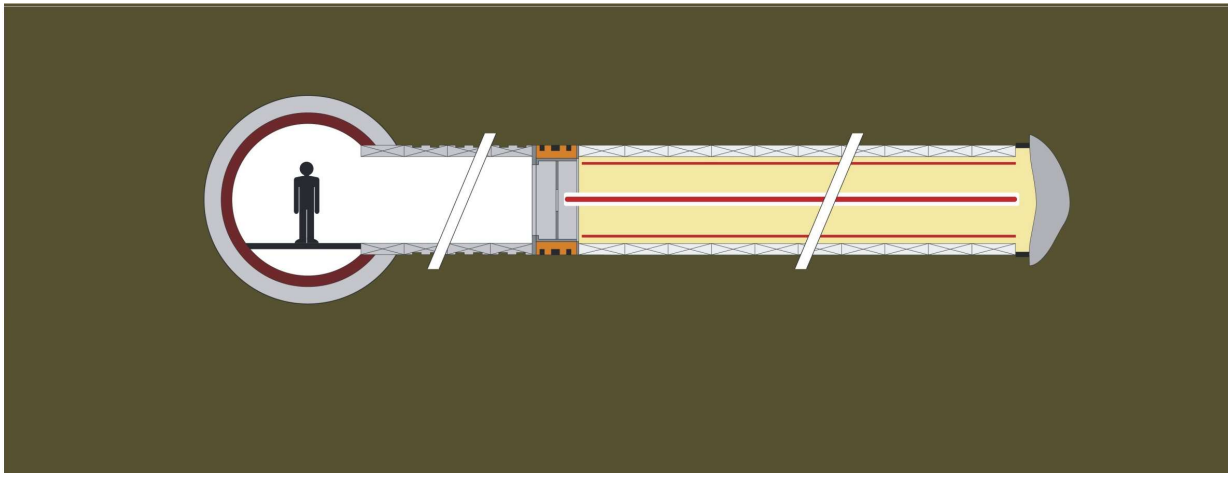
THE PRACLAY EXPERIMENT – OBJECTIVES AND DESIGN

- Feasibility of construction gallery and crossing
- Seal test ➔ Design and installation of the hydraulic seal
- Large scale-heater test ➔ Simulate the heat-emitting high-level radioactive waste



THE PRACLAY EXPERIMENT - PHASES



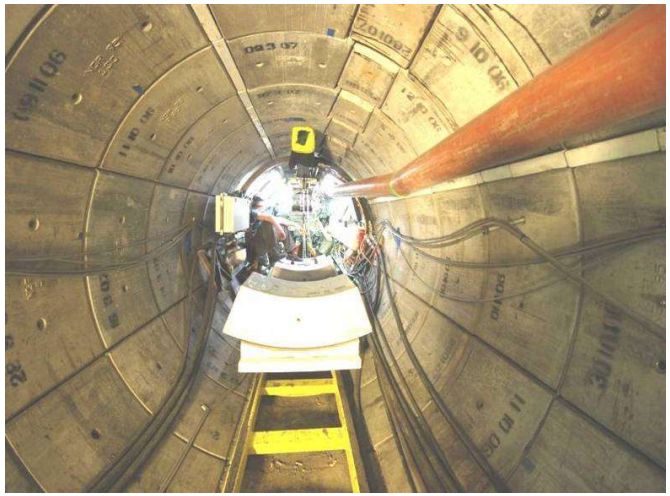


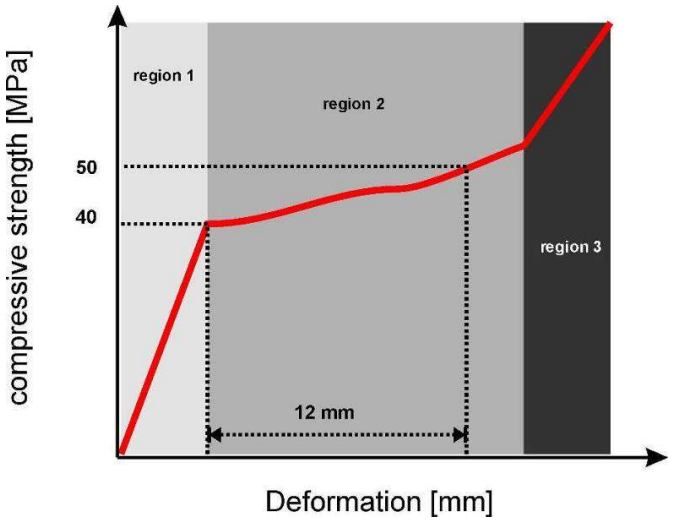
PRACLAY GALLERY EXCAVATION (2007)

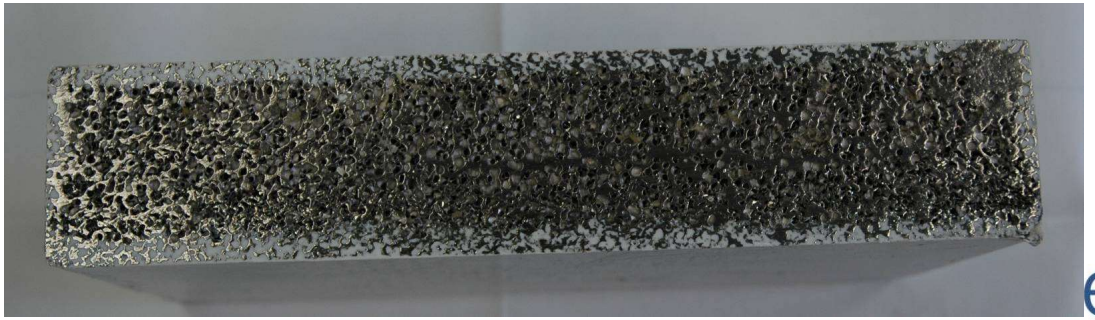
- Designed for geotechnical and thermal loads
- Segmental tunnel lining
- Compressive materials

PRACLAY GALLERY EXCAVATION (2007)

- Installation of foam panels

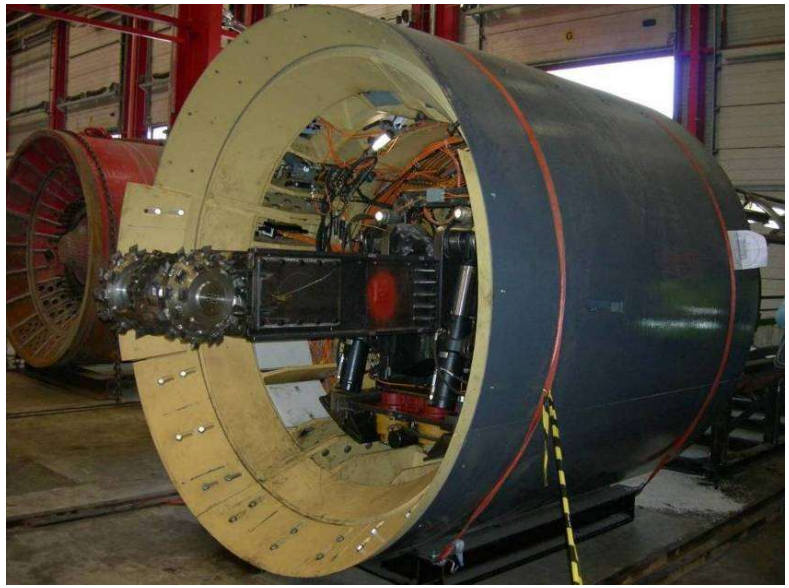


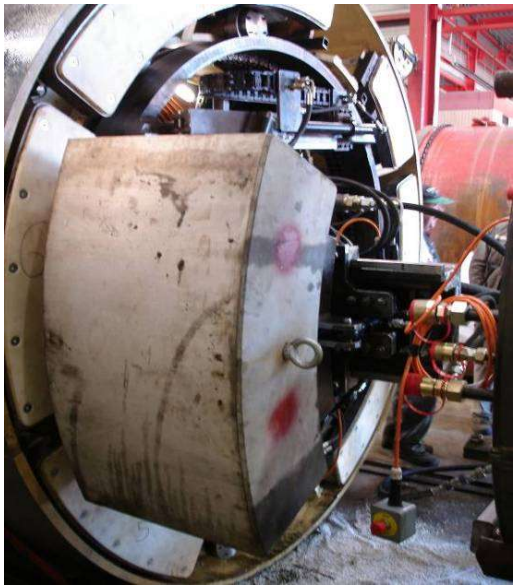




PRACLAY GALLERY EXCAVATION (2007)

- Open-face tunnel boring machine with a roadheader
- Segment erector for the placement of the segment blocks



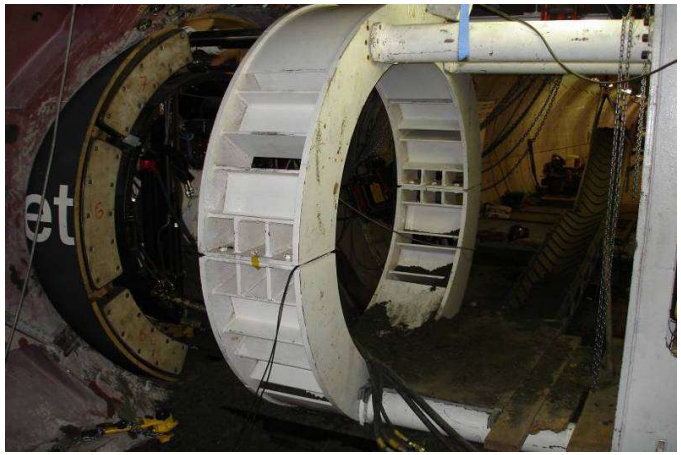


PRACLAY GALLERY EXCAVATION (2007)

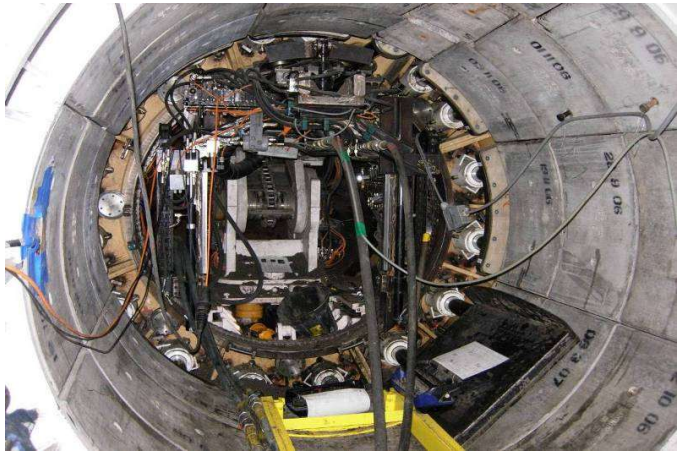
- Crossing with the installation of a steel reinforcement ring

PRACLAY GALLERY EXCAVATION (2007)

PRACLAY GALLERY EXCAVATION (2007)

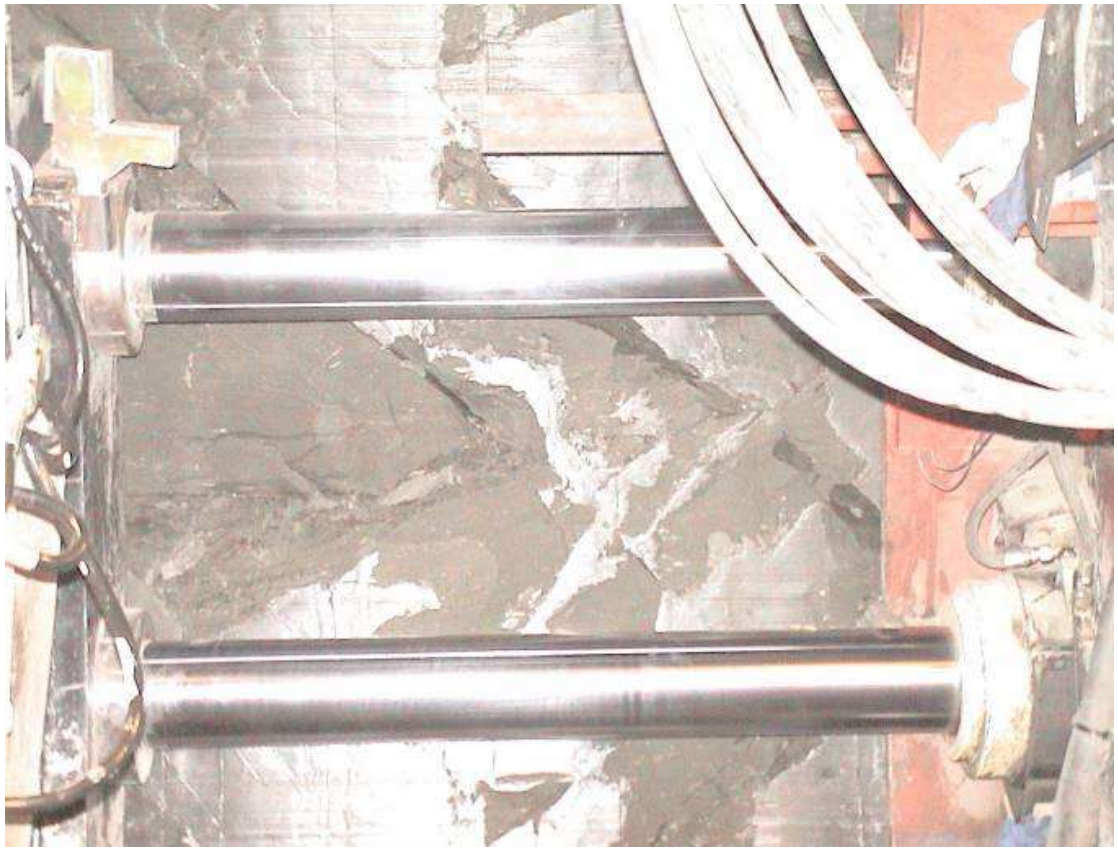


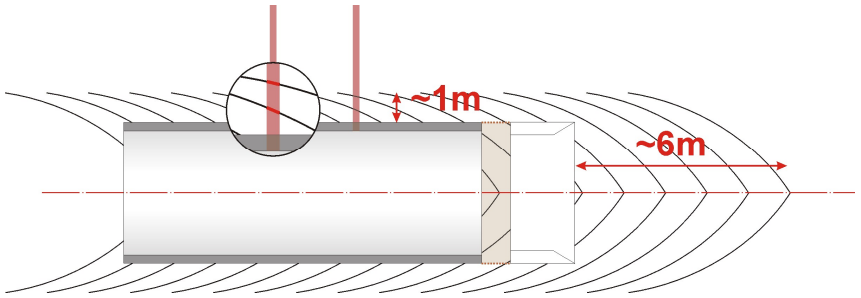
PRACLAY GALLERY EXCAVATION (2007)



PRACLAY GALLERY EXCAVATION (2007)

Excavation induced fractures: gallery side-wall





Observations during the excavation of the Connecting gallery

PRACLAY GALLERY EXCAVATION (2007)

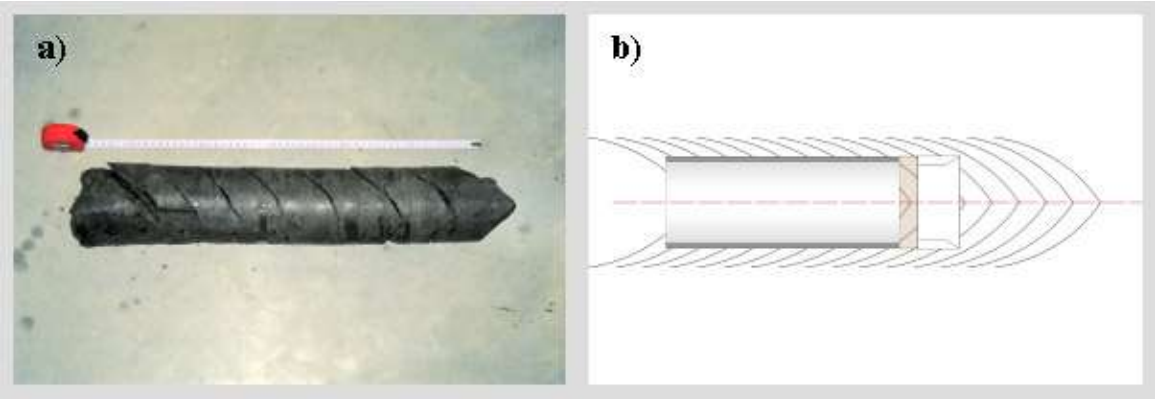
- Installation of a temporary lining for the hydraulic seal

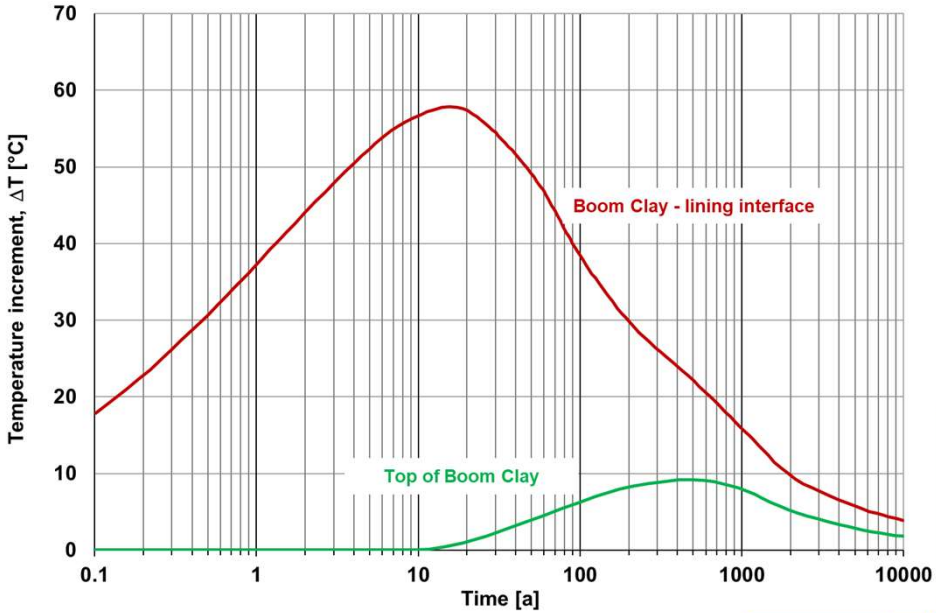
PRACLAY GALLERY – HYDRAULIC SEAL INSTALLATION

PRACLAY GALLERY – HEATER SYSTEM, BACKFILLING

THE PRACLAY EXPERIMENT – OBJECTIVES

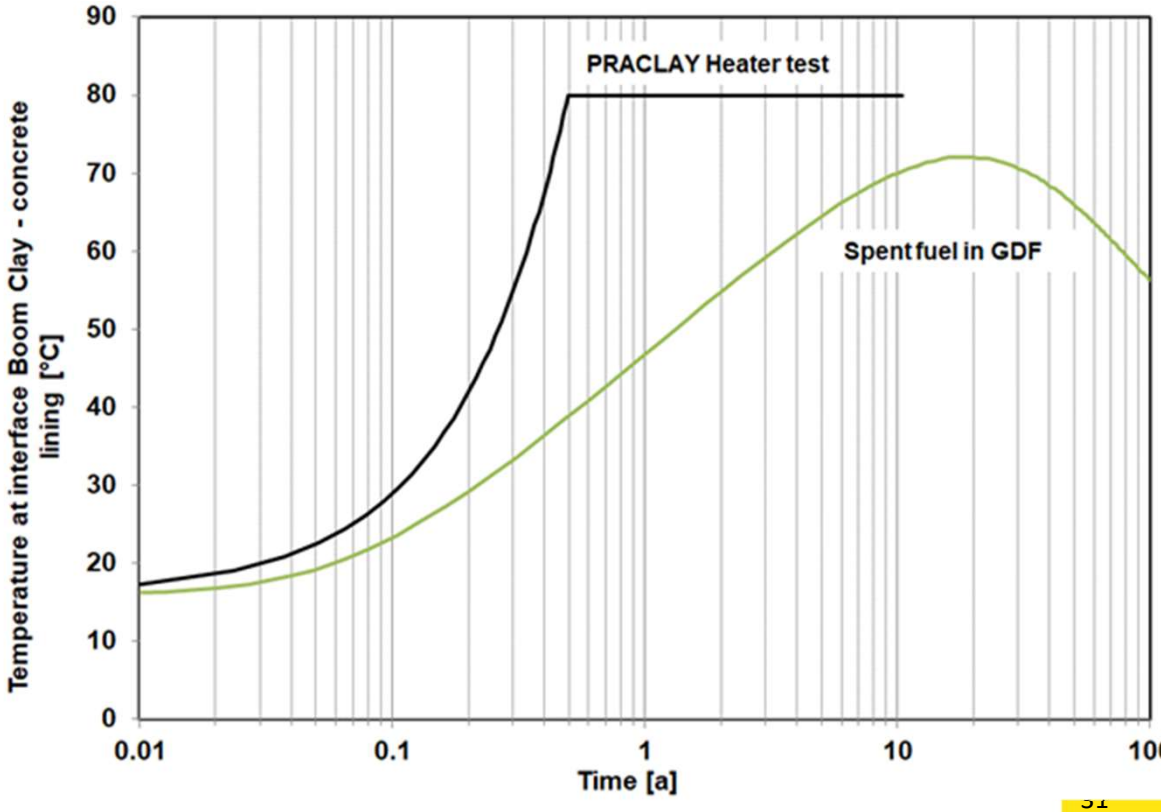
- Boom Clay retains its ability to contain radioactive waste when heated?
- Study combined disturbances :
  - hydro-mechanical caused by gallery construction
  - large-scale thermal load on the Boom Clay due to heat-emitting high-level waste





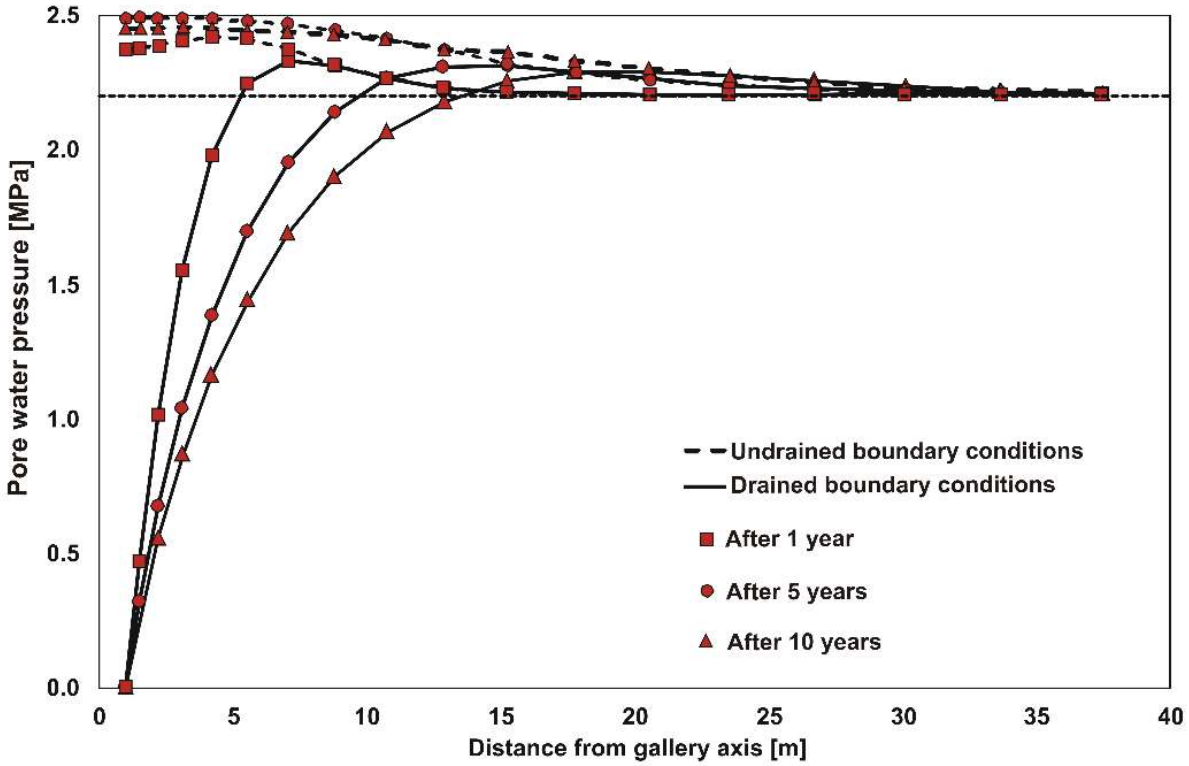
THE PRACLAY EXPERIMENT – DESIGN – THERMAL CONDITIONS

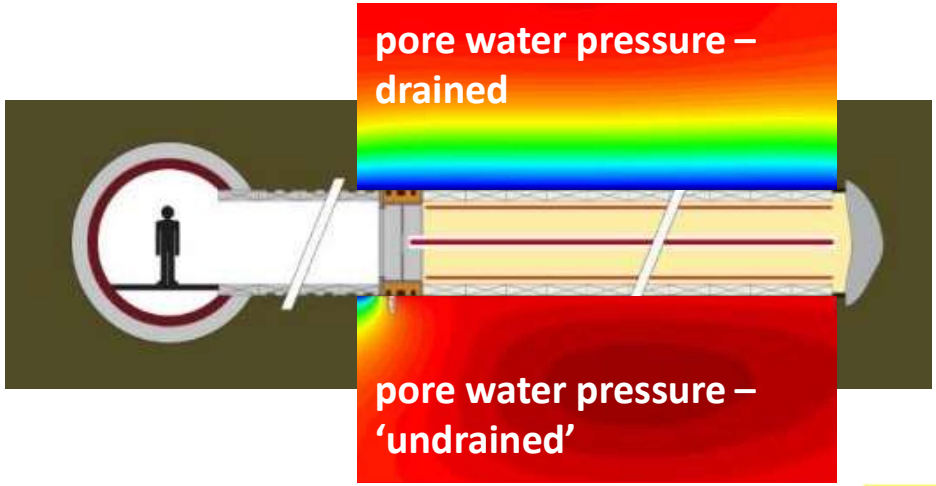
- Temperature at gallery extrados = 80°C
- Faster temperature increase



THE PRACLAY EXPERIMENT – DESIGN – HYDRAULIC CONDITIONS

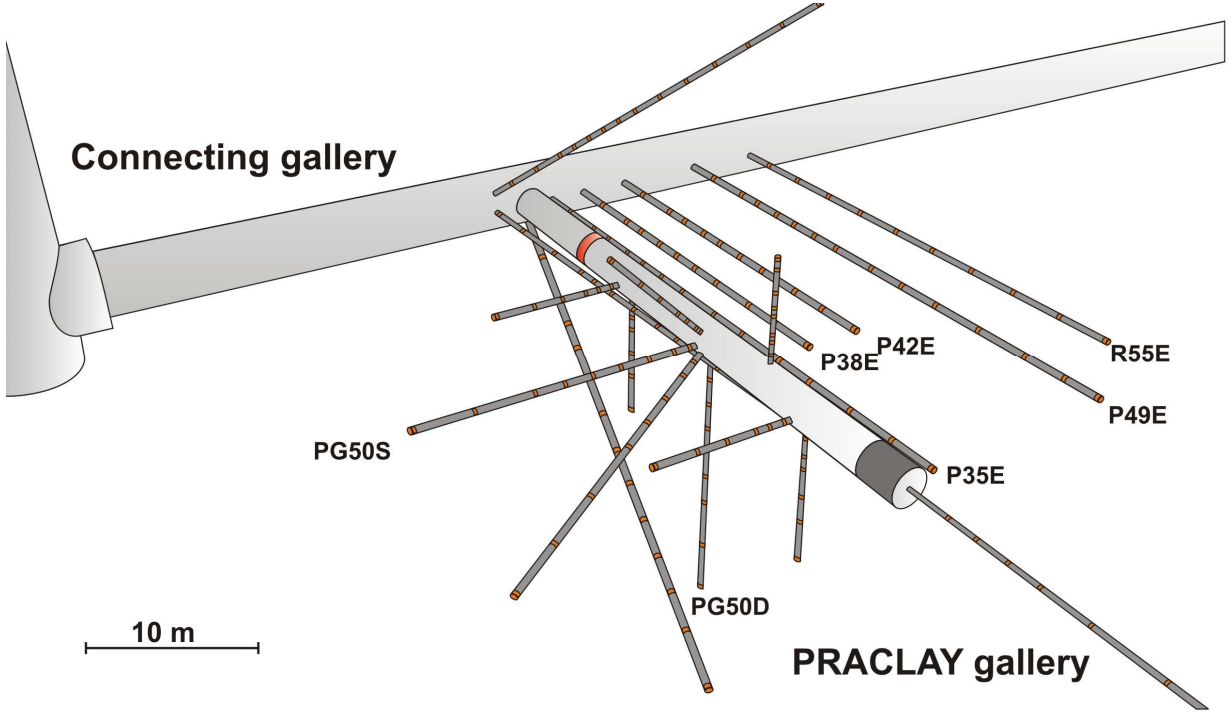
- More penalizing conditions ➔ as much undrained as possible





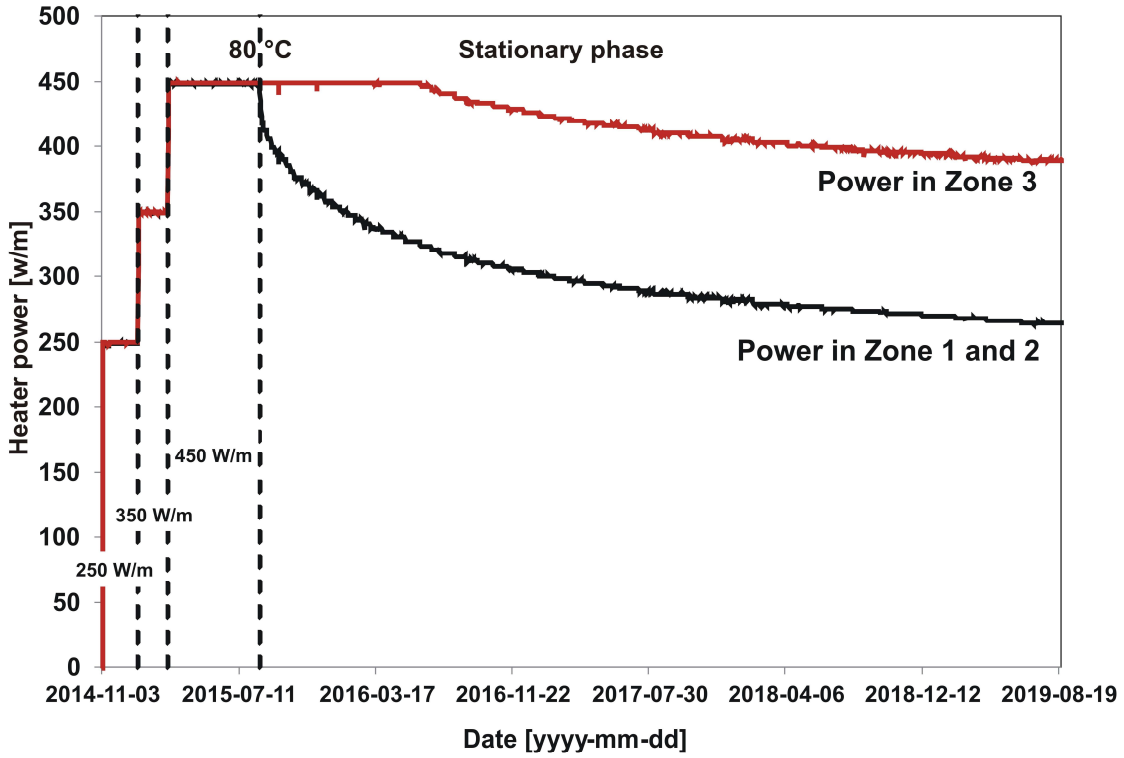
THE PRACLAY EXPERIMENT - MONITORING

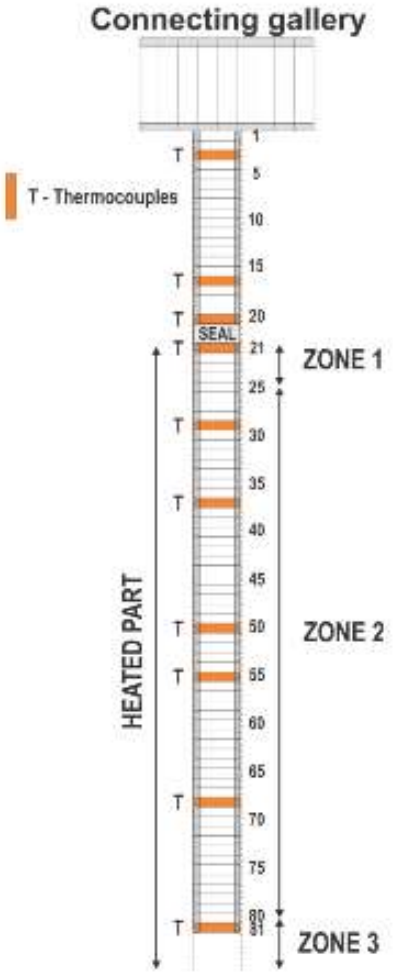
- Number of sensors (1100): temperature, pore water pressure, stresses, displacements



THE PRACLAY EXPERIMENT – THERMAL LOADING PLAN

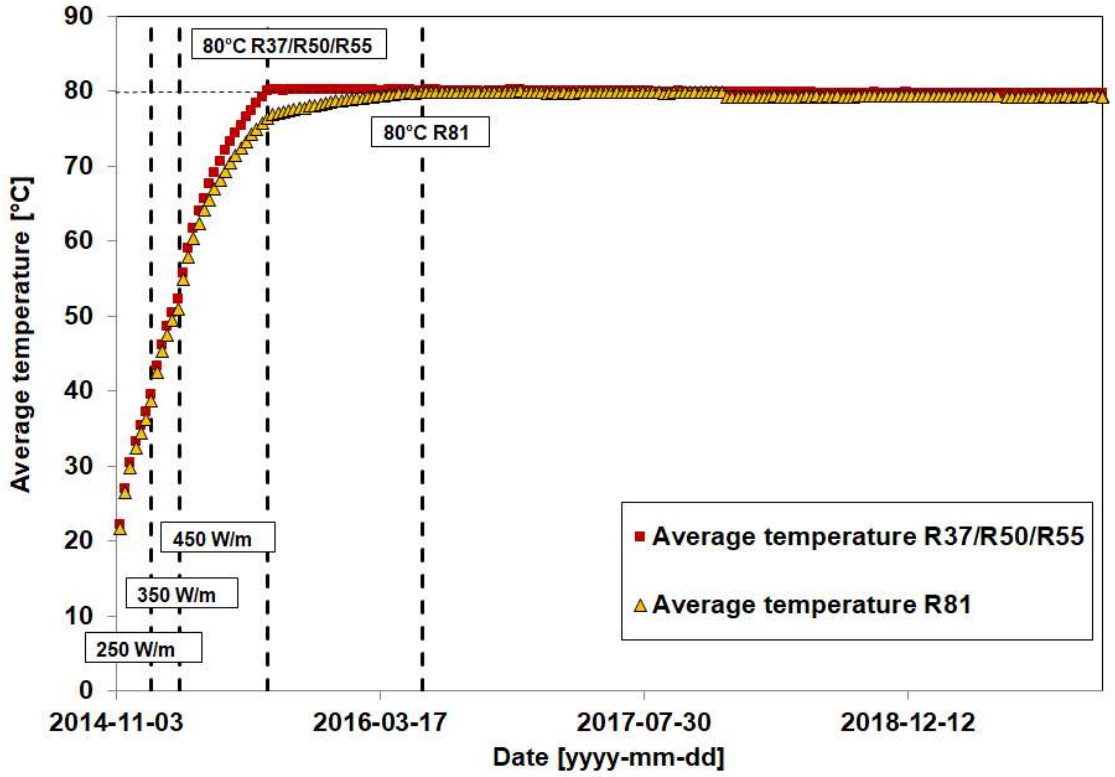
- 3 heating steps to reach 80°C at Boom Clay/ concrete lining interface (250 W/m representative from geological disposal facility)

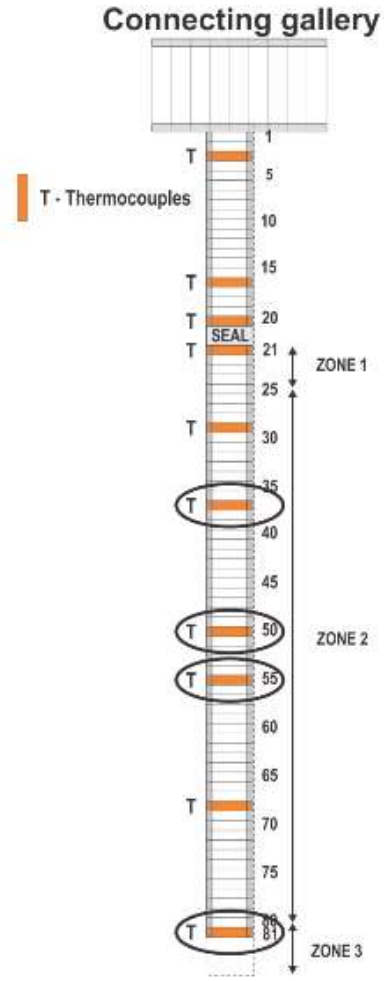




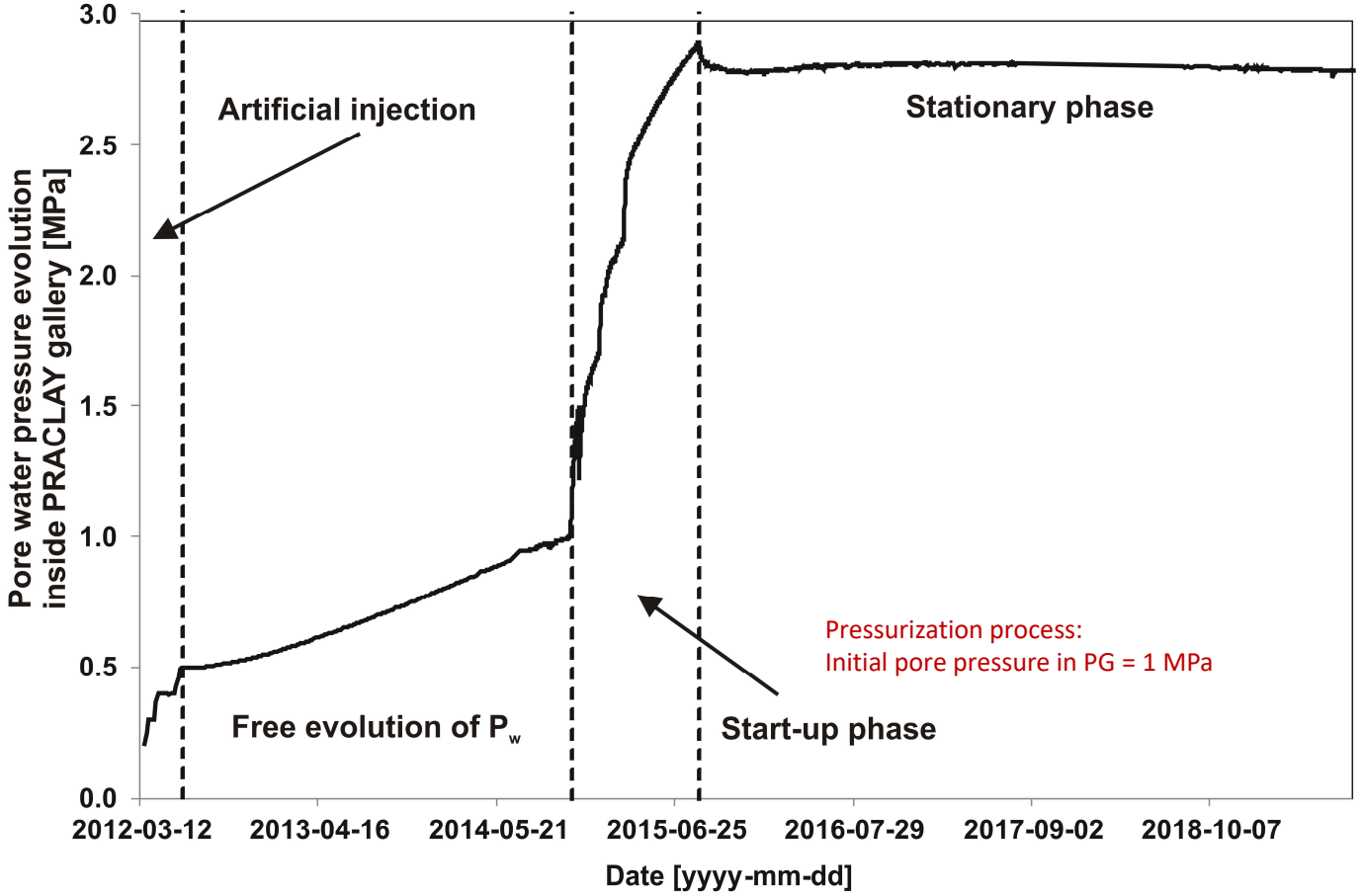
THE PRACLAY EXPERIMENT - THERMAL LOADING PLAN

- Increase of the temperature in the concrete lining
- Current situation: 80°C at Boom Clay/ lining interface



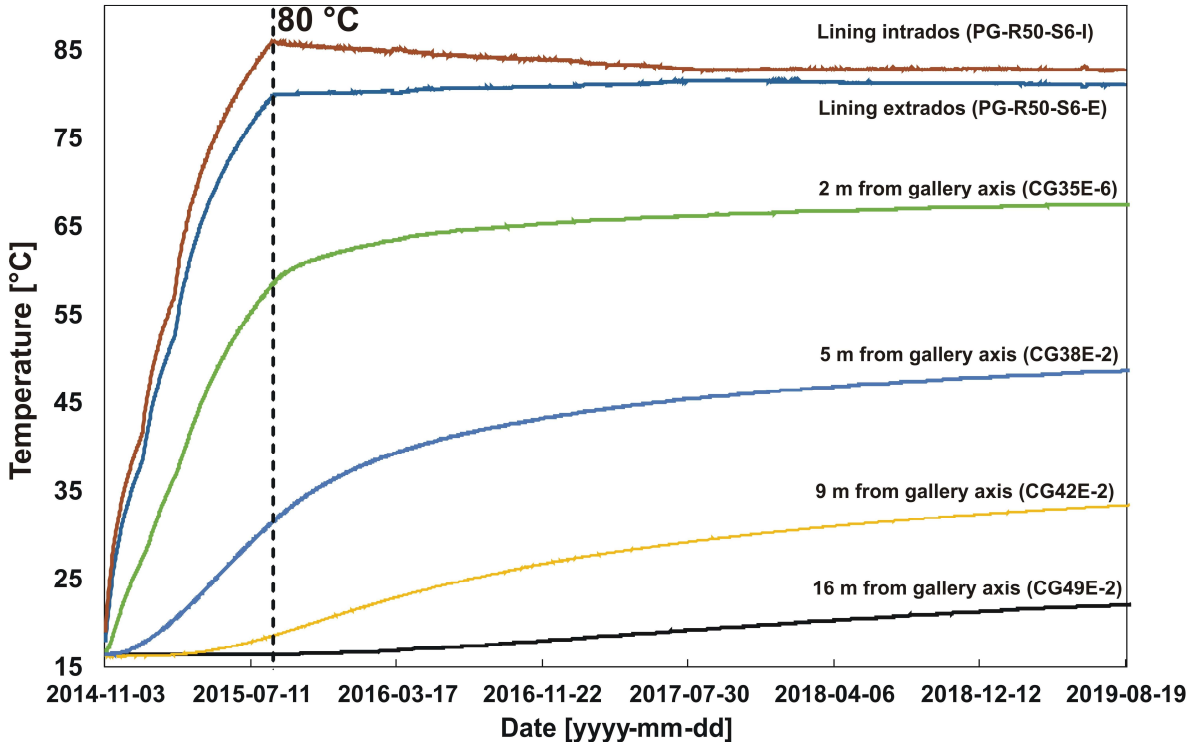


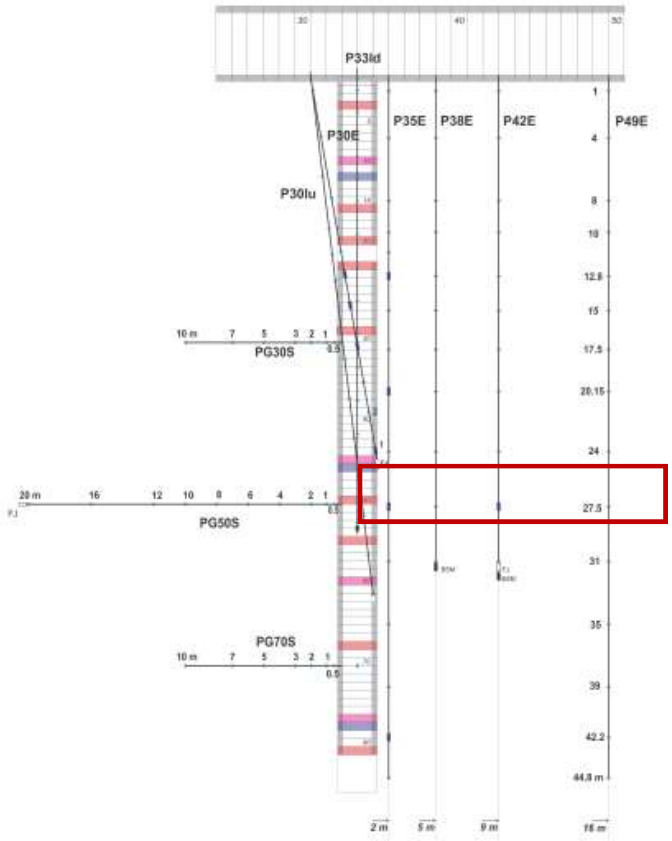
THE PRACLAY EXPERIMENT – PORE PRESSURE INSIDE THE GALLERY



THE PRACLAY EXPERIMENT – TEMPERATURE OBSERVATIONS

- Temperature evolution

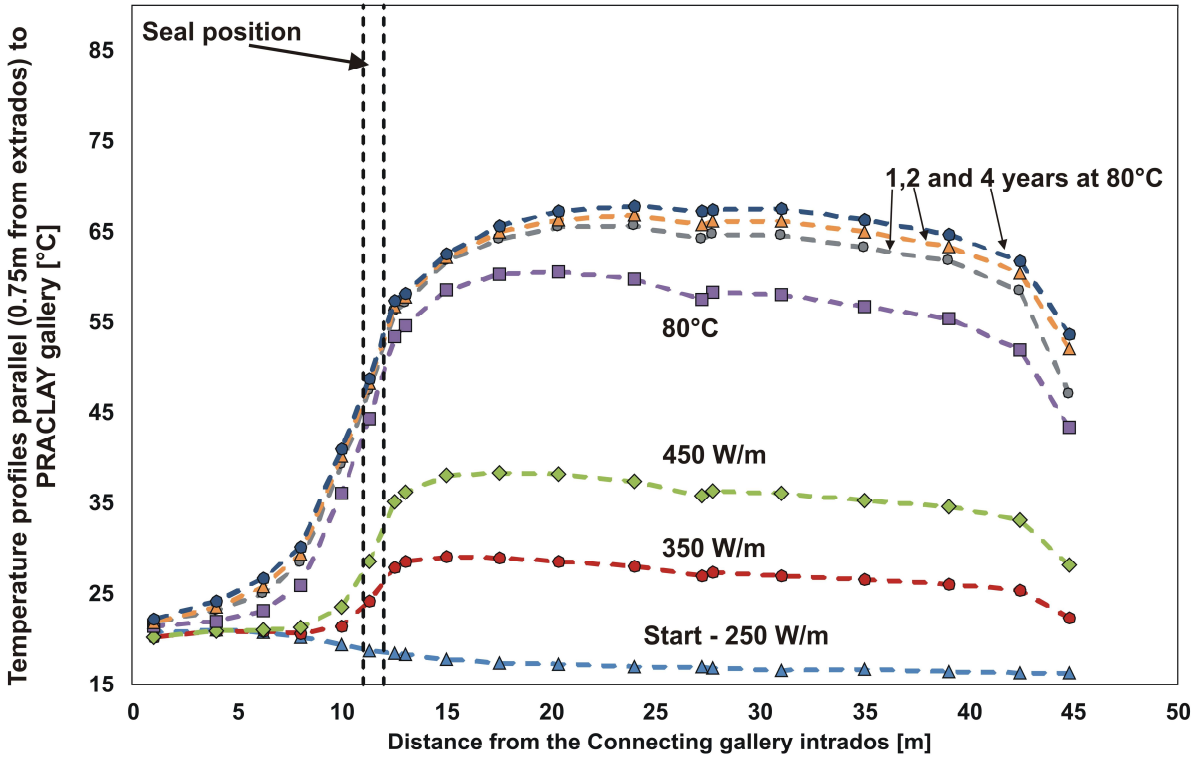


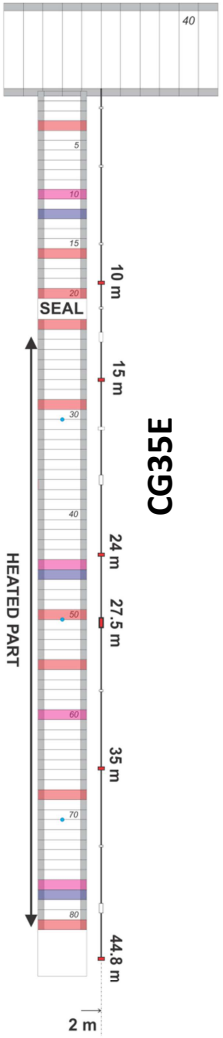


Extension of the thermally affected zone : > 16 m

THE PRACLAY EXPERIMENT – TEMPERATURE OBSERVATIONS

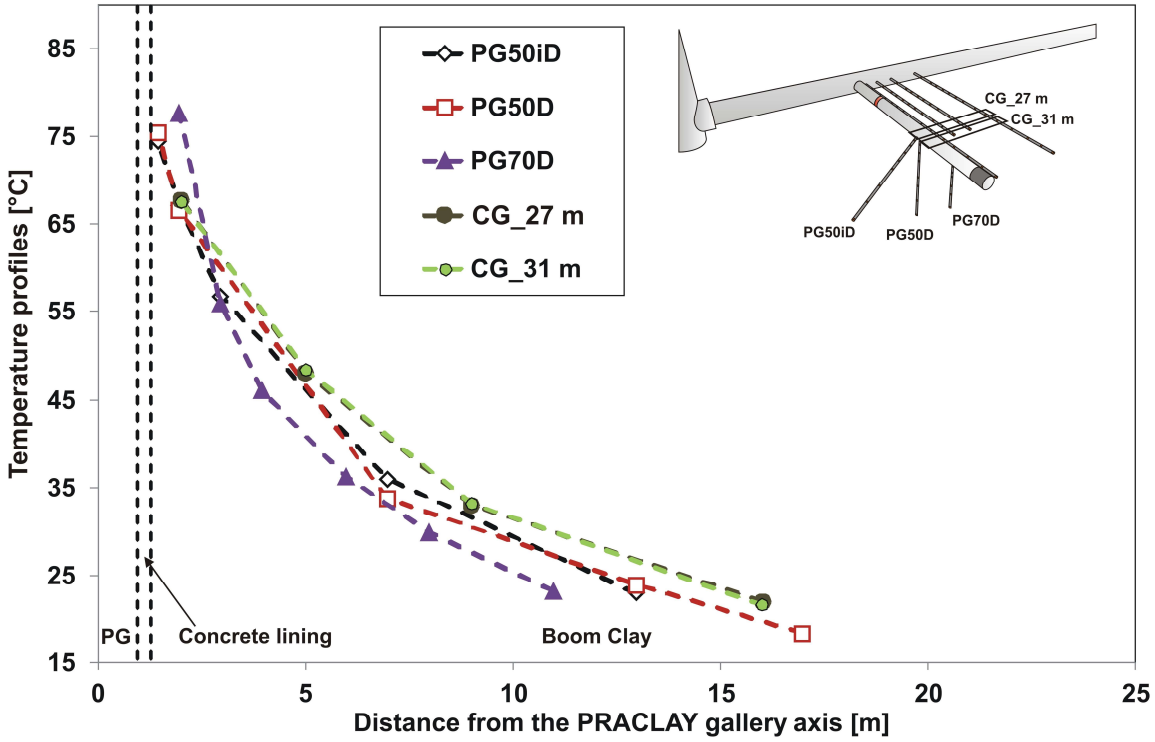
- **Profiles // to PRACLAY gallery in CG35E**





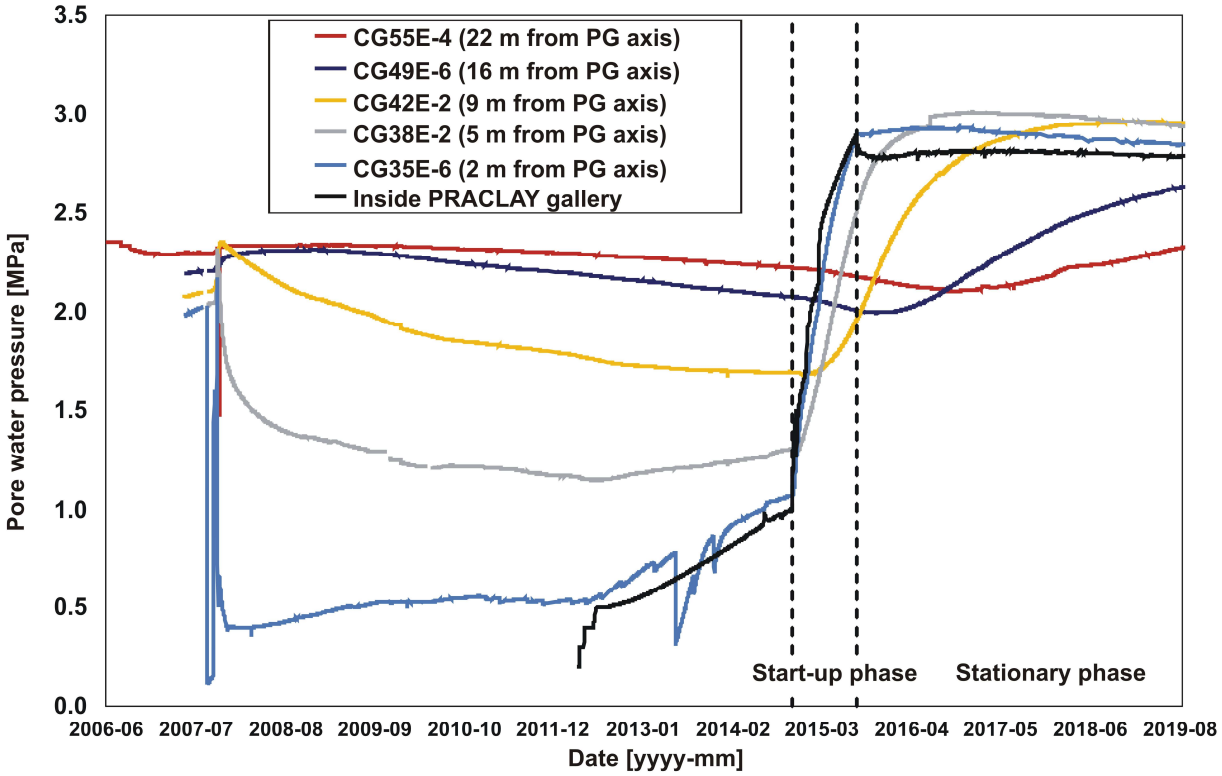
THE PRACLAY EXPERIMENT – TEMPERATURE OBSERVATIONS

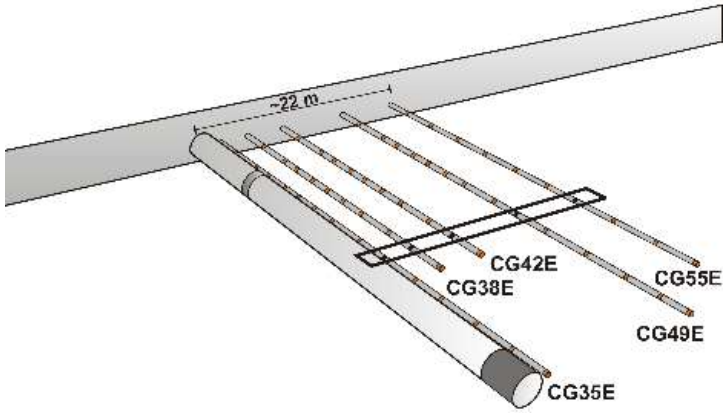
- Temperature profiles in different directions



THE PRACLAY EXPERIMENT - PORE WATER PRESSURE OBSERVATIONS

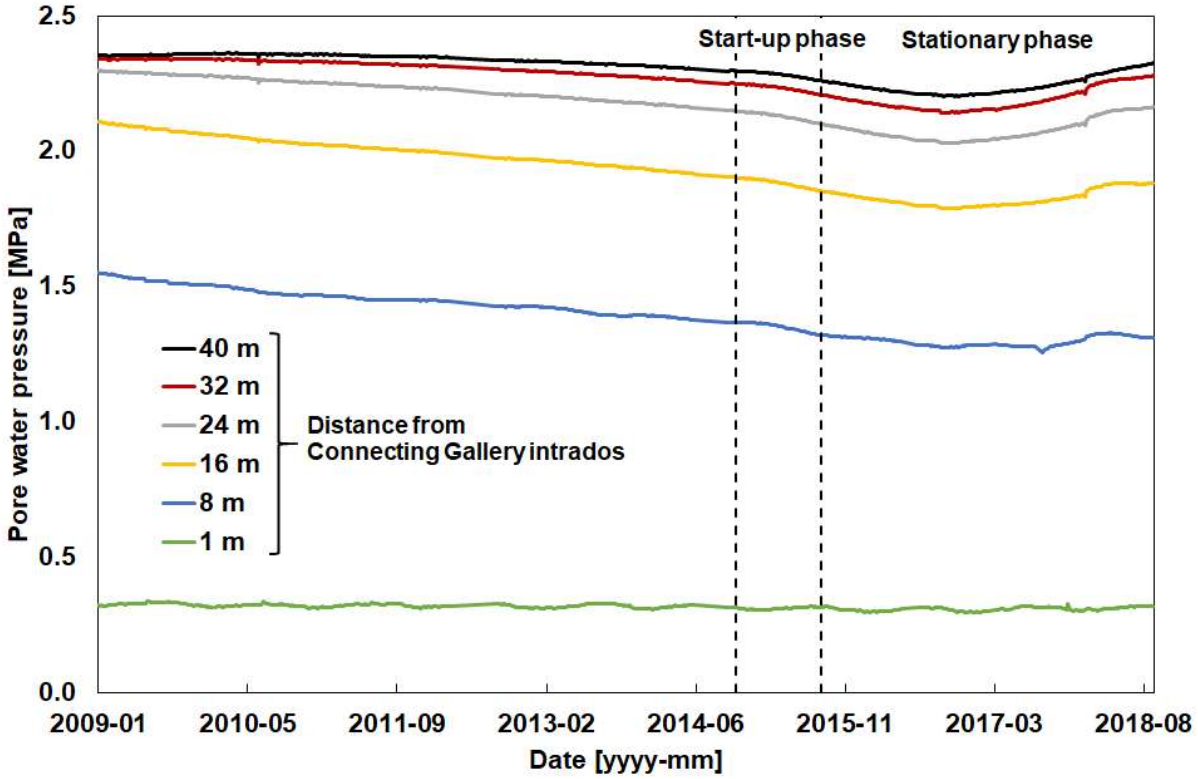
- Pore pressure evolution

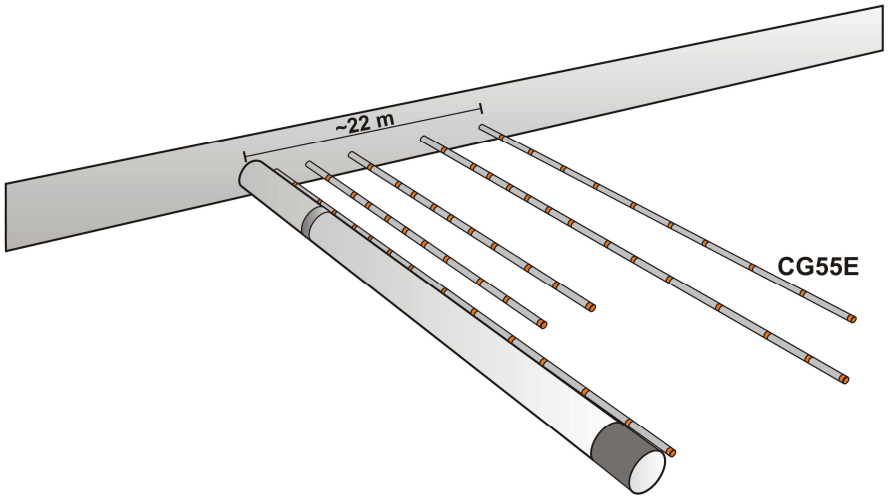




THE PRACLAY EXPERIMENT – PORE WATER PRESSURE OBSERVATIONS

- Pore pressure evolution in CG55E

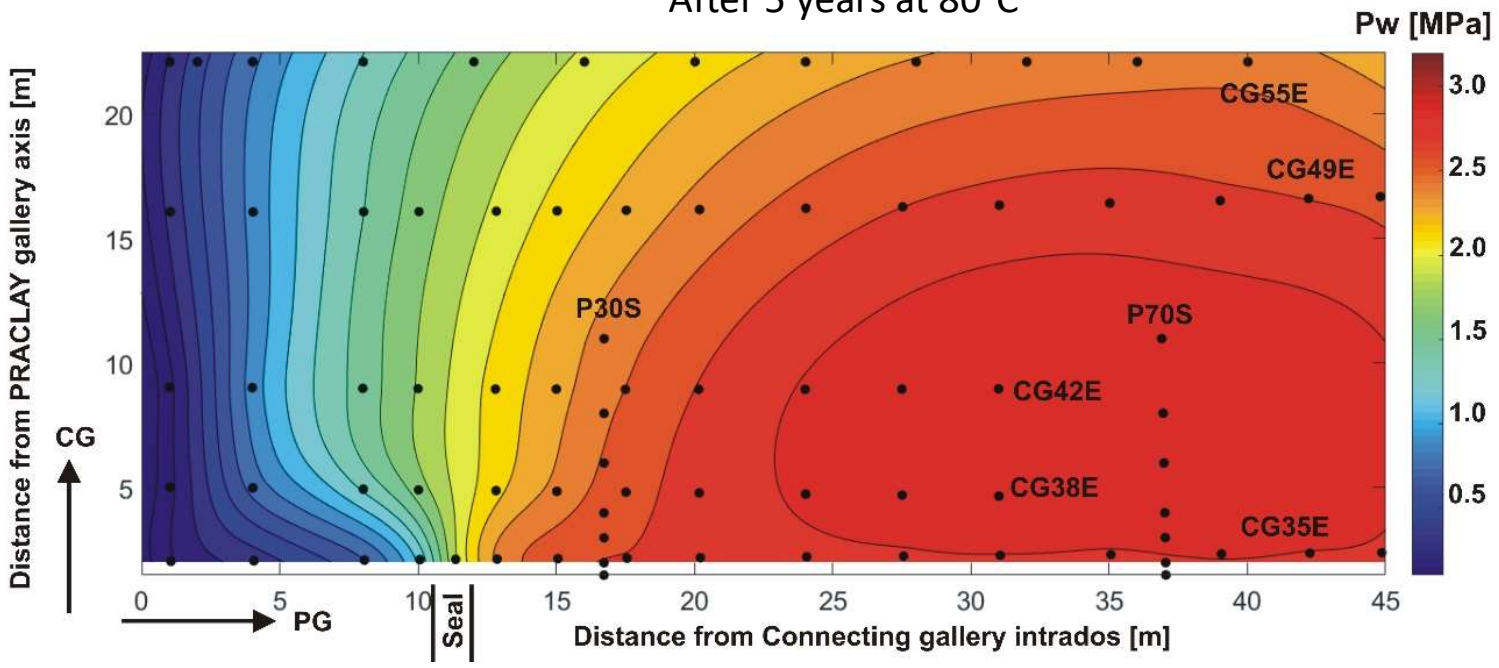




THE PRACLAY EXPERIMENT - PORE WATER PRESSURE OBSERVATIONS

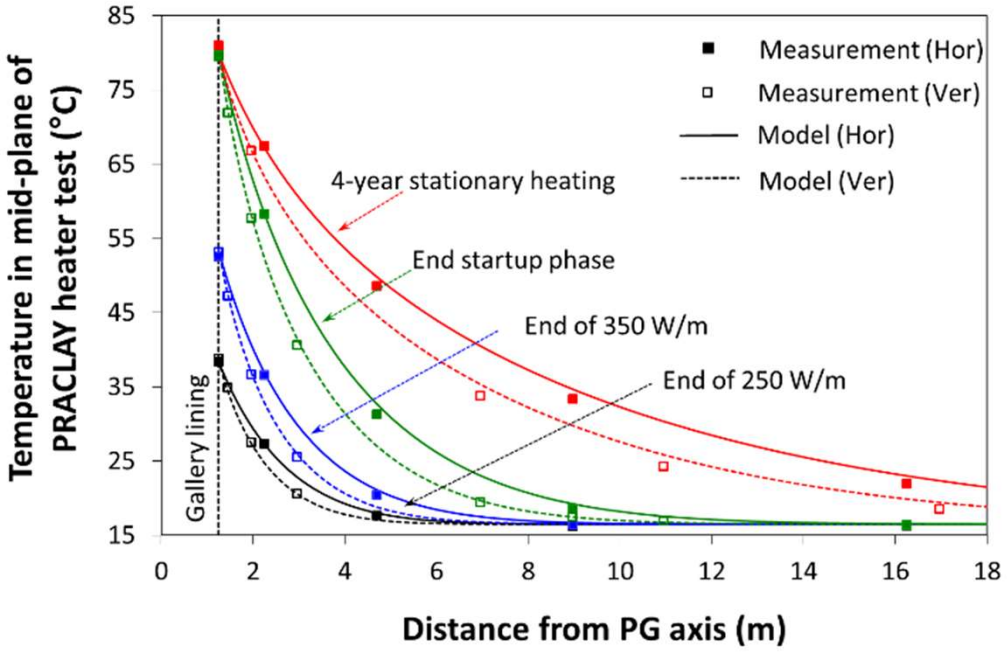
- Pore water distribution in Boom Clay

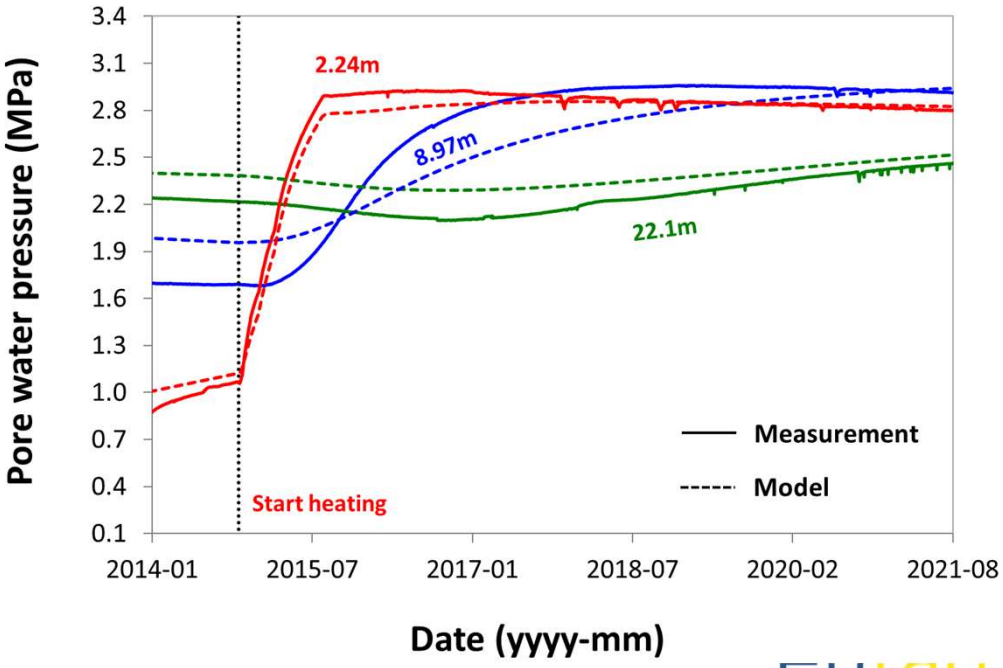
After 5 years at 80°C



THE PRACLAY EXPERIMENT – NUMERICAL INTERPRETATION

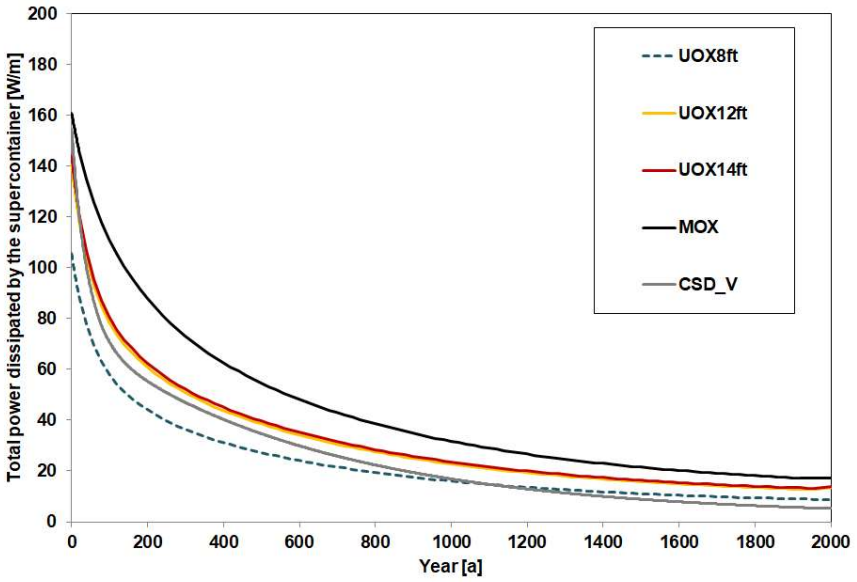
- Comparison between measurements and modelling results



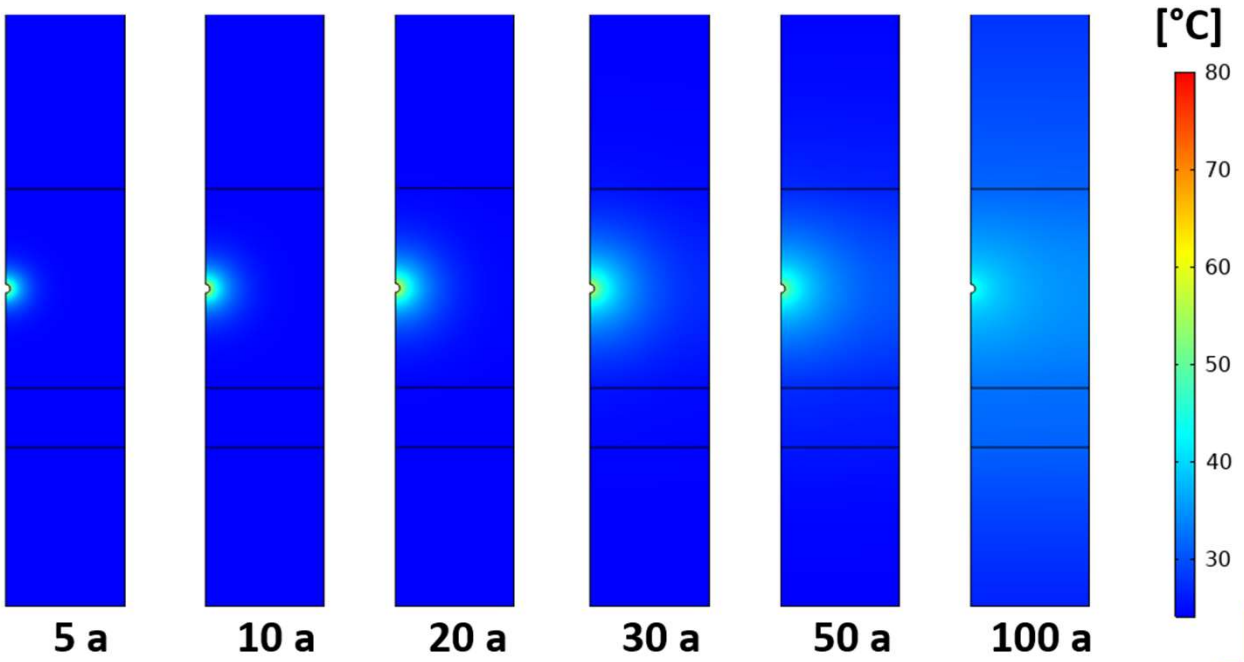


FINITE ELEMENT ANALYSIS OF A GEOLOGICAL DISPOSAL FACILITY

- Fully coupled THM finite element simulations with COMSOL© of a geological disposal facility in poorly indurated clay formation



Heat input

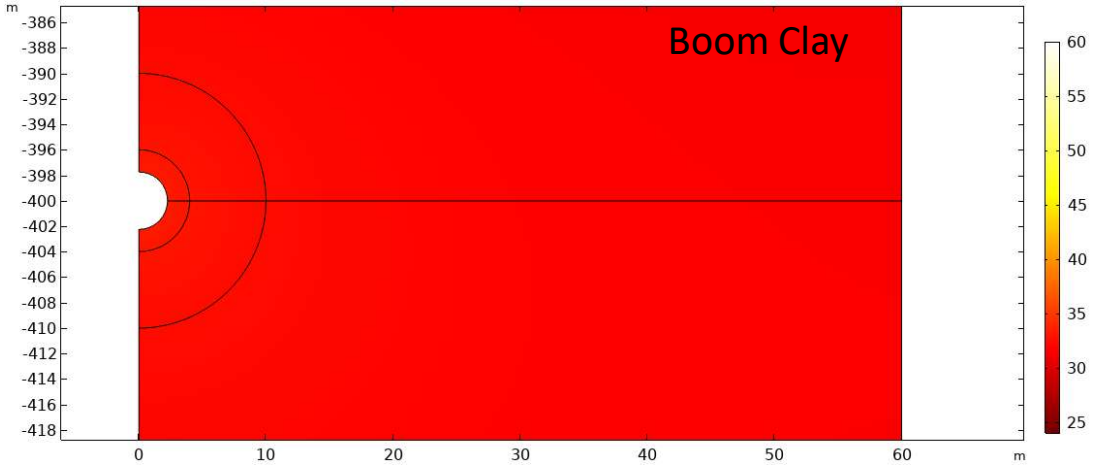


Temperature distribution

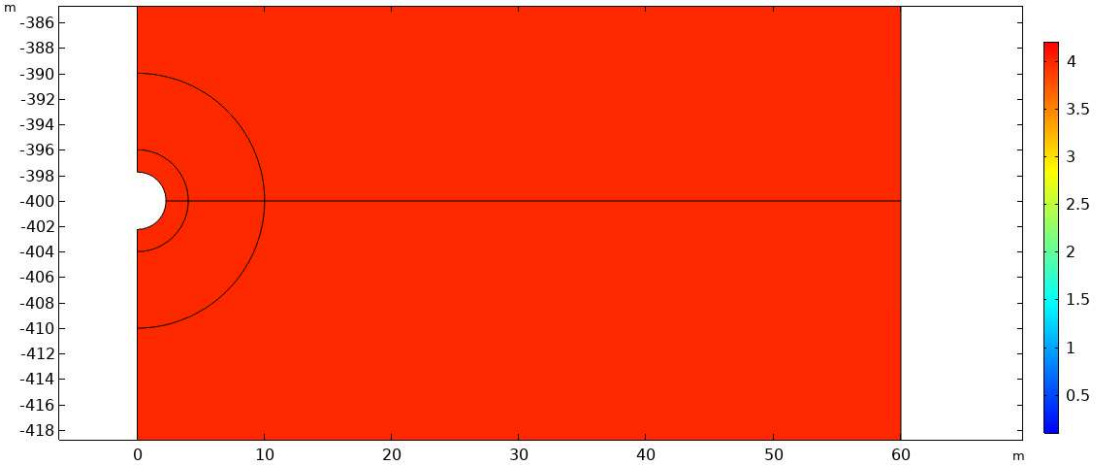
FINITE ELEMENT ANALYSIS OF A GEOLOGICAL DISPOSAL FACILITY

- Fully coupled THM finite element simulations with COMSOL© of a geological disposal facility in poorly indurated clay formation

Temperature



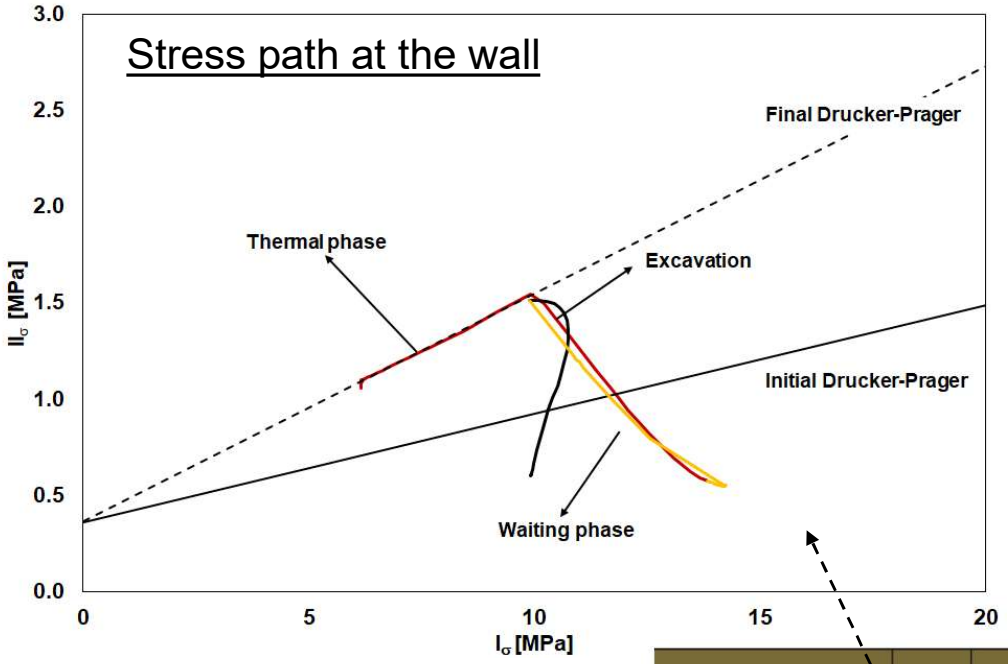
Pore water pressure

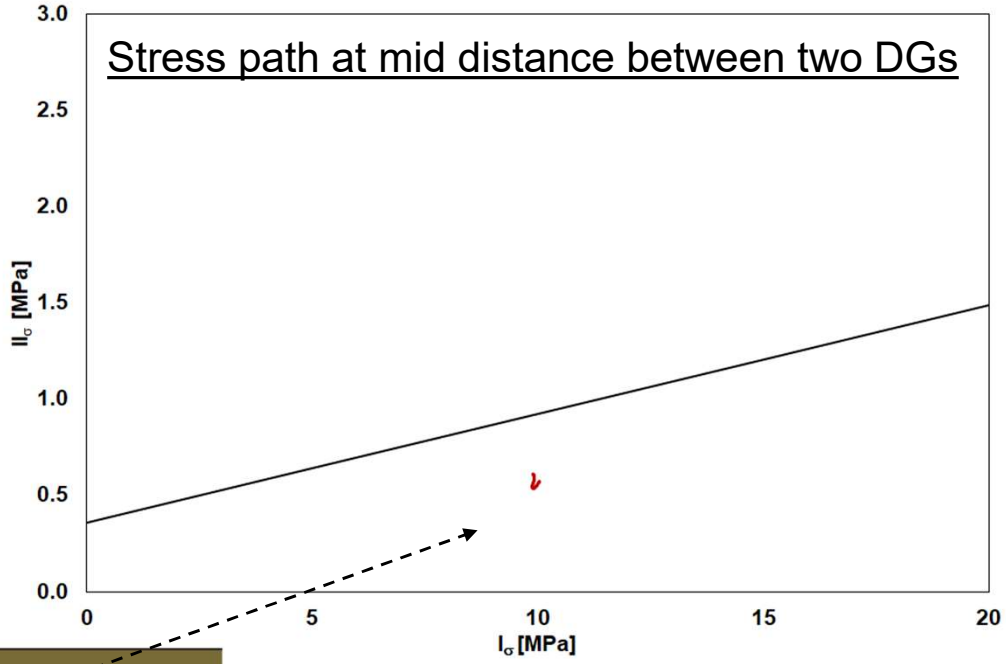


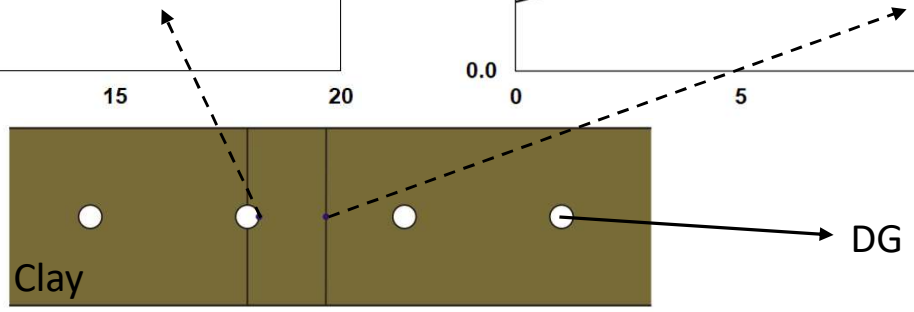
After 2000 years of heating

FINITE ELEMENT ANALYSIS OF A GEOLOGICAL DISPOSAL FACILITY

- Fully coupled THM finite element simulations with COMSOL© of a geological disposal facility in poorly indurated clay formation







CONCLUSIONS

Long term investigation in THM coupled processes in poorly indurated clay

- Large scale in situ PRACLAY heater test:
  - Boom Clay is able to sustain the thermal load
    - ✓ Anisotropic responses, as expected (vertical vs horizontal profiles)
    - ✓ No indication of abrupt changes in pore water pressure nor large displacement
  - No interruption of the heater system
  - Good performance of the test set-up
  - Seal fulfils its role as a hydraulic cut-off

- Interpretation by back-analysing the measurements of heater tests
  - Determination of a set of THM properties/ parameters
  - Important input for the design/ optimization of a future GDF

Li et al., 2023. Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES. Geological society, special publication 536 (open access https://doi.org/10.1144/SP536**)**

VISIT OF THE HADES URL (1ST SEPTEMBER)

7:30 Departure to Mol

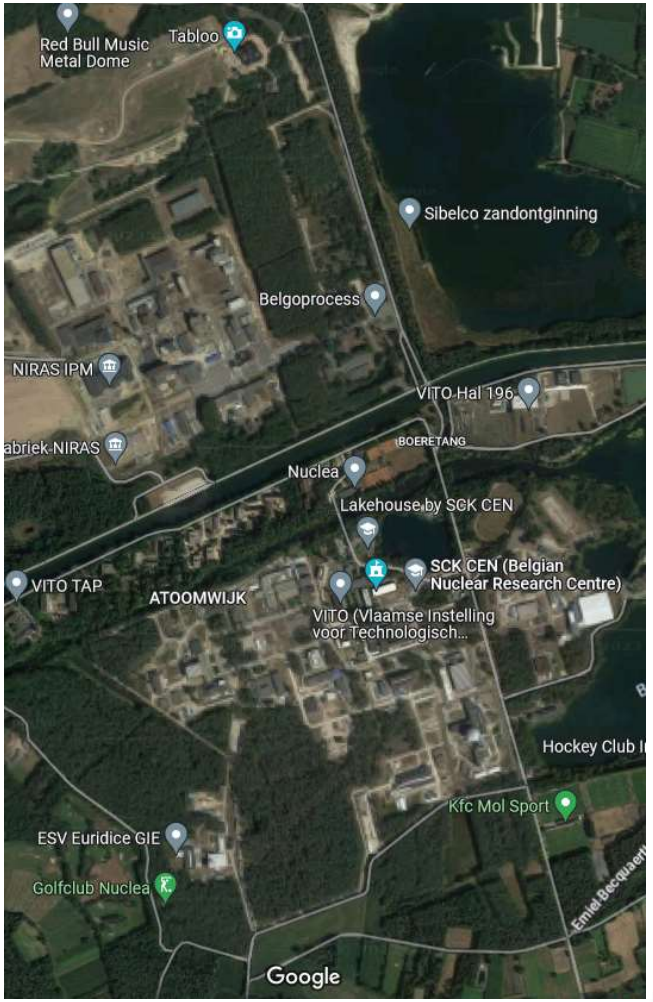
9:00 – 9:30 Transfer from Tabloo to EURIDICE

9:30 – 12.15 Visit of the HADES URL

12:30 – 13:15 Sandwich lunch Bistroo (in Tabloo)

13:15 – 15:30 Visit of the Tabloo expositions

Tabloo : Gravenstraat 3, 2480 Dessel



EIG EURIDICE

European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment

Boeretang 200 – BE-2400 MOL

ESV EURIDICE GIE