

20th Exchange Meeting

The PRACLAY Heater test

First results after one and a half years of heating



13:30 Welcome

Marc Demarche, chairman of the board of EIG EURIDICE

13:40 Objectives of the PRACLAY Heater test and the importance for the R&D programme on geological disposal

Maarten Van Geet (ONDRAF/NIRAS)

13:50 From small-scale heater tests to the large-scale PRACLAY Heater test

S  verine Levasseur (ONDRAF/NIRAS), Xiangling Li (EIG EURIDICE)

14:20 Monitoring and data management of the PRACLAY Heater test

Jan Verstricht (EIG EURIDICE)

14:40 First results PART 1 - Observations during one and a half year of heating

Arnaud Dizier (EIG EURIDICE)

15:10 Coffee break

15:30 First results PART 2 - Comparison with the blind predictions

Guangjing Chen (EIG EURIDICE)

16:00 Possible impact of temperature on the chemical characteristics of the Boom Clay

Norbert Maes (SCK•CEN)

16.30 Conclusions

Peter De Preter, director EIG EURIDICE

Welcome

20th Exchange Meeting

Mol, 4 May 2016

Marc Demarche

Chairman of the board - EIG EURIDICE



ONDRAF/NIRAS

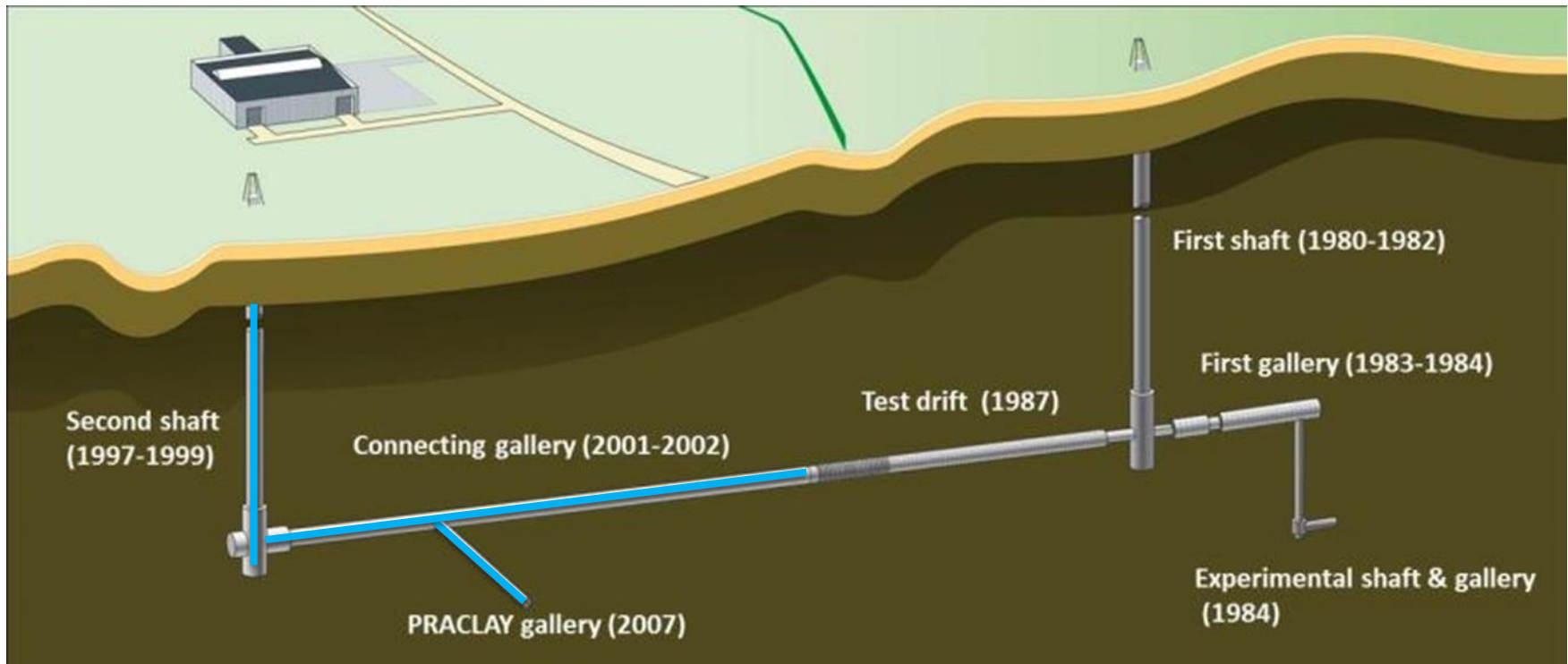


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Major milestones of the EIG EURIDICE

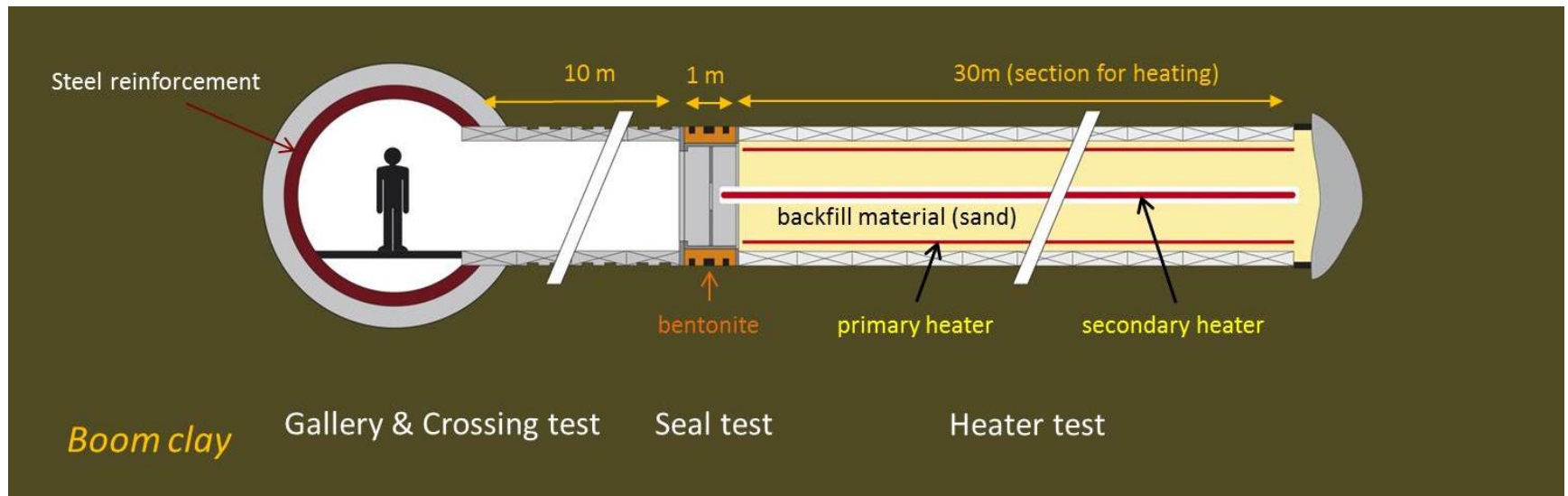
1. 1997 – 2007: Demonstration of the **construction feasibility**



Major milestones of the EIG EURIDICE

2. 2008-2014: Preparation of PRACLAY Seal & Heater experiment

- Development of the scientific basis for the design, steering and follow-up of the experiment
- Installation of all experimental components in the HADES URL
- November 2014: switch-on of the heating system



Major milestones of the EIG EURIDICE

3. 2014 - 2025: PRACLAY Heater test running

⇒ Experiment runs successfully since the heater switch-on, 3 November 2014

⇒ Already important achievements, but still a major challenge to bring PRACLAY to a successful end

What about the future?

2016 - ...

Reflections started **on the future role of the EIG EURIDICE**,
in interaction with the two members of the EIG,
SCK•CEN & ONDRAF/NIRAS.



20th Exchange Meeting

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First results after one and a half years of heating





ONDRAF/NIRAS

Objectives of the PRACLAY Heater test and the importance for the R&D programme on geological disposal

Maarten Van Geet

ONDRAF/NIRAS

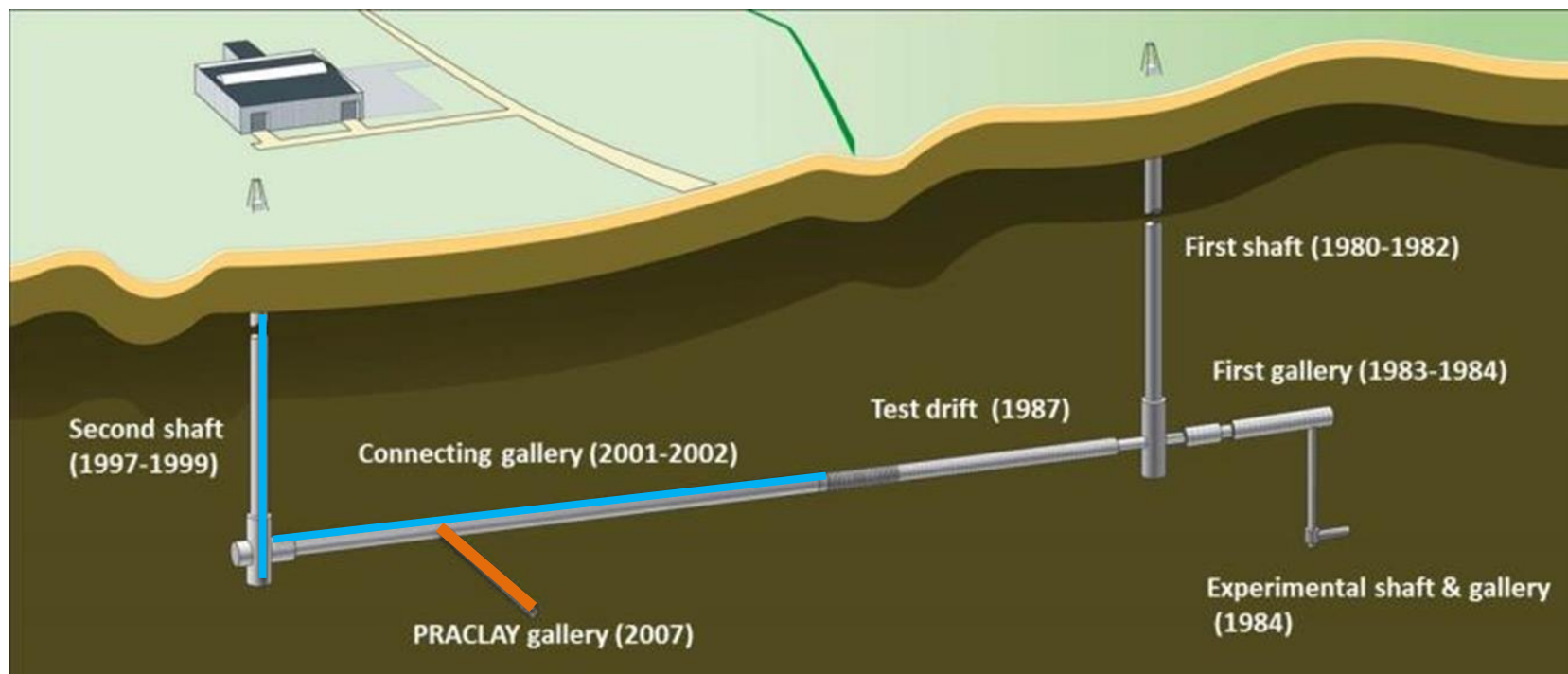
20TH EXCHANGE MEETING ESV EURIDICE

The PRACLAY Heater test – First results after one and a half year of heating
Mol, 4 May 2016



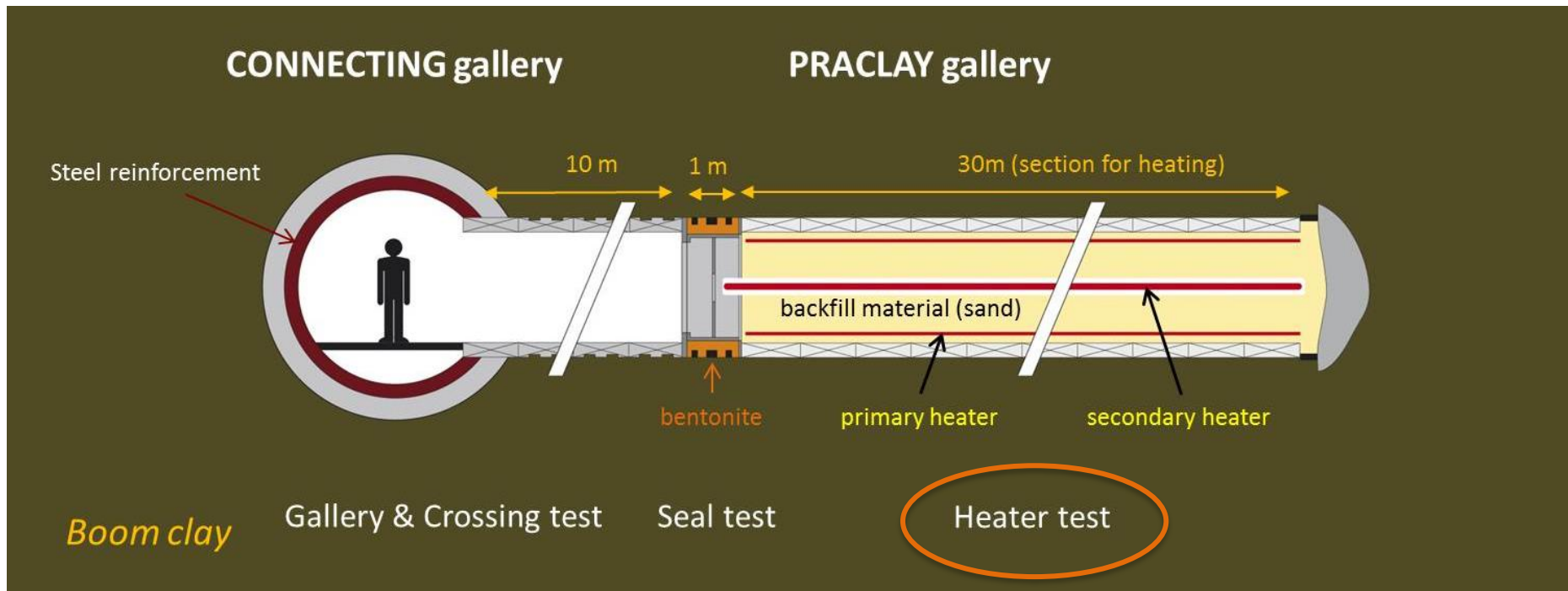
The PRACLAY project

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



The PRACLAY In-Situ Experiment

The PRACLAY In-Situ Experiment



The PRACLAY Heater test

- 30m long section, closed off by a seal
- 10 years of heating
- 80° C on the contact of the lining with the Boom Clay

The PRACLAY Heater test – general objective

- **Examine the combined impact of hydro-mechanical disturbances caused by gallery construction and a large-scale thermal load on the Boom Clay due to heat-emitting high-level waste**
 - Design independent
 - Conditions that are representative for a real repository
- ⇒ **Assess the impact of a thermal stress on the repository system originating from heat emitting waste**
- **To be sure that poorly indurated clay like Boom Clay retains its ability to contain radioactive waste when it is heated**

Success criteria (1)

- ***Capability to assess the heat dissipation from a repository containing heat-emitting waste***
 - Mainly confirm the thermal properties of the Boom Clay
 - Can have a direct influence on the geometry of the repository layout
- ***Capability to assess the consequences of a THM impact on the damaged/disturbed zone of the host rock***
 - Major focus on the confinement safety function
 - Allow describing the evolution of the damaged and disturbed zone
 - Multiple lines of evidence gathered and remaining uncertainties identified
- ***Demonstrating the absence of liquefaction of Boom Clay***
 - Based on our current knowledge, this will not occur, but PRACLAY will enable confirmation at large scale

Success criteria (2)

- ***Capability to assess the stability of concrete lining under thermal stress***
 - Opportunity to study the properties of compressive materials
- ***Increase capabilities to substantiate the limited influence of thermal loading on RN transport-related parameters***
 - Understanding of the effects on Boom Clay characteristics after a thermal pulse with main focus on retention safety function
 - Confinement → no RN release during thermal phase
 - Post-mortem analyses
 - No first priority and should not jeopardise achievement of other objectives
- ***Progress in monitoring in realistic conditions to help elaborating a monitoring strategy***
 - Increasing the capability to provide an effective range of reliable and validated systems to monitor disturbances within the clay as a result of gallery excavation and heat-emitting waste emplacement
 - Input to the development of a monitoring plan and monitoring objectives



Success criteria (3)

- ***Incorporate the PRACLAY experiment in the general communication strategy***
 - The underground research laboratory HADES plays an important role in informing the public
 - PRACLAY experiment, being a major experience within the HADES URL

Importance for the R&D programme - consequences of failure

Failure	PRACLAY Heater test	Belgian R&D programme
Liquefaction occurs	Stop	Showstopper
Unexpected heat dissipation	Major objective not obtained	Large uncertainties
Unexpected THM impact	Major objective not obtained	Large uncertainties
Instability of lining	Dismantling more difficult	Retrievability excluded for this design
Major effect on RN transport	None	Large uncertainties
General failure monitoring system	Re-installation	Important input
Communication	Missed opportunity	Missed opportunity

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From small-scale heater tests to the large-scale PRACLAY Heater test

20th Exchange Meeting

Mol, 4 May 2016

Séverine Levasseur - *ONDRAF/NIRAS*

Xiangling Li - *EIG EURIDICE*



ONDRAF/NIRAS



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Outline

1. Disposal of heat-emitting waste: pre-design considerations
2. Thermo-hydro-mechanical (THM) behaviour of Boom Clay
3. THM experiments in HADES – heater tests
 - ATLAS
 - PRACLAY

Disposal of heat-emitting waste: pre-design

Multi-barrier design

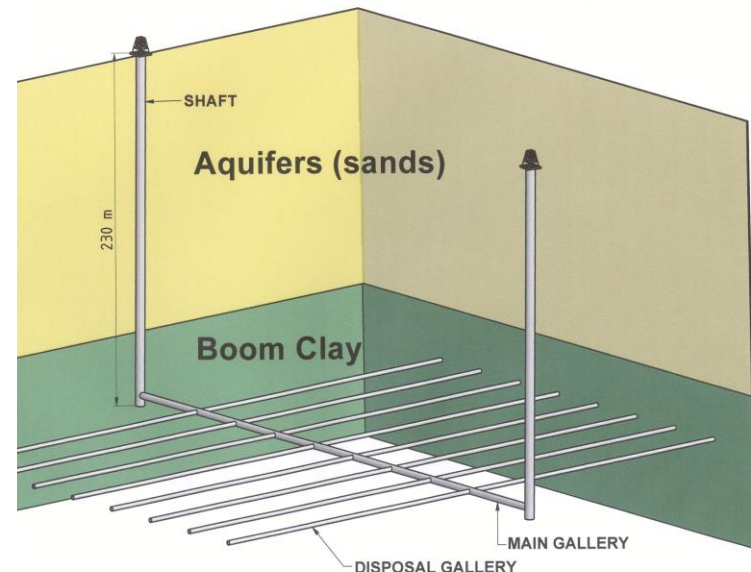
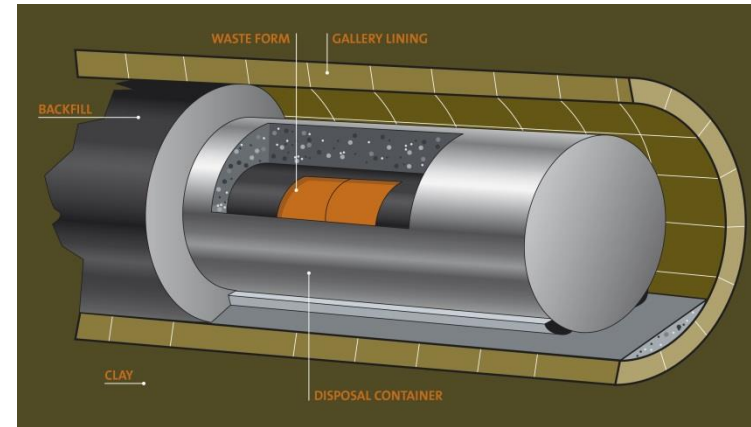
- Supercontainer: overpack & concrete buffer
- Deep geological layer

Thermal pre-design requirements

- T at the overpack $< 100^{\circ}\text{C}$ (overpack corrosion)
- T at the interface Boom Clay – upper aquifer $< 25^{\circ}\text{C}$ (environment)

Design parameters to accommodate the heat output

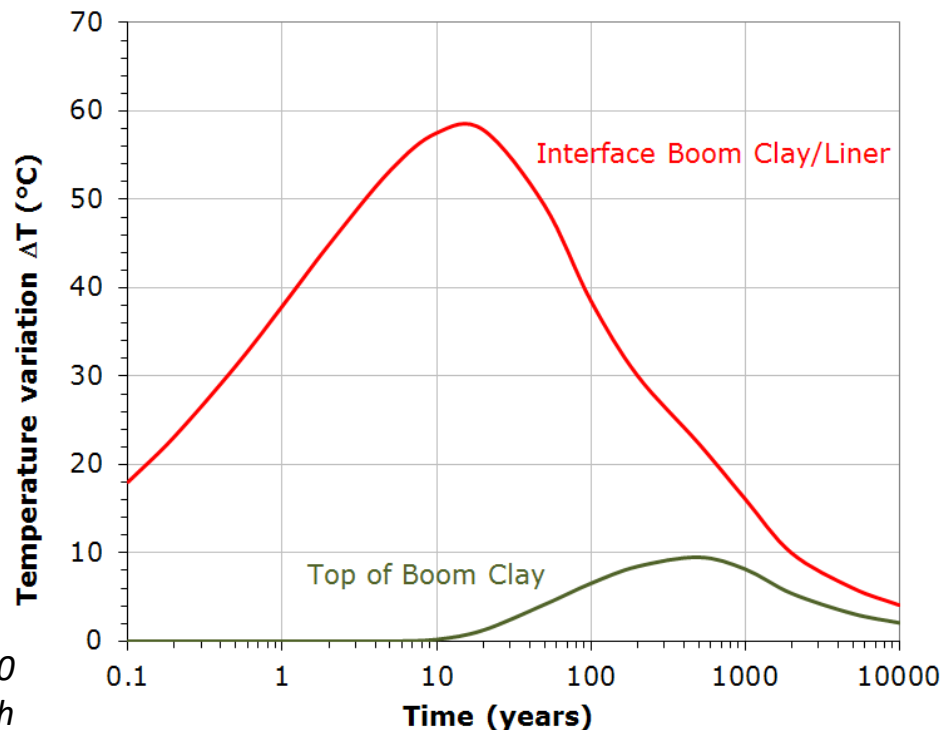
- Cooling time before disposal
- The number of VHLW canisters / SF assemblies in a supercontainer
- The distance between supercontainers within a disposal gallery
- The distance between disposal galleries



Disposal of heat-emitting waste: pre-design

Thermal perturbations

- Thermal load in gallery at time of disposal about 250 W/m
- Temperature variations at the interface between repository lining and Boom Clay estimated higher for spent fuel than for vitrified high level waste
→ Max. 60°C



*Example of Spent Fuel – UOX50
for a disposal at HADES URL depth
where initial temperature is about 16°C*

Disposal of heat-emitting waste: pre-design

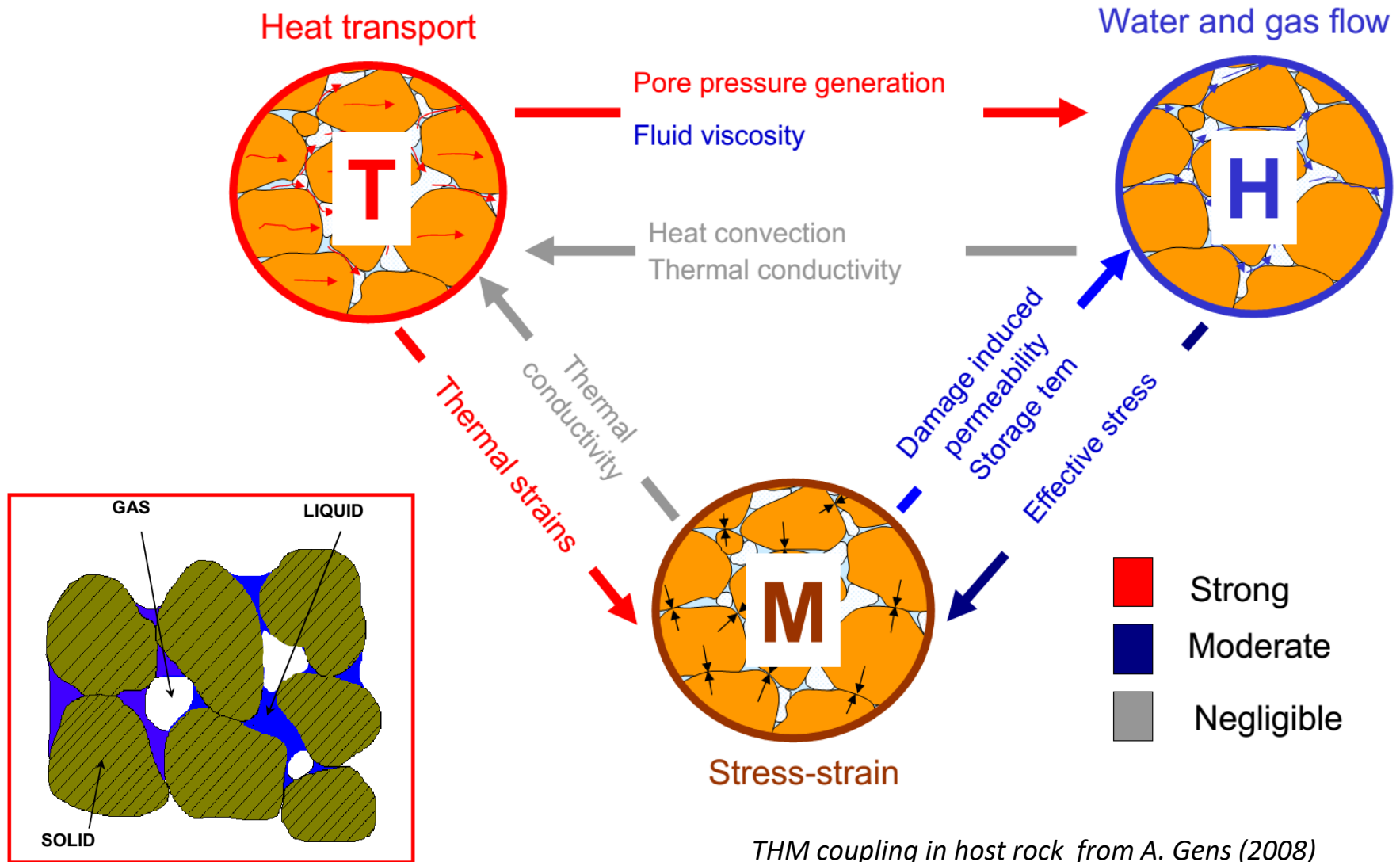
Thermal perturbations

- From a **geomechanical** point of view, need to evaluate the consequences of
 - thermal transient on the evolution of the Excavation Damaged Zone (EDZ)
 - the possible additional damage created by thermal load
 - the thermal load impact on:
 - the safety relevant properties of Boom Clay
 - far field stress state, deformations & uplift
- From a **geochemical** point of view, need to evaluate the consequences of
 - T-induced chemical perturbations: fate of organic matter, CO₂, carbonate buffer

**Near field &
far field THM
behaviour of
Boom Clay**

→ See Norbert Maes' presentation

Thermo-hydro-mechanical behaviour of Boom Clay



THM coupling in host rock from A. Gens (2008)

Thermo-hydro-mechanical behaviour of Boom Clay

Importance of temperature recognised early on (1985-1990's)

- Thermo-mechanical (TM) and thermo-hydro-mechanical (THM) characterisation as old as the idea of disposing heat-emitting waste in clay

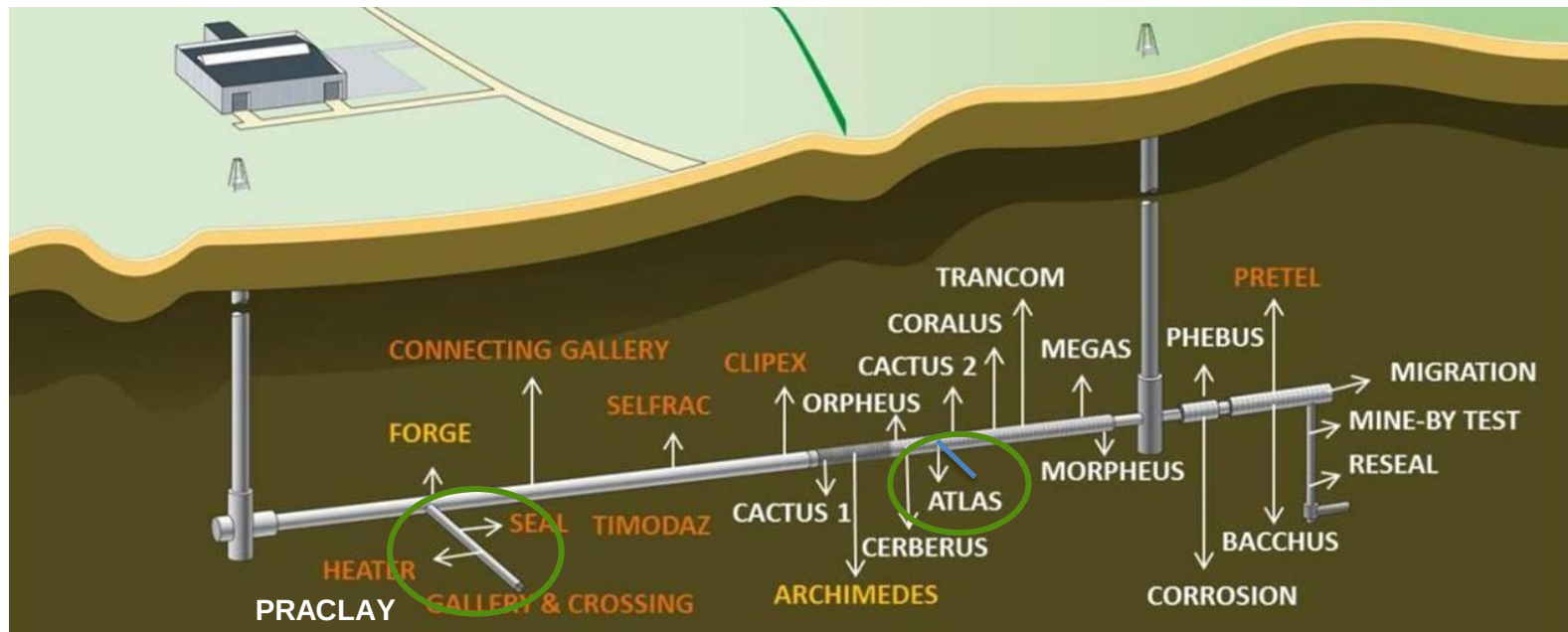
THM behaviour at lab scale reasonably well understood

- Elastic & plastic thermal strains + possible reduction of strength
 - Thermo-elasticity tends to dilate the clay → Reversible volume change with T
 - Thermo-plasticity (and creep) tends to compact the clay → Additional non linear and irreversible volume change with T
- Unchanged intrinsic permeability with T under constant volume conditions
 - Variation of hydraulic conductivity with water viscosity
- Faster self-sealing of the pre-existing discontinuities in clay samples
 - Under a confining environment (expected in repository conditions), closed fractures remain closed, open fractures tend to seal faster with temperature

Thermo-hydro-mechanical behaviour of Boom Clay

In situ validation of the Boom Clay capacity to support the thermal load imposed by heat emitting wastes

- In-situ small-scale heater tests: ATLAS (1993 – ...)
- In-situ large-scale heater test: PRACLAY (2014 – ...)



THM experiments in HADES – ATLAS

Small scale heater tests ATLAS I-II, III & IV

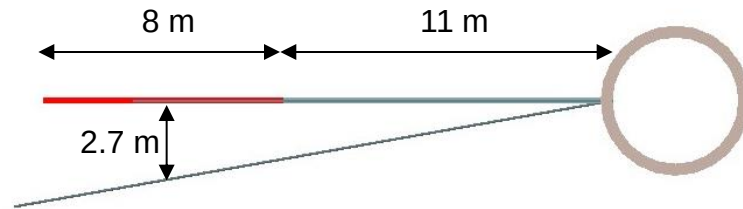
(Admissible Thermal Loading for Argillaceous Storage)

Objectives:

Validate and/or improve knowledge on BC THM behaviour by studying in-situ thermal properties and anisotropy

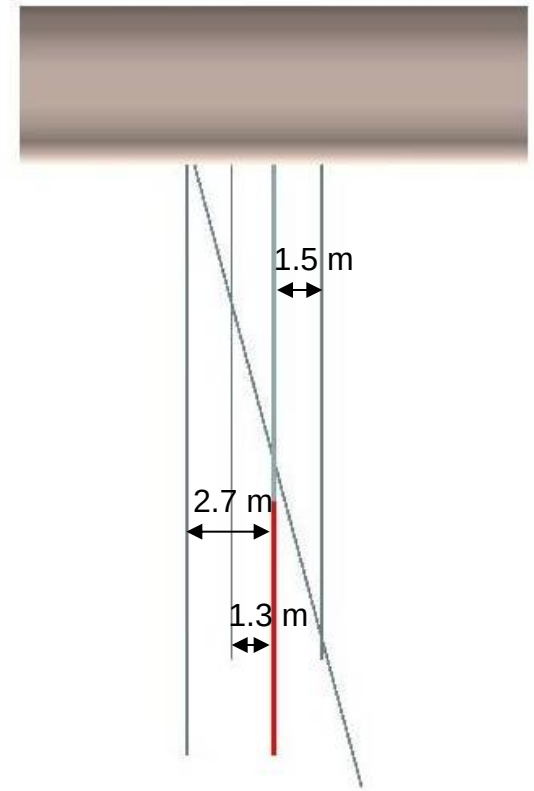
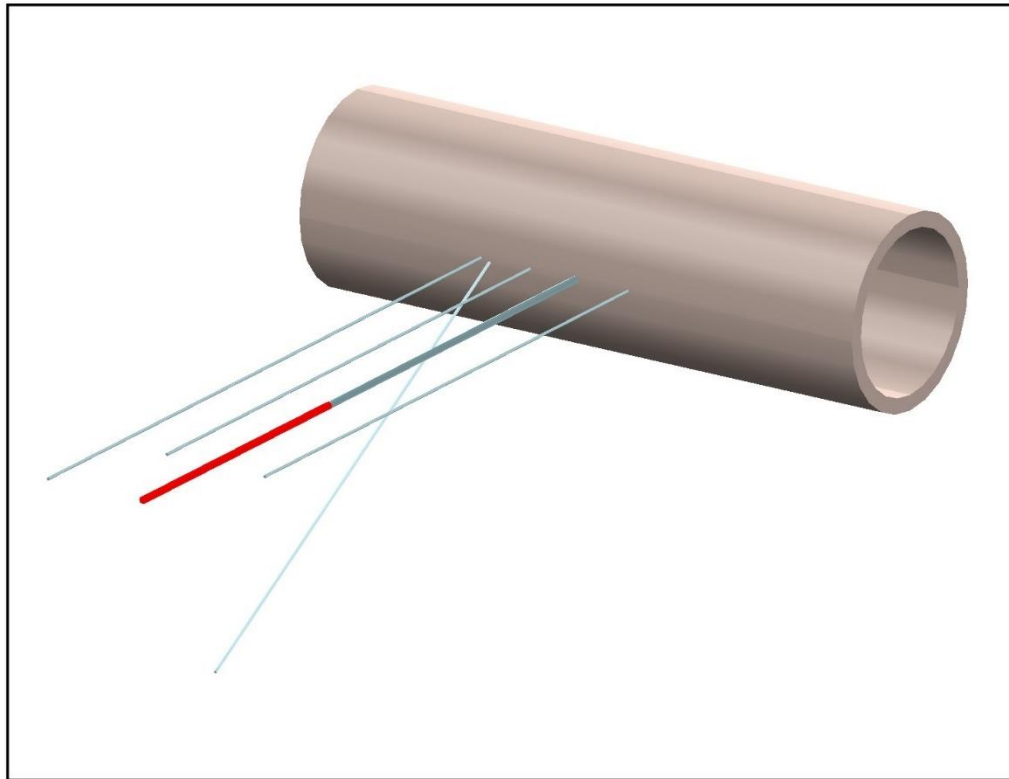
- Confirm/update thermal properties of Boom Clay
 - Especially the thermal conductivity λ [W/(m·°C)]
- Investigate T→HM coupling in Boom Clay
 - A simple THM experiment
 - 1 Heater, several observation boreholes
 - Focus is only on the behaviour of the Boom Clay
 - No radioactive source (CERBERUS)
 - No backfill material (BACCHUS) or simulated Engineered Barrier System (EBS)

THM experiments in HADES – ATLAS



Test drift
Heater
Observation boreholes

*Illustration ATLAS III
experiment*



THM experiments in HADES – ATLAS

ATLAS heater tests: 4 tests in 2 stages

- **ATLAS I-II**

- 2 observation boreholes drilled in the same horizontal plane than the heater
- 3 years of heating at 112W/m (ATLAS I) + 1 year of heating at 225W/m (ATLAS II) (1993 – 1997). Cooling in one step.
- Limitations:
 - Relatively little instrumentation and low data acquisition rate (manual)
 - Sharp heating transients

- **ATLAS III & IV**

- Additional boreholes (horizontal and inclined) + Additional T & p sensors
- Stepwise heating in 1 year: 0 → 50 → 112 → 175 W/m. Cooling in one step.
- Same heating strategy for ATLAS III (2007 – 2008) and ATLAS IV (2011 – 2012)
- Improvements:
 - High data acquisition rate
 - Investigation of thermal anisotropy
 - Small ΔT and small scale

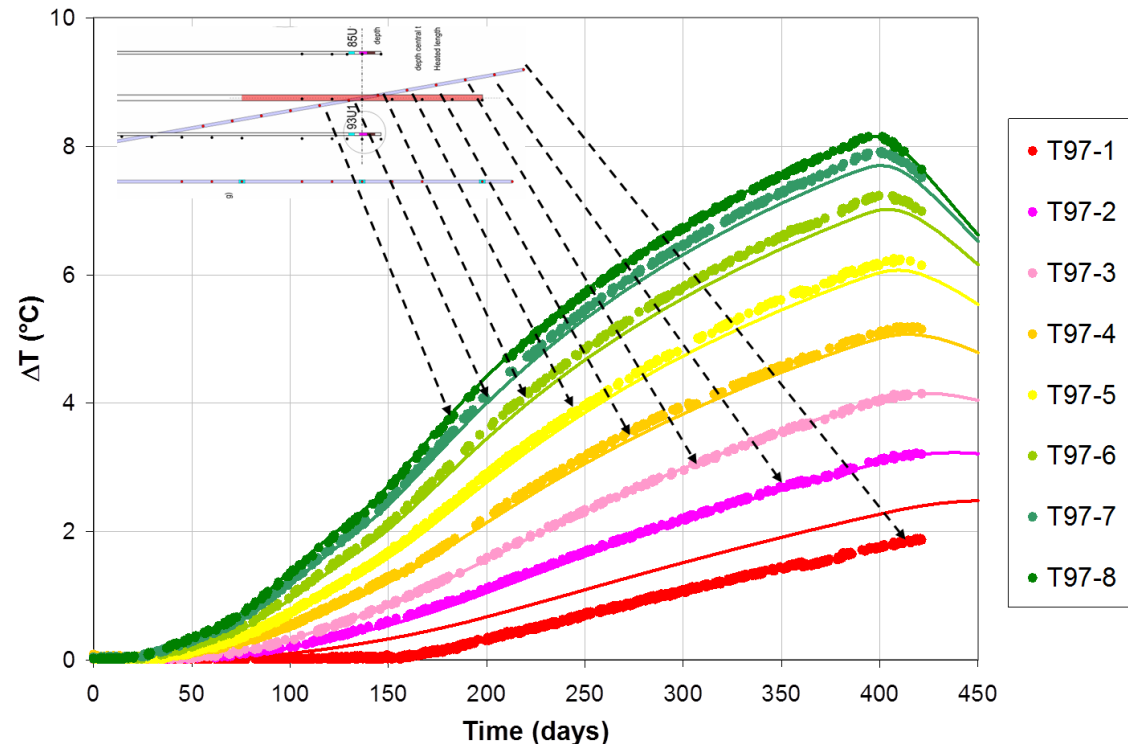
→ **representative of far field**
→ **complementary to PRACLAY**

THM experiments in HADES – ATLAS III

ATLAS III: Temperature and pore water pressure evolution

Modelling (3D FEM)

- Anisotropic Thermo-hydro-poro-elastic model: transverse isotropic elasticity
- Heat transport (conduction)
- Model parameter values:
 - Consistent with previous studies
 - Limited optimisation except elastic moduli (far field)
 - Valid transverse anisotropy of intrinsic permeability: $K_h \approx 2 \times K_v$



THM experiments in HADES – ATLAS

Main learnings from ATLAS experiments on the far field Boom Clay behaviour

- Anisotropic thermal conductivity of Boom Clay well estimated
- Importance of small strain stiffness characteristics in the far field and of the cross anisotropy in THM coupling
- Quite insignificant effect of thermo-plasticity in the far field

→ Validation of thermo-elastic model & THM parameters

- Predictive capability of modelling: temperature & pore water pressure evolutions of ATLAS III well captured by models
- ATLAS IV yields identical results to ATLAS III (no irreversible processes)

Limitations of the ATLAS experiments

- Small-scale → no information on pore water pressure and stress evolutions in the EDZ – near field

THM experiments in HADES – PRACLAY

The PRACLAY Heater test (*Preliminary demonstration test for clay disposal*)

Objectives:

Validate and/or improve knowledge on BC THM behaviour by studying in situ thermal properties and anisotropy at large scale

- 1. Confirm the T→HM coupling in Boom Clay at a scale representative of a disposal gallery and estimate the possible upscaling effect**
 - As ATLAS heater tests, “simple” THM experiment
 - 1 Heater, several observation boreholes
 - Main focus is on the behaviour of the Boom Clay (near field & far field)
 - Independent of a particular design to make sure that the test remains valid if the geological disposal design changes in future

THM experiments in HADES – PRACLAY

The PRACLAY Heater test (*Preliminary demonstration test for clay disposal*)

Objectives:

Validate and/or improve knowledge on BC THM behaviour by studying in situ thermal properties and anisotropy at large scale

2. Verifying that the Boom Clay can withstand the thermal transient up to the time of maximum near field temperature

- Fully reproduce the timescale, the spatial scale and the boundary conditions of a real repository is not possible
 - the time period over which the thermal load applies is long (several hundreds or thousands of years)
 - the length of the disposal galleries is about several hundreds of meters

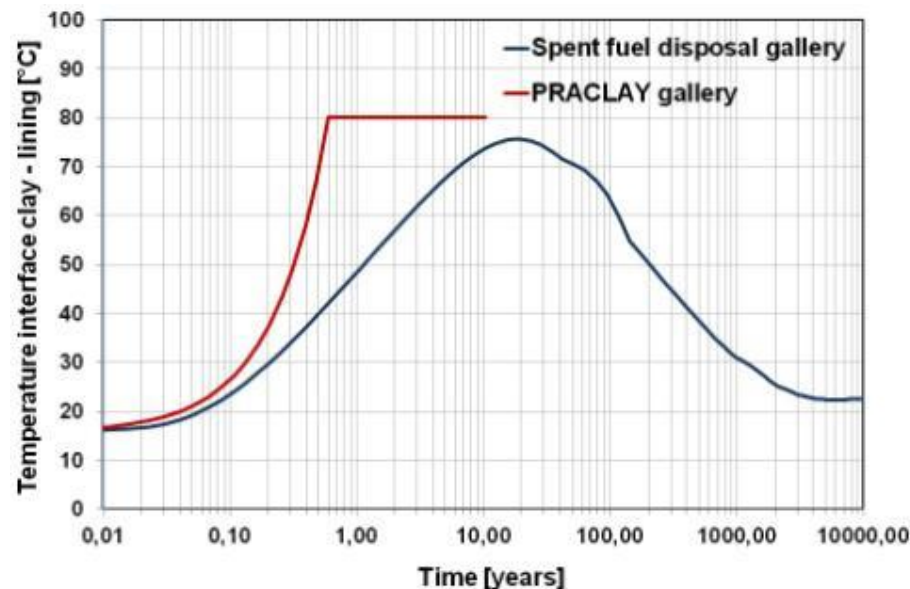
→ ***Conducted under a reasonably conservative combination of thermal and hydraulic boundary conditions***

THM experiments in HADES – PRACLAY

The PRACLAY Heater test – design

Thermal conditions

- temperature at gallery extrados = 80°C (> real repository)
- faster temperature increase (more penalising; heating rate limited by lining stability)
- heating during 10 years (or more)

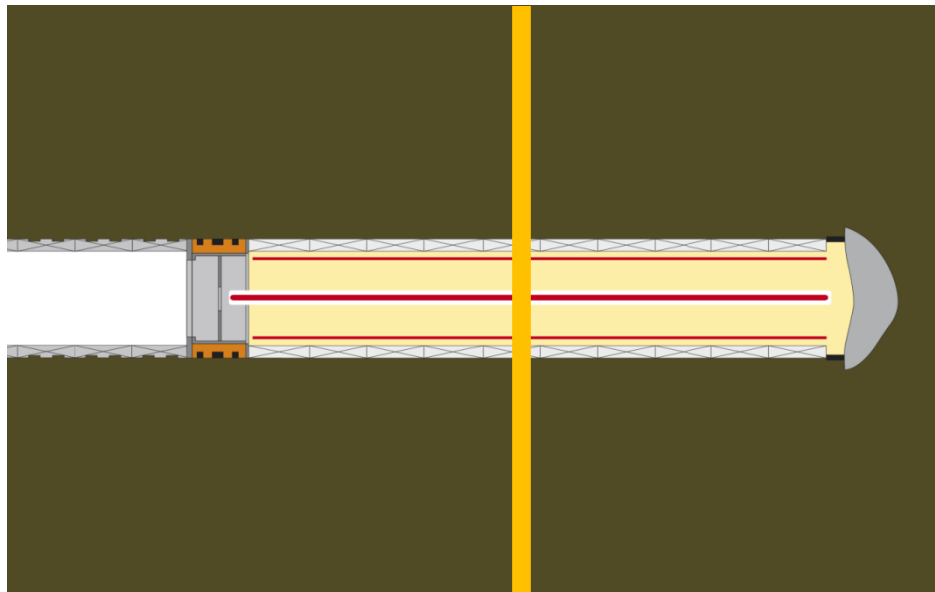


THM experiments in HADES – PRACLAY

The PRACLAY Heater test – design

Thermal conditions

- heated gallery section = 30 m (no gain in test representativity by longer length)
- sufficiently far from the Connecting gallery
- the mid plane simulates a section around a disposal gallery

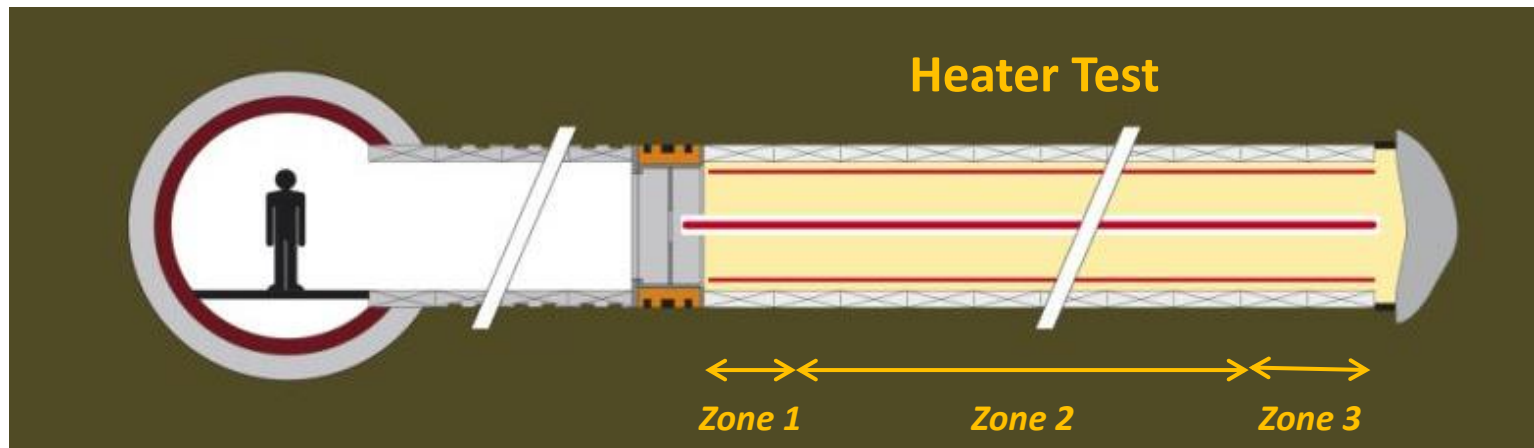


THM experiments in HADES – PRACLAY

The PRACLAY Heater test – design

Thermal conditions

- Primary heater
 - electrical heater cables close to the gallery lining split in 3 heating zones
 - inaccessible during the Heater Test and therefore twice as much heater cables than necessary (100% redundancy)
- Secondary or backup heater
 - electrical heater inside a central tube
 - accessible and replaceable at all times during the test



THM experiments in HADES – PRACLAY

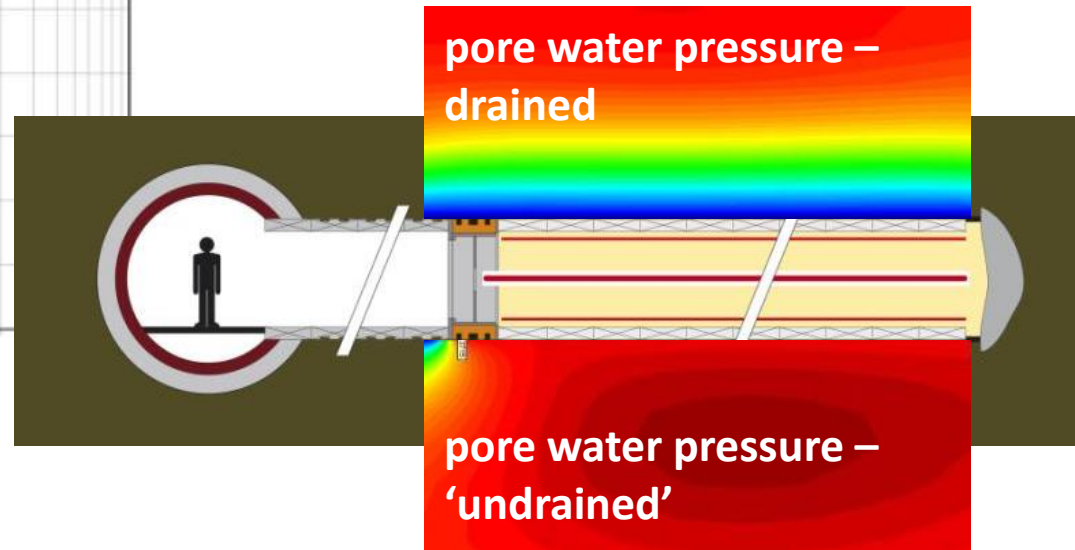
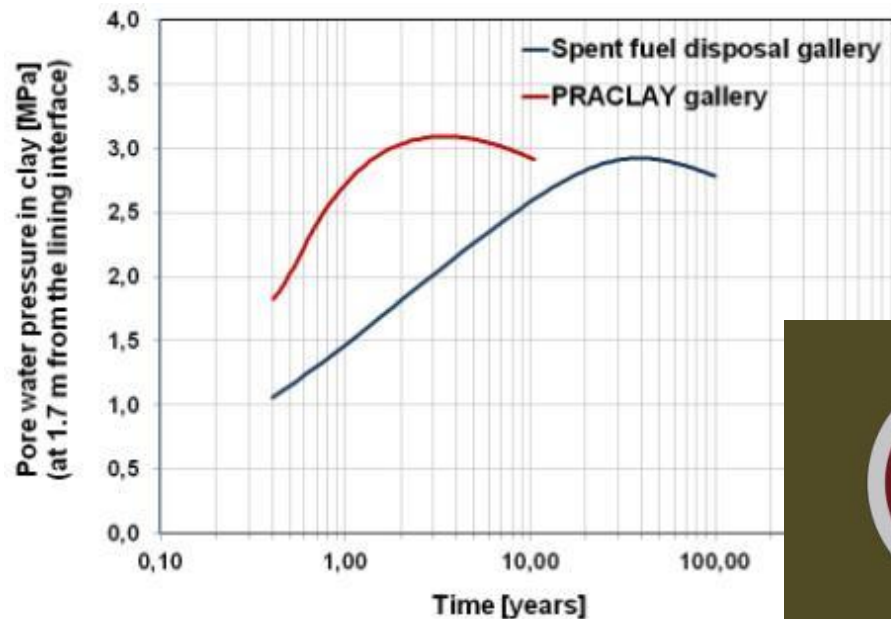


THM experiments in HADES – PRACLAY

The PRACLAY Heater test – design

Hydraulic boundary conditions

- As much undrained as possible (more penalising : the higher the pore pressure build-up during heating, the higher the risk of damage/failure for host rock)

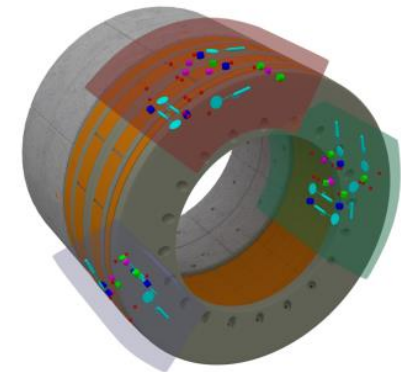
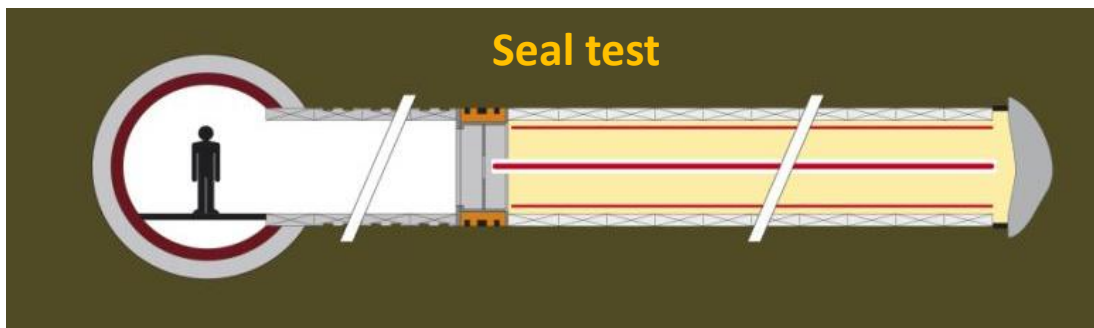


THM experiments in HADES – PRACLAY

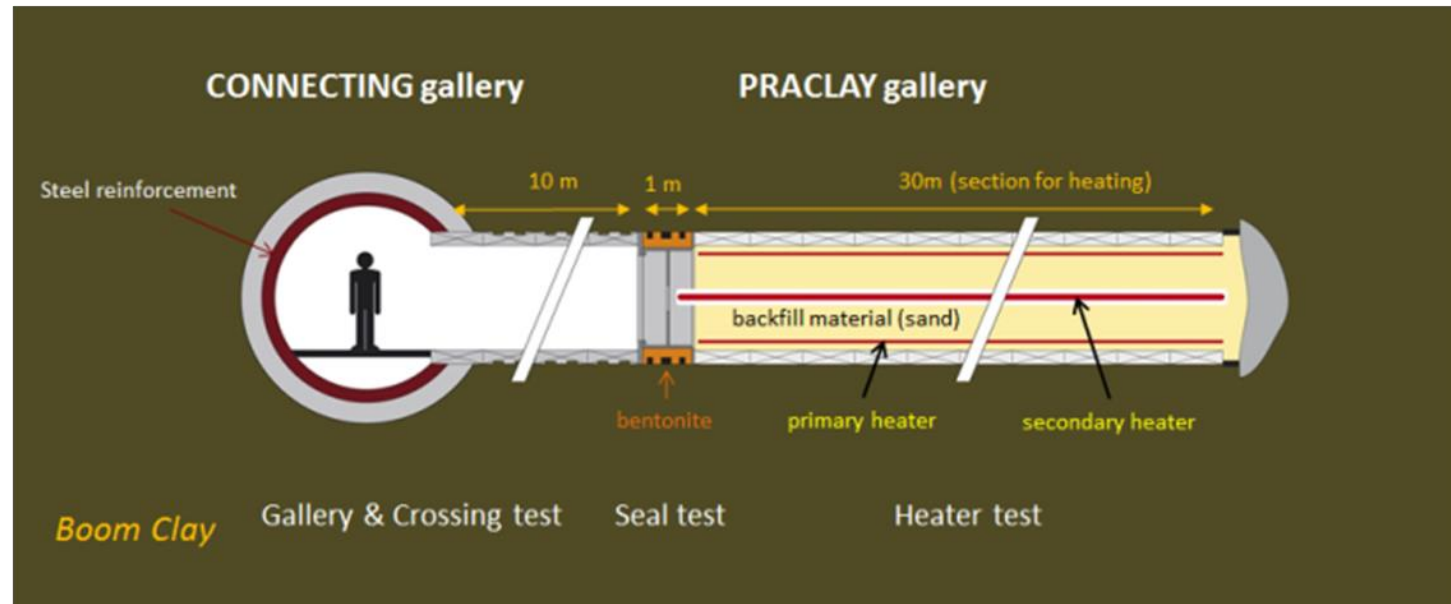
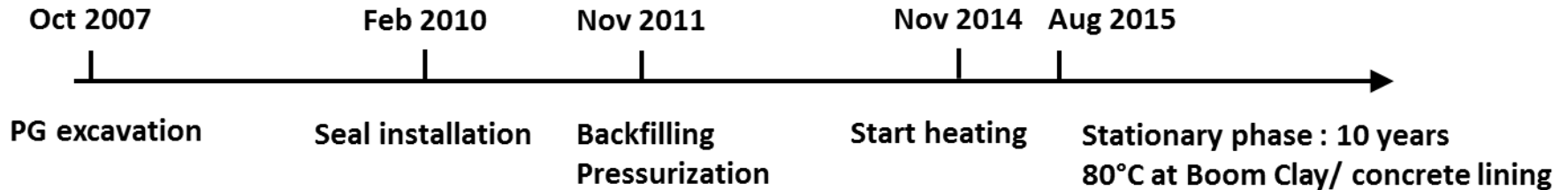
The PRACLAY Heater test – design

Hydraulic boundary conditions

- Backfilling the heated part of the gallery with saturated high permeable material
- Hydraulic seal at intersection heated and non-heated section with bentonite (not representative for a repository seal)
 - create an “impermeable zone” to “close” the PRACLAY gallery (by swelling)
 - maintain the PW at the heated section



THM experiments in HADES – PRACLAY



- Heating in 3 steps, during 9 months: 0 → 250 → 350 → 450 W/m
- 80°C at Boom Clay/ concrete lining interface during 10 years

In summary

Small-scale heater tests => large-scale PRACLAY Heater test

- THM behaviour of Boom Clay (process and properties) is well characterised at laboratory scale (cm scale)
- ATLAS experiments have validated models and parameters at intermediate scale (m scale)
- The results of the first 18 months of **PRACLAY large-scale Heater test are consistent (so far...) with our knowledge on Boom Clay behaviour at a scale representative of a disposal gallery and under more penalising conditions than a future repository**

→ See presentations of Arnaud Dizier and Guangjing Chen

20th Exchange Meeting

The PRACLAY Heater test

First results after one and a half years of heating



Monitoring and data management of the PRACLAY Heater Test

20th Exchange Meeting
Mol, 4 May 2016

Ioannis Troullinos, Jan Verstricht
EIG EURIDICE



ONDRAF/NIRAS



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Outline

- **Monitoring objectives**
- **Lay-out of the PRACLAY Monitoring Programme**
- **Data management**
- **Current status**

Why monitoring the PRACLAY Heater test?

- **Assess (model predictions of) impact of**
 - gallery excavation – *hydro-mechanical disturbance*
 - gallery heating – *thermal load*
- **Daily follow-up / test control**
 - decision making
- **Operational safety**
 - Seal as a critical component in the experimental set-up
- **Experience with monitoring in realistic conditions**
 - input for repository monitoring strategy

Monitoring: sensors and more...

Making monitoring data available

- monitoring data → representative
 - sensor failure, artefacts, logging issues,...
- data files → digestable information
 - data visualisation

Ensuring a traceable data flow

→ data management approach

Outline

- Monitoring objectives
- **Lay-out of the PRACLAY Monitoring Programme**
- Data management
- Current status

Lay-out of the PRACLAY Monitoring Programme

Three main monitoring areas

1. Host rock (Boom Clay) instrumentation

- overall THM response to heating
- instrumented boreholes from
 - Connecting gallery
 - PRACLAY gallery

2. Gallery lining & gallery interior

- thermal boundary condition
- integrity of lining

3. Seal instrumentation

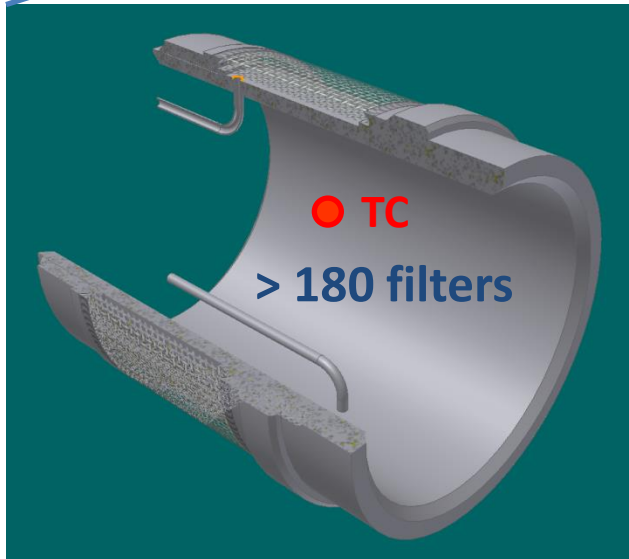
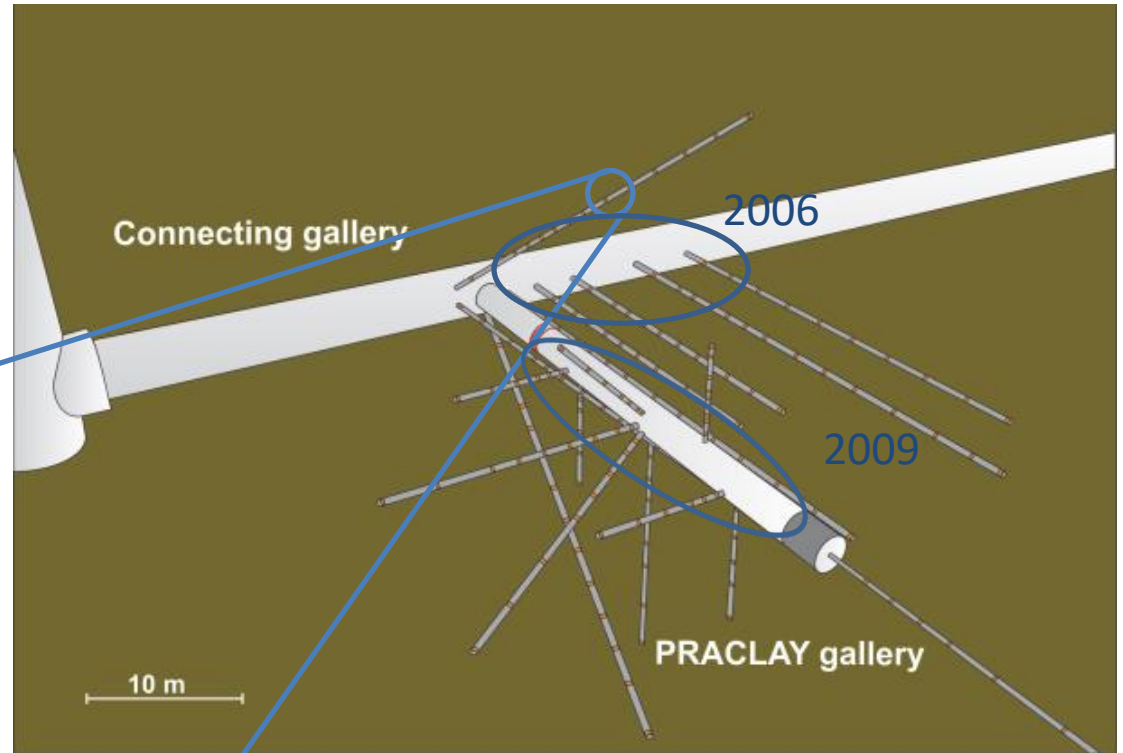
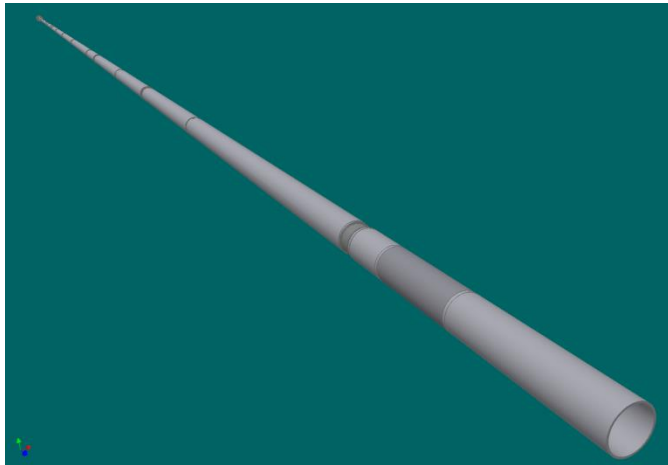
- Seal performance (hydraulic / thermal)

Host rock instrumentation

Instrumented boreholes

- mainly **multifilter piezometers**
 - pore pressure filters and thermocouples
 - options: total pressure cells / geochemical filters
 - CG: mainly in horizontal plane, few inclined boreholes
 - PG: both horizontal and vertical direction
- **other** instrumentation boreholes:
 - inclinometer
 - extensometer (fiber optics)

Host rock instrumentation



Gallery and gallery lining sensors

Gallery lining

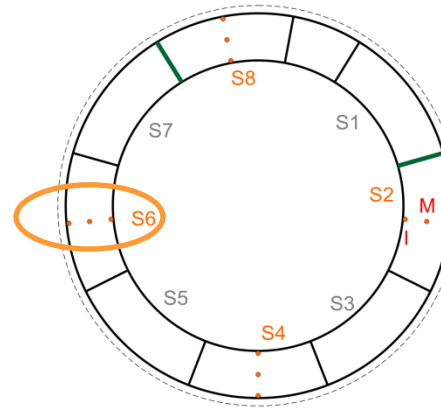
- lining segments instrumented with
 - thermocouples
 - strain gauges
 - total pressure / load cells
 - displacement sensors (foam block deformation)

Gallery interior / backfill

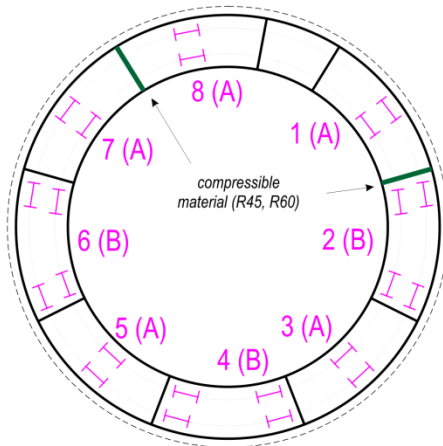
- equipped with
 - thermocouples (heater elements)
 - pore pressure filters
 - extensometers

Gallery and gallery lining sensors

temperature sensors



strain gauges



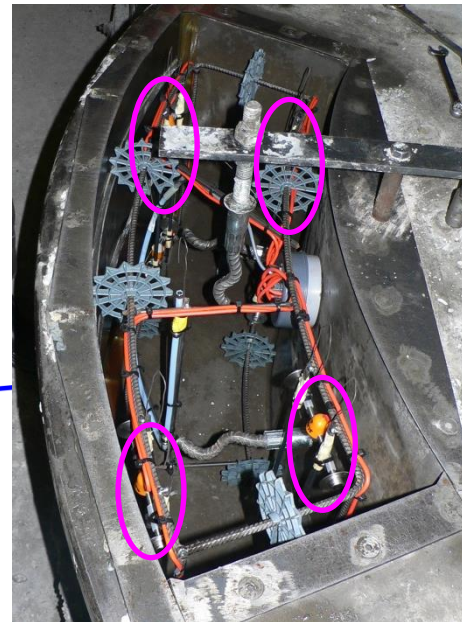
configuration A
(4 gauges)



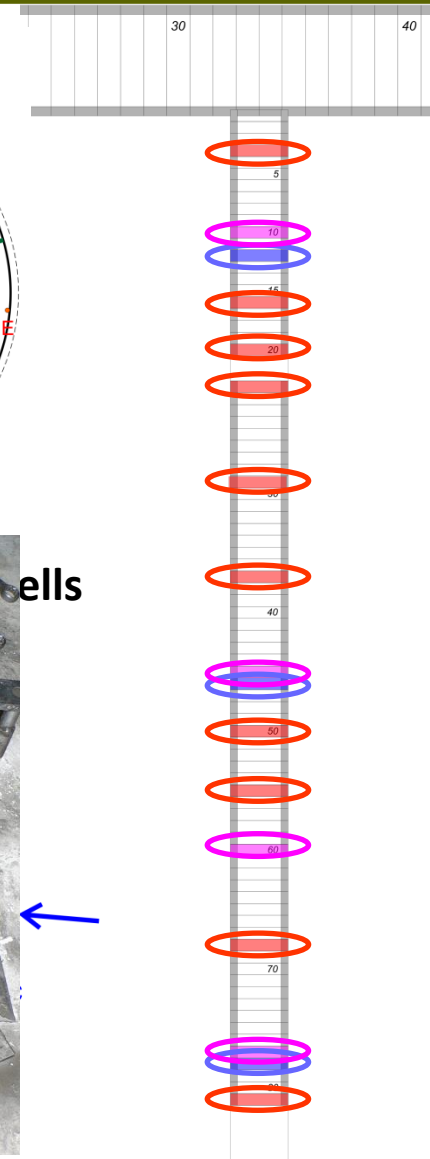
configuration B
(8 gauges)



— vibrating wire SG



ells

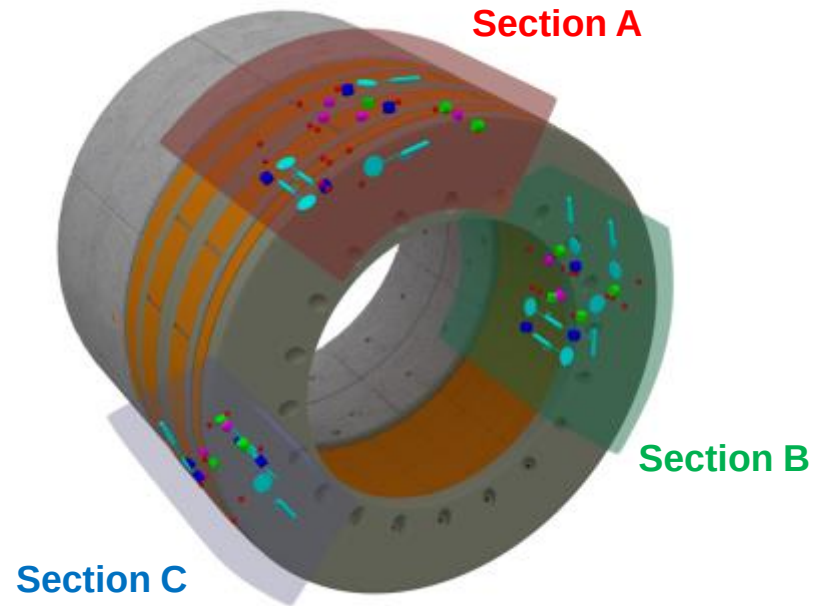


Seal instrumentation

Bentonite and its interfaces (Boom Clay & steel structure)

Instrumentation clustered in three sections

- porewater pressures
- total pressures
- thermocouples



SECTION B

RING 21

2a TC-B1 1a

2b PK-B2 TC-B6 1b

2c PK-B1 PG-B1 TC-B2 PP-B1 (twin tube)

2d TC-B12 PK-B3 TC-B8

2e PP-B6 RH-B4 1c

2f TC-B13 PG-B4 PG-B2 TC-B3 P-B3 RH-B2

2g PG-B5 TC-B10 1d TC-B4 TC-B5

RING 20

— total pressure cell (flatjack)

□ total pressure cell (Kulite)

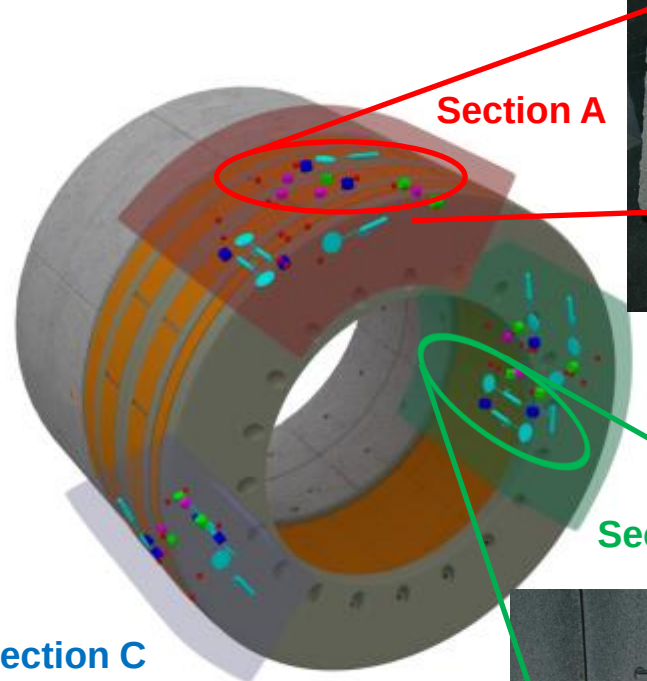
• thermocouple

▬ piezometer filter

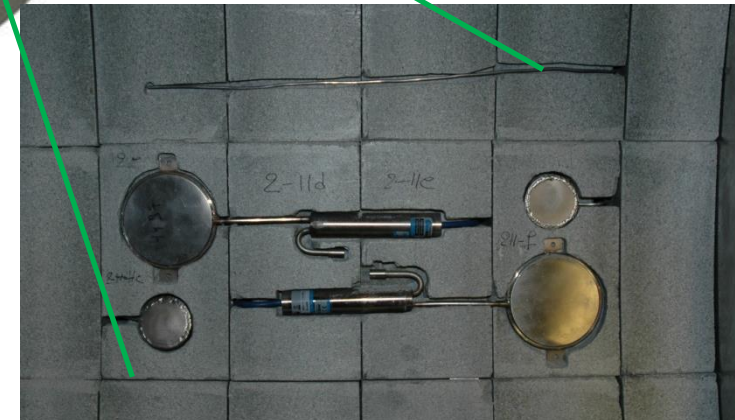
● piezometer filter with RH sensor



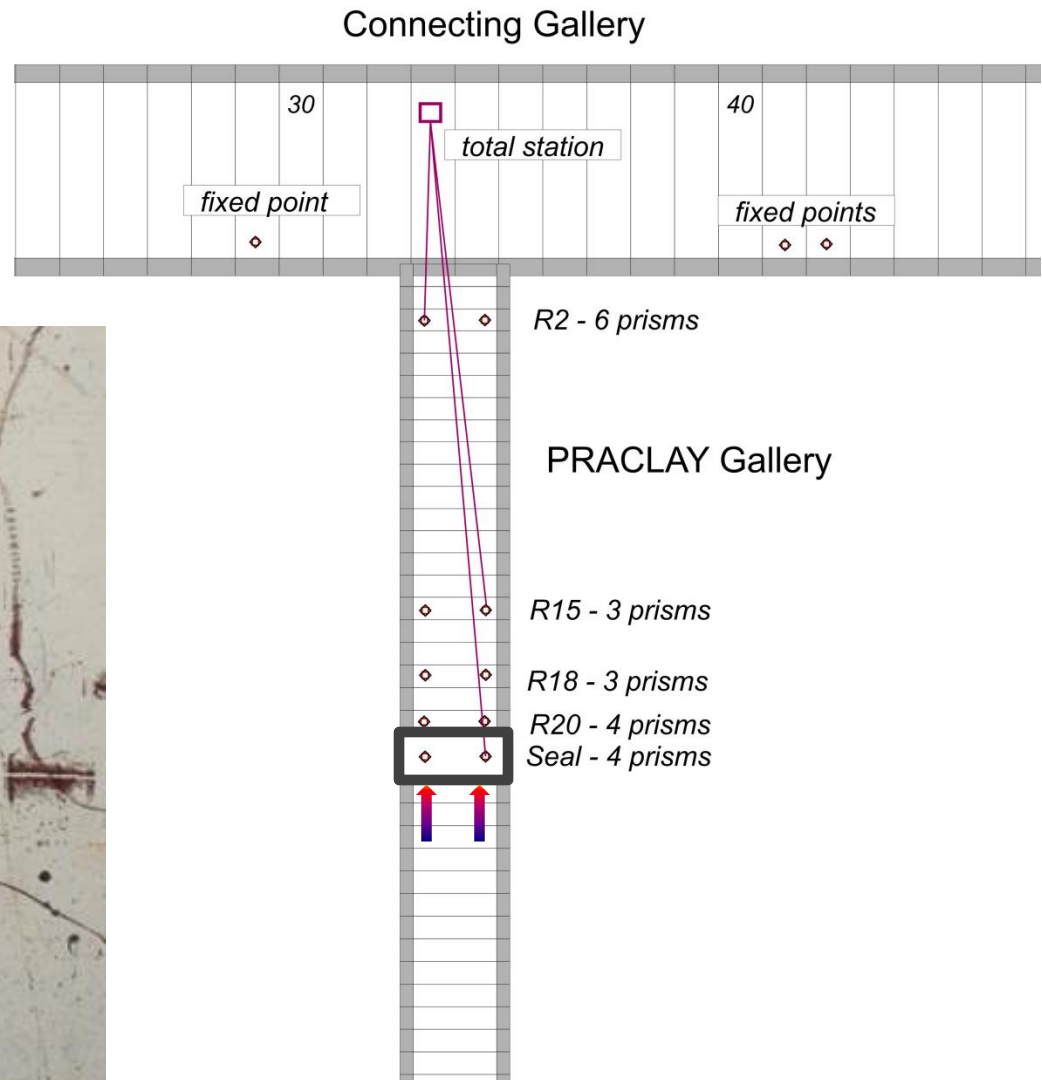
Seal instrumentation



Section C



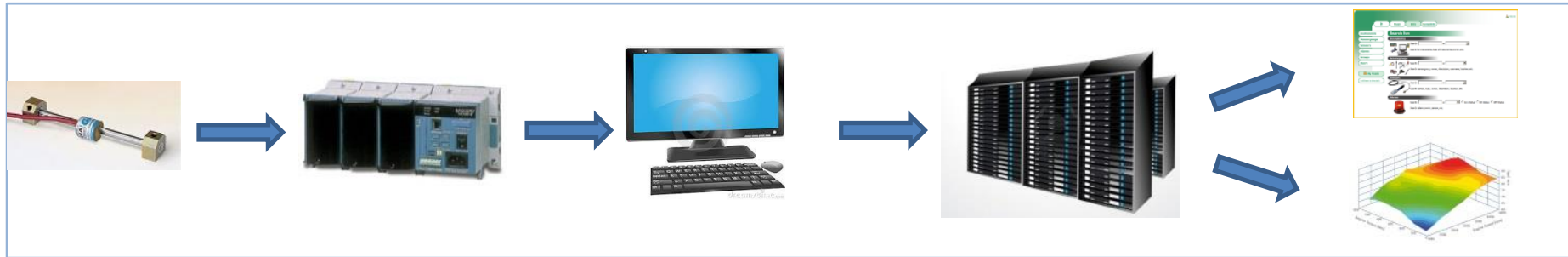
Total station for Seal (and PG) displacement



Outline

- Monitoring objectives
- Lay-out of the PRACLAY Monitoring Programme
- **Data management**
- Current status

Data management flow



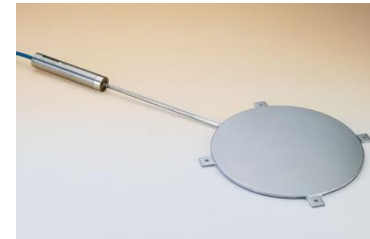
From sensor to presented data

Over 24000 new data points daily!

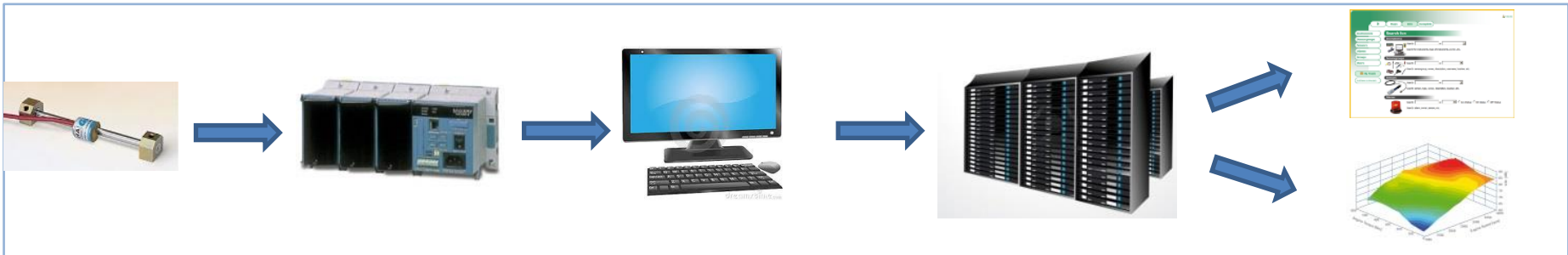
- Raw data (*sensor signal*)
- Engineered data (*physical value*)
- Corrected data (*e.g. logging errors, manipulations,...*)
- Validated data (*after interpretation by principal scientist*)

Data management - sensor input

- > 220 pore pressure transmitters
- > 600 temperature sensors
- 70 total pressure sensors



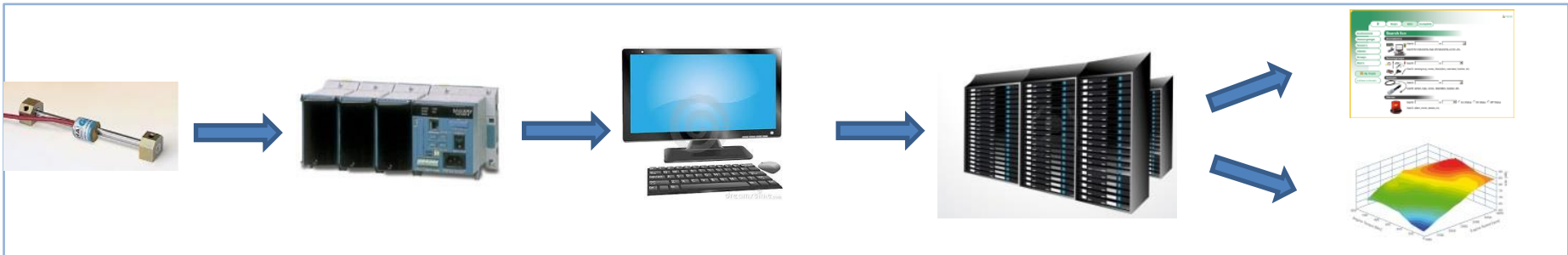
Sensors



Data management - logging

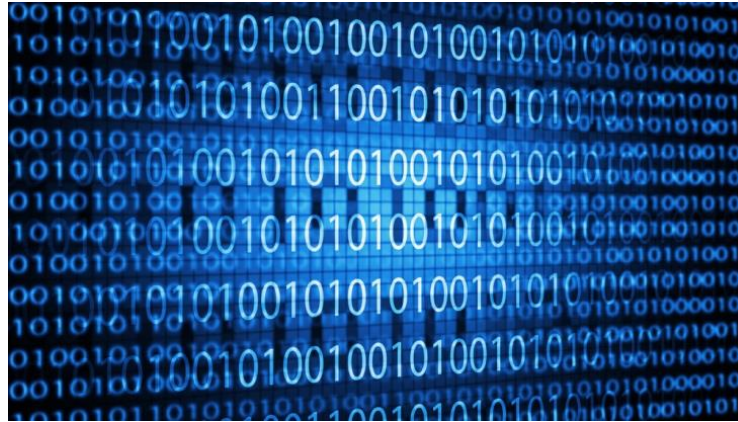
30 Logging units

Loggers

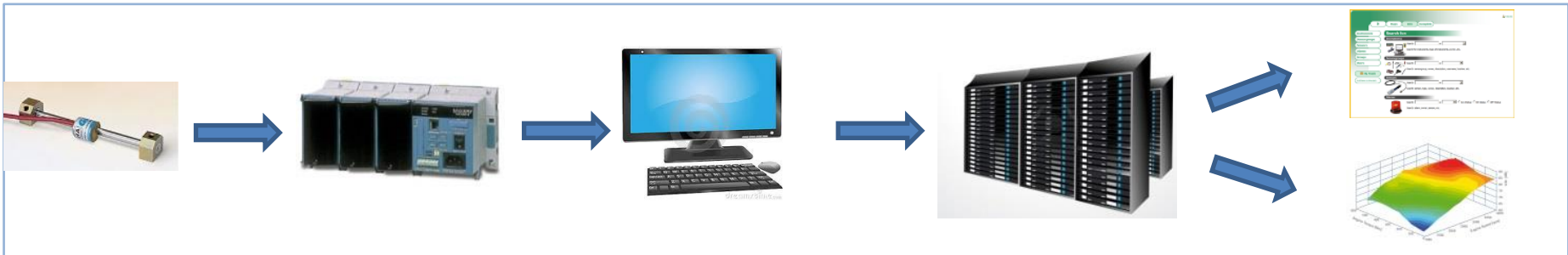


Data management - control

1 DAQ PC



DAQ PC



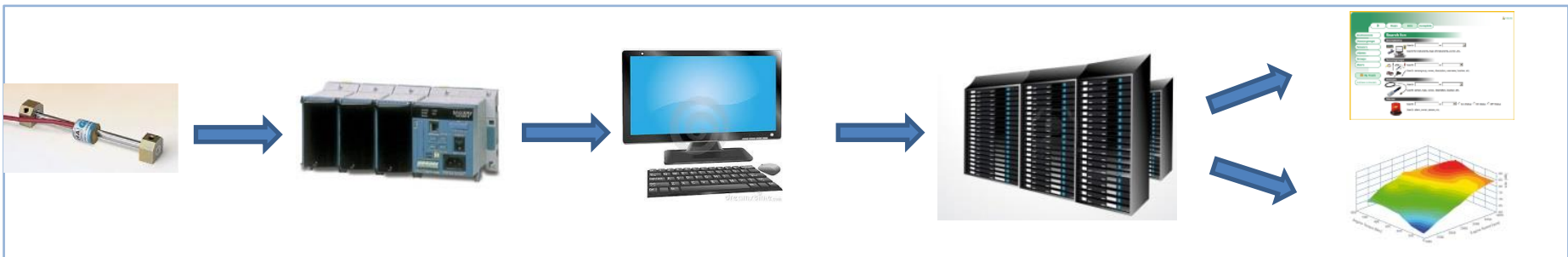
Data management - database

1 Database

from raw to final data



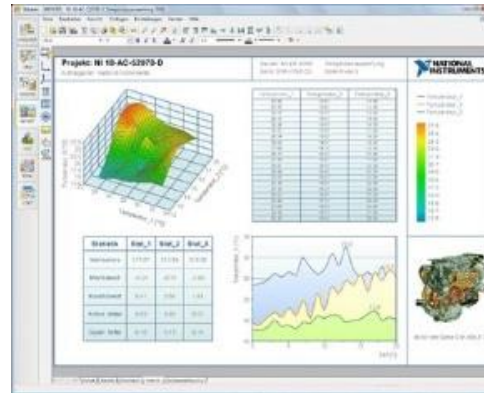
Data server



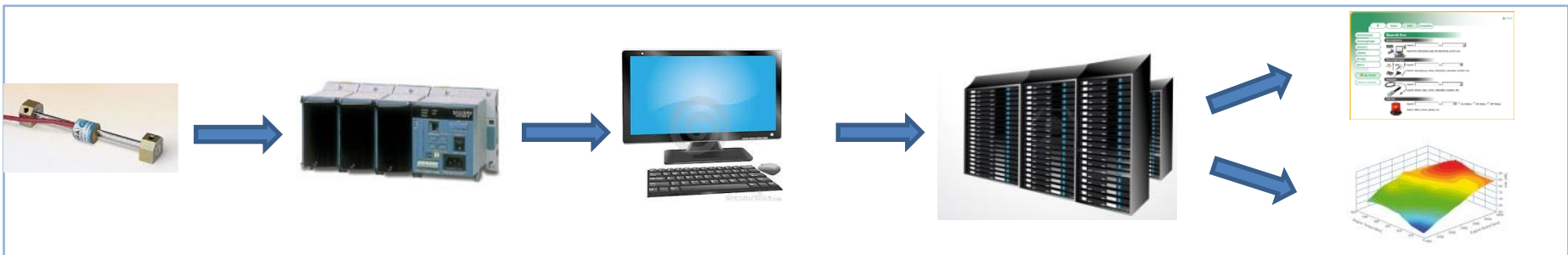
Data management - data output

2 Visualization systems

customized screens & reports

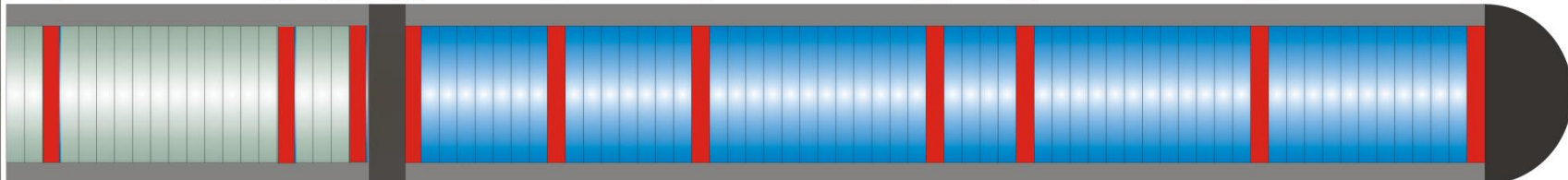


Visualization



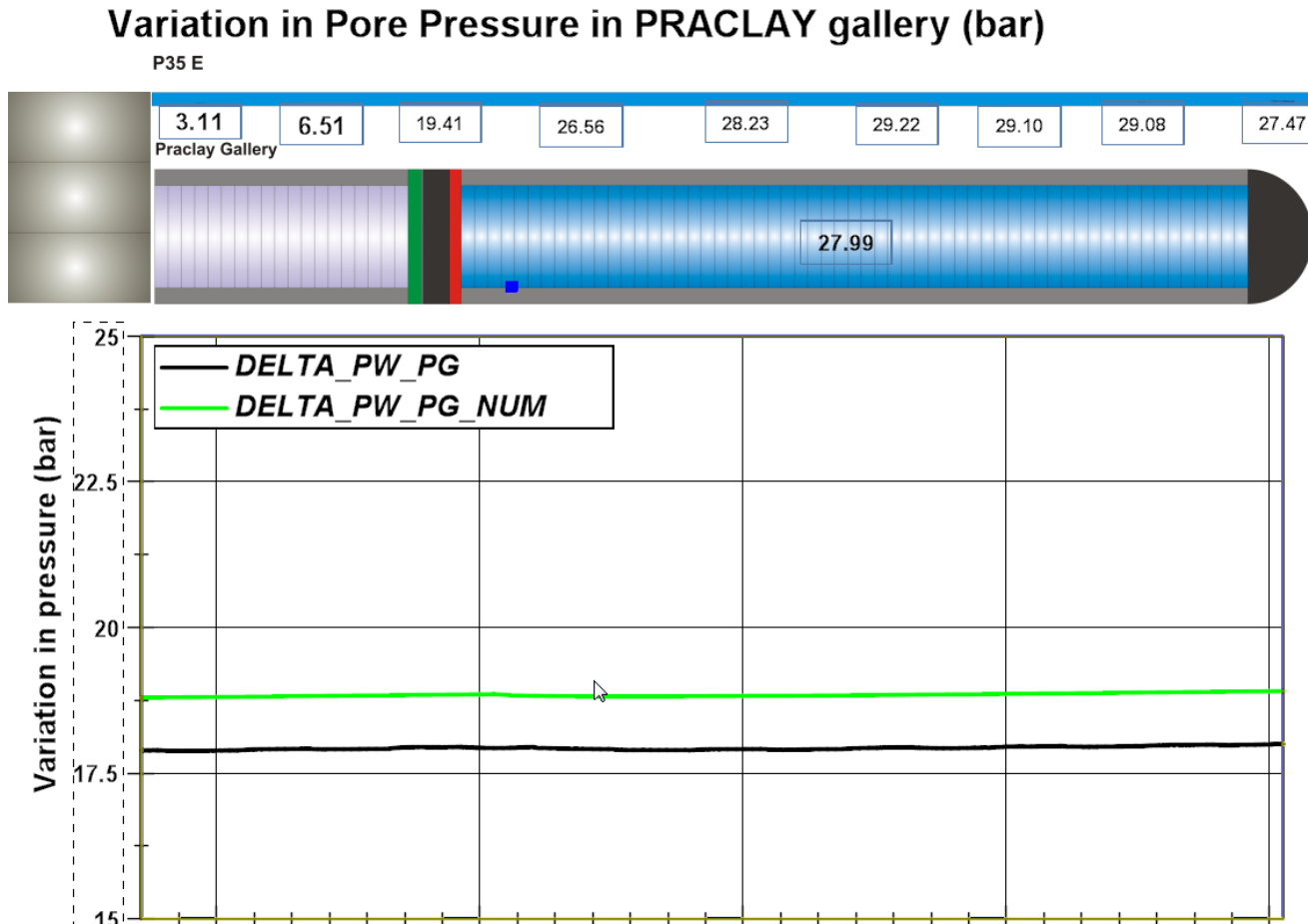
PRACLAY Heater Control

3 16 20 21 29 37 50 55 68 81



Data management - data output

Immediate comparison field data with model predictions



Data management - data output

Safety Reports

Daily safety report: 2016-04-18 07:51

System is Online

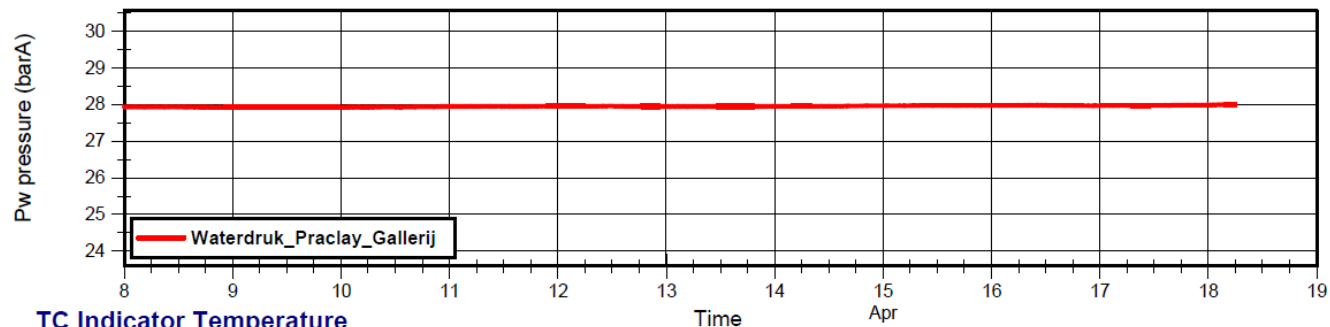


ESV EURDICE GIE

PRACLAY Gallery PWP pressure

The PRACLAY backfill pressure safety limit is 30 bar. Decreasing pore water pressure can be an indication for seal leakage.

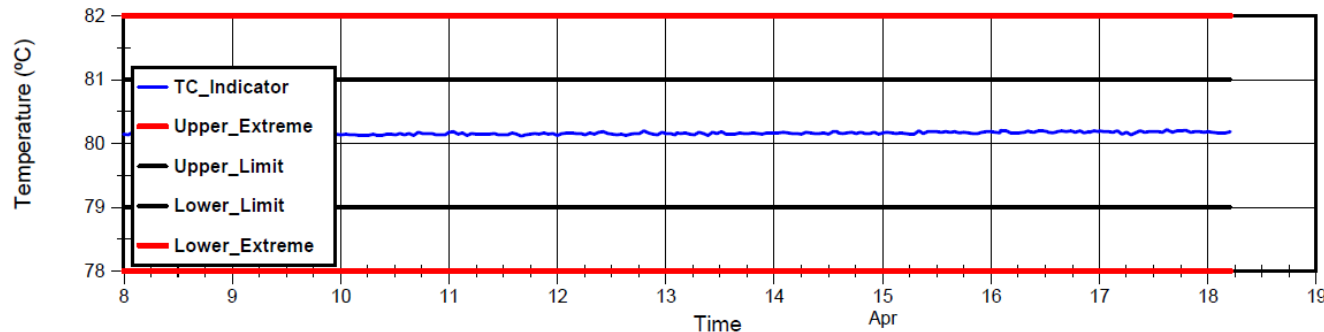
This sensor is connected to saturation filter 6.



TC Indicator Temperature

The TC_Indicator is the average of extrados thermocouples, R37_2 R37_4 R37_6 R50_2 R50_4 R50_6 R50_8

R55_2 R55_4 R55_6 R55_8. The deviation from 80 °C should remain lower than 2 °C initiate procedure



Outline

- Monitoring objectives
- Lay-out of the PRACLAY Monitoring Programme
- Data management
- **Current status**

Performance of the monitoring set-up

Sensors

- overall good performance
 - some (expected) failure
 - inherent to experimental set-up
 - depending on sensor type or location
- => enough redundancy built in for continuous follow-up

Data management

- current system allows efficient follow-up
- further development/improvement of database functionality (including data validation)

20th Exchange Meeting

The PRACLAY Heater test

First results after one and a half years of heating



First results PART 1

OBSERVATIONS during one and a half year of heating

20th Exchange Meeting

Mol, 4 May 2016

Arnaud Dizier

EIG EURIDICE



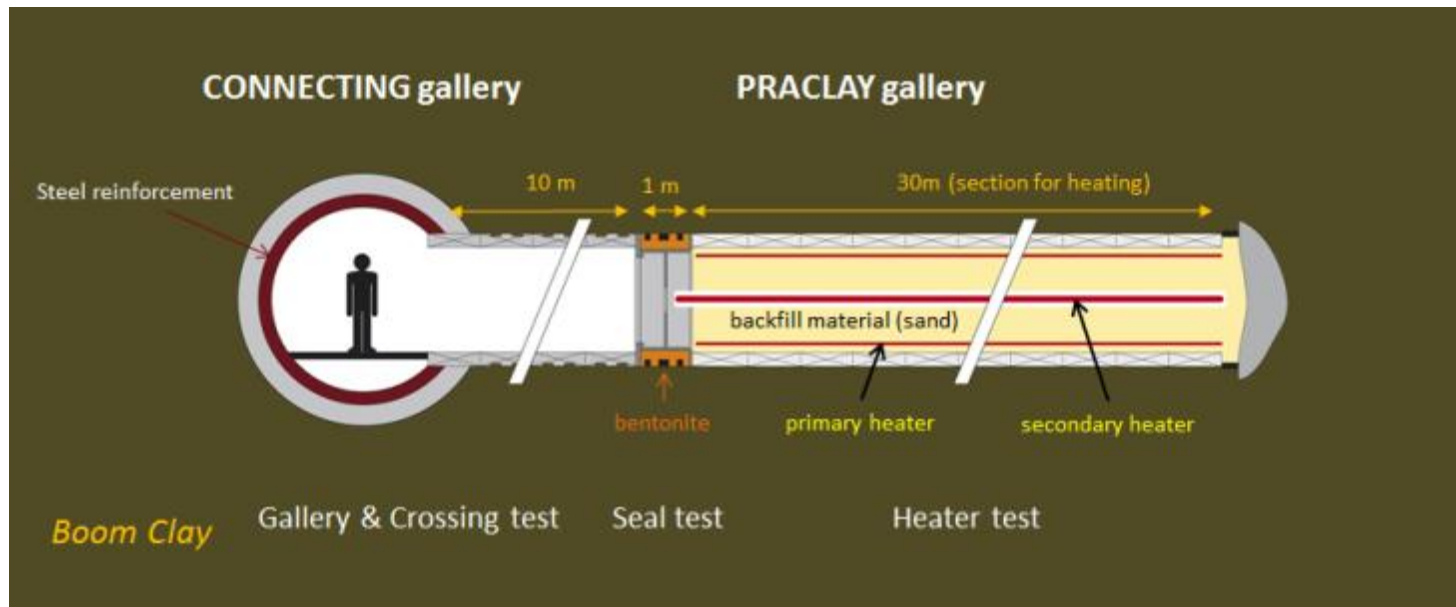
ONDRAF/NIRAS



ESV EURIDICE GIE

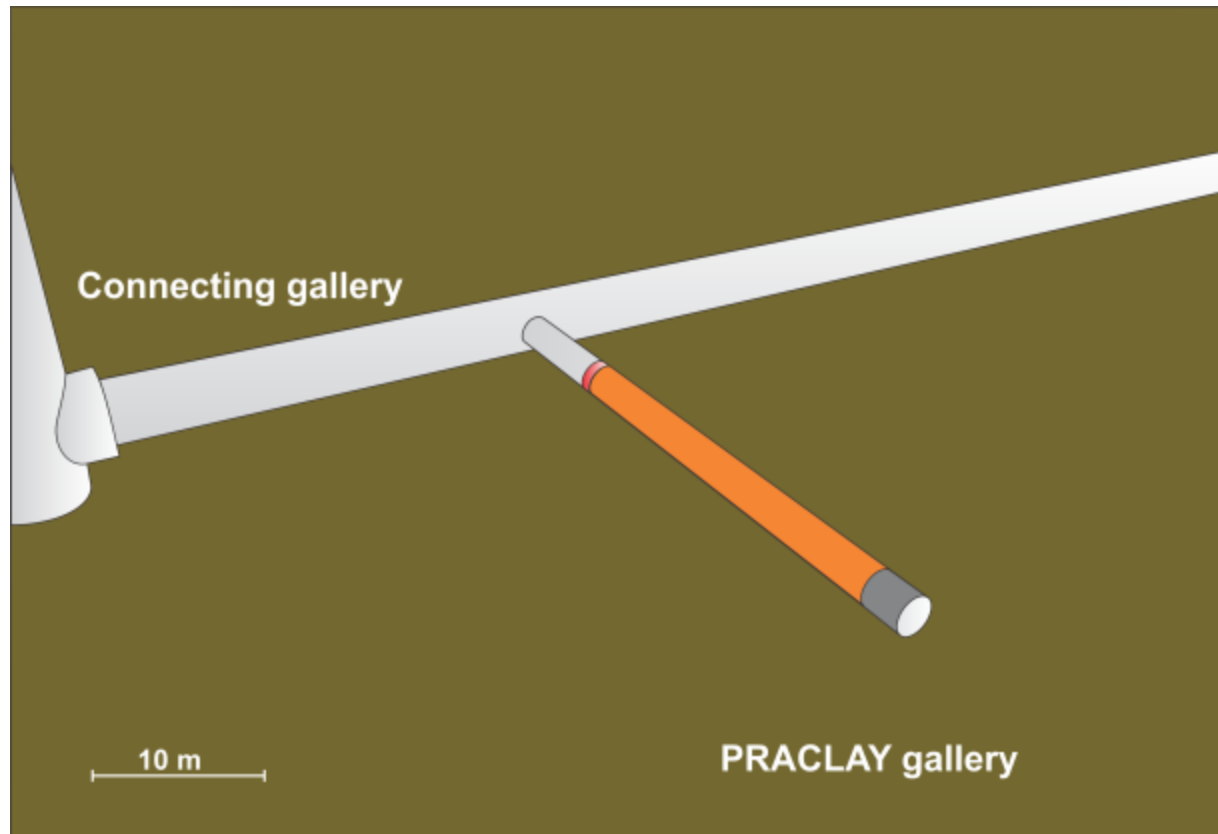


The PRACLAY Heater test



The PRACLAY Heater test

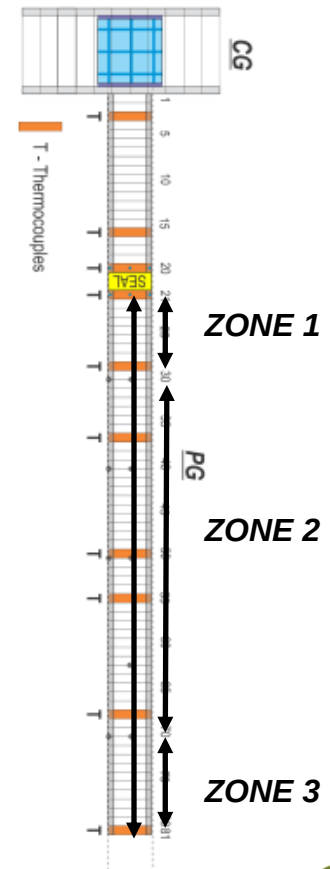
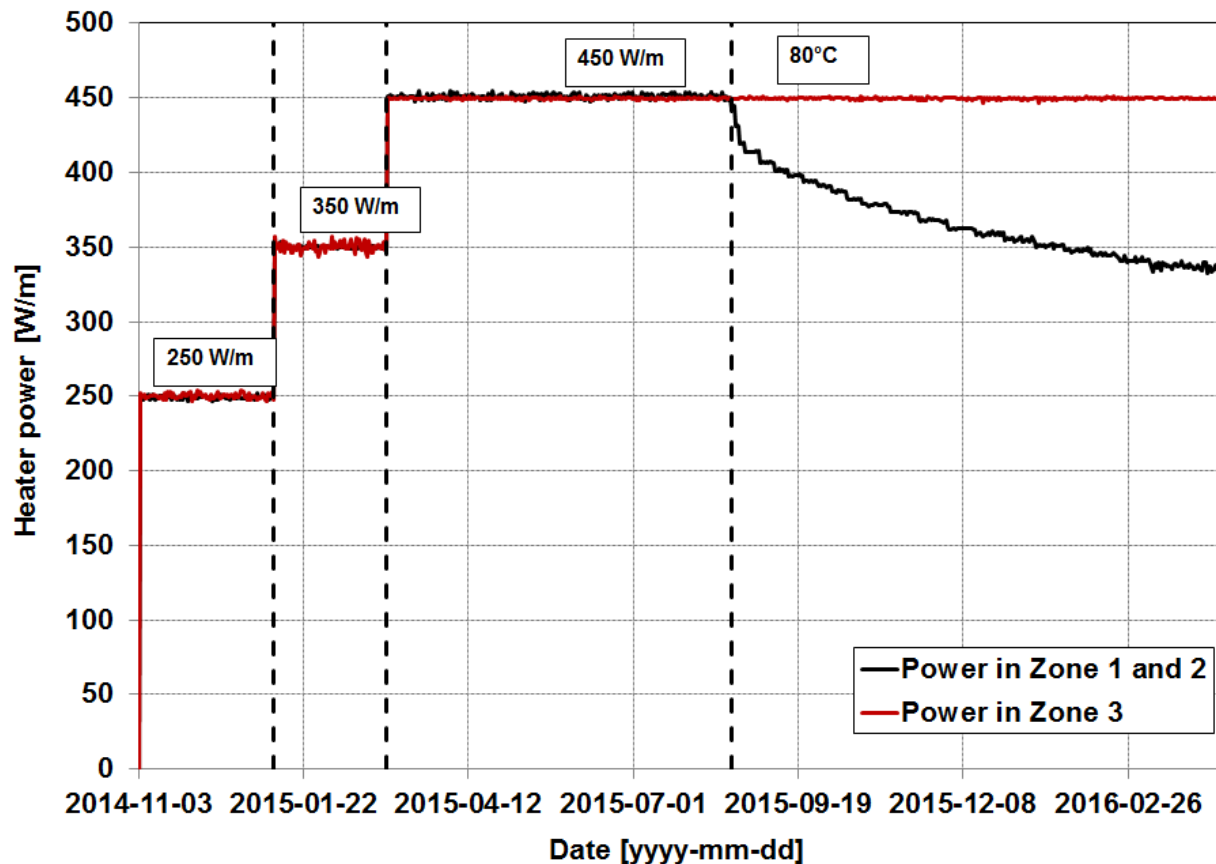
- ❑ Monitoring network: temperature, pore water pressure, stresses...



The PRACLAY Heater test

□ PRACLAY thermal loading:

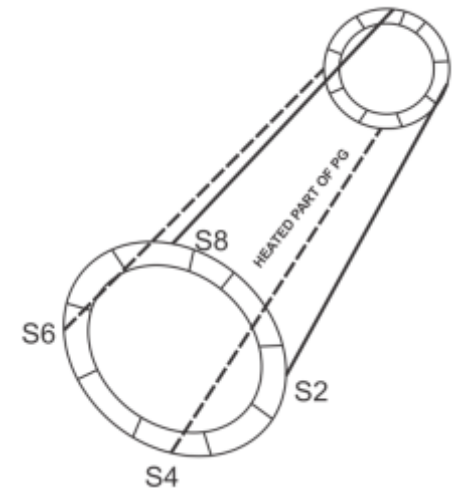
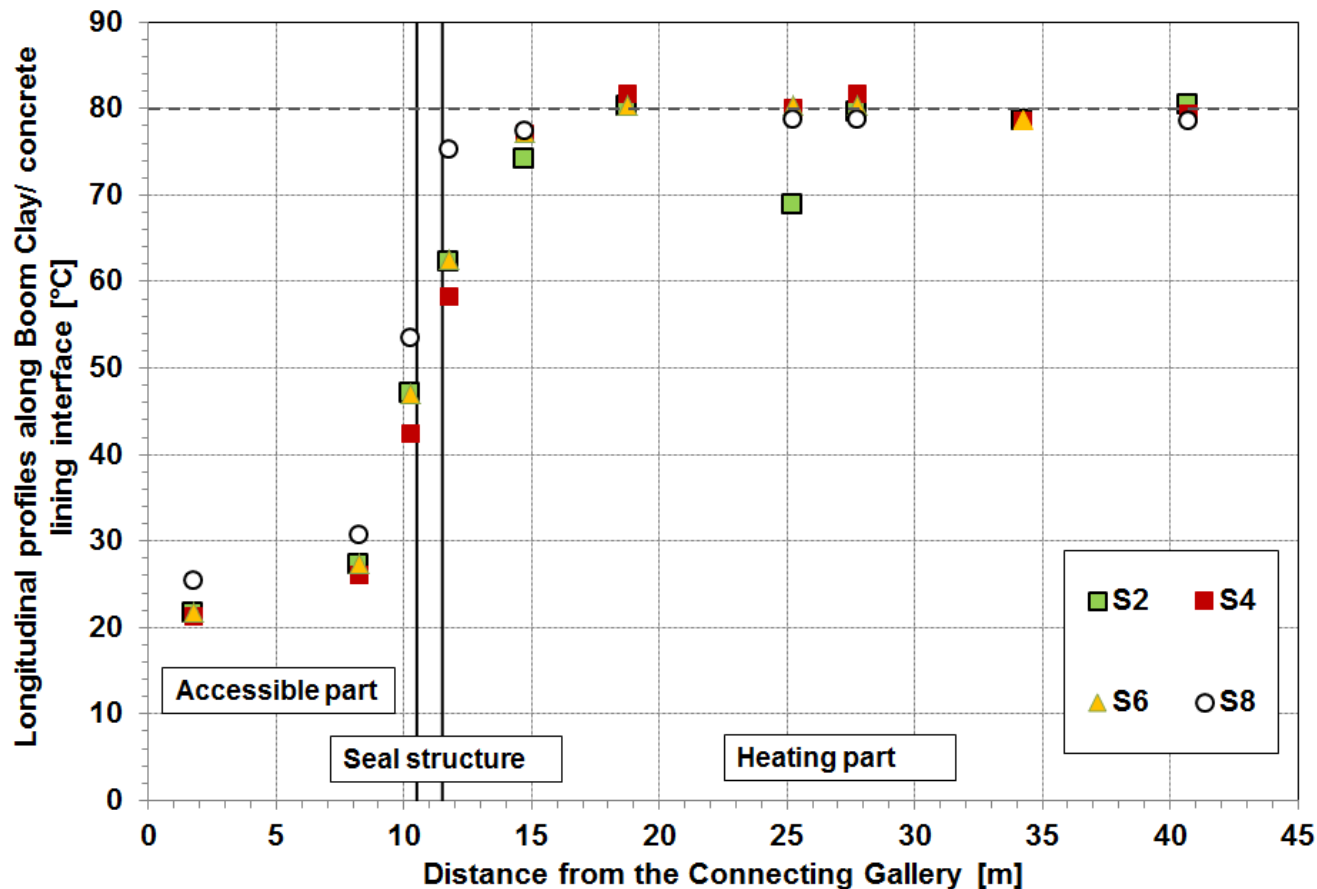
- 3 heating steps to reach 80°C at Boom Clay/ concrete lining interface
- 250 W/m = heat flux representative from a nuclear waste repository



The PRACLAY Heater test

PRACLAY thermal loading:

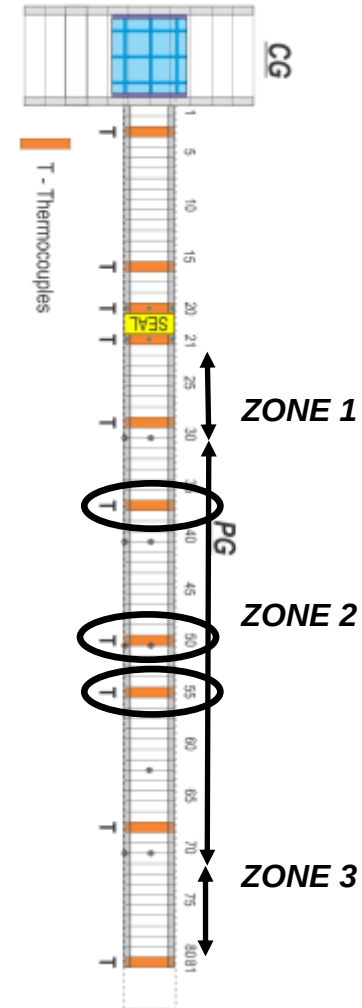
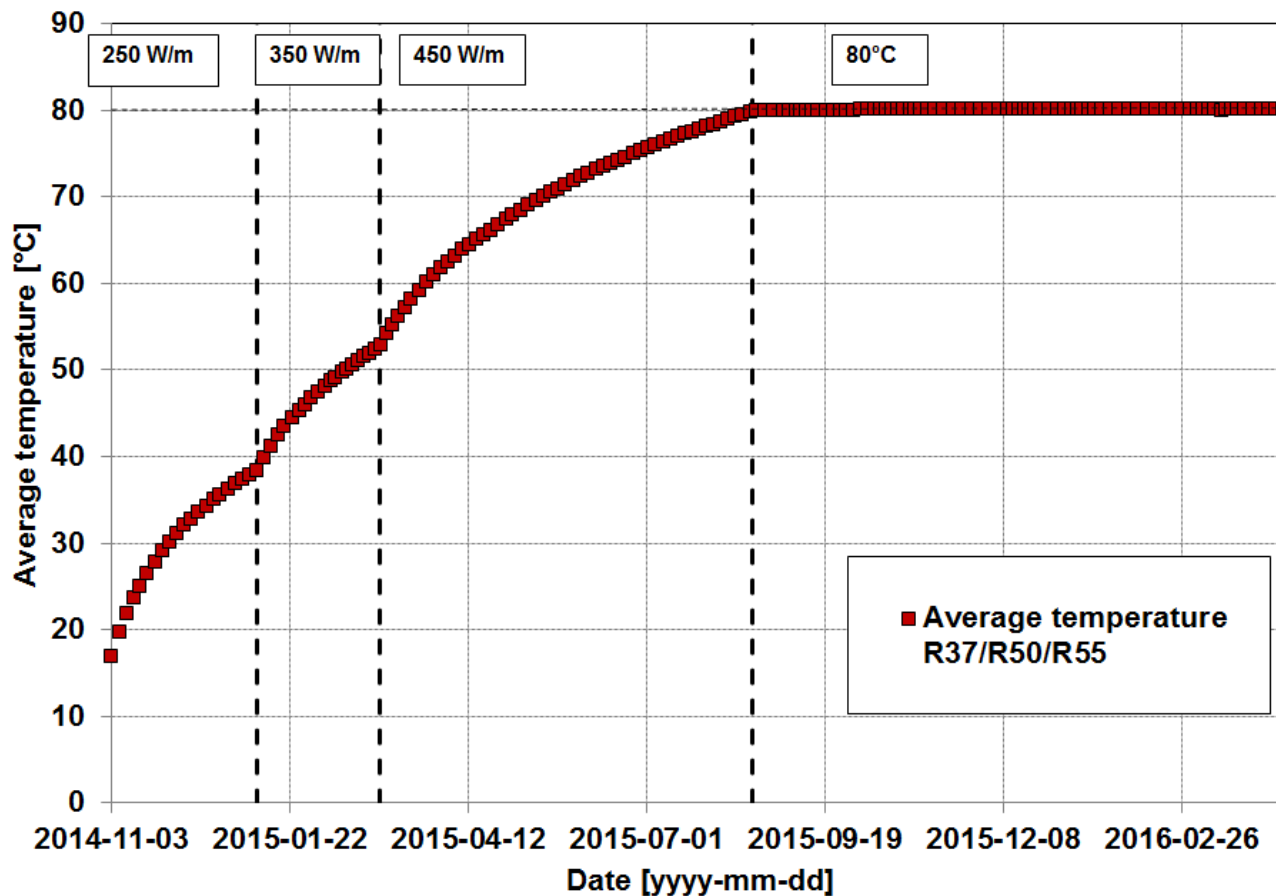
- Increase of the temperature in the concrete lining
- Current situation: 80°C at Boom Clay/ lining interface



The PRACLAY Heater test

□ PRACLAY thermal loading:

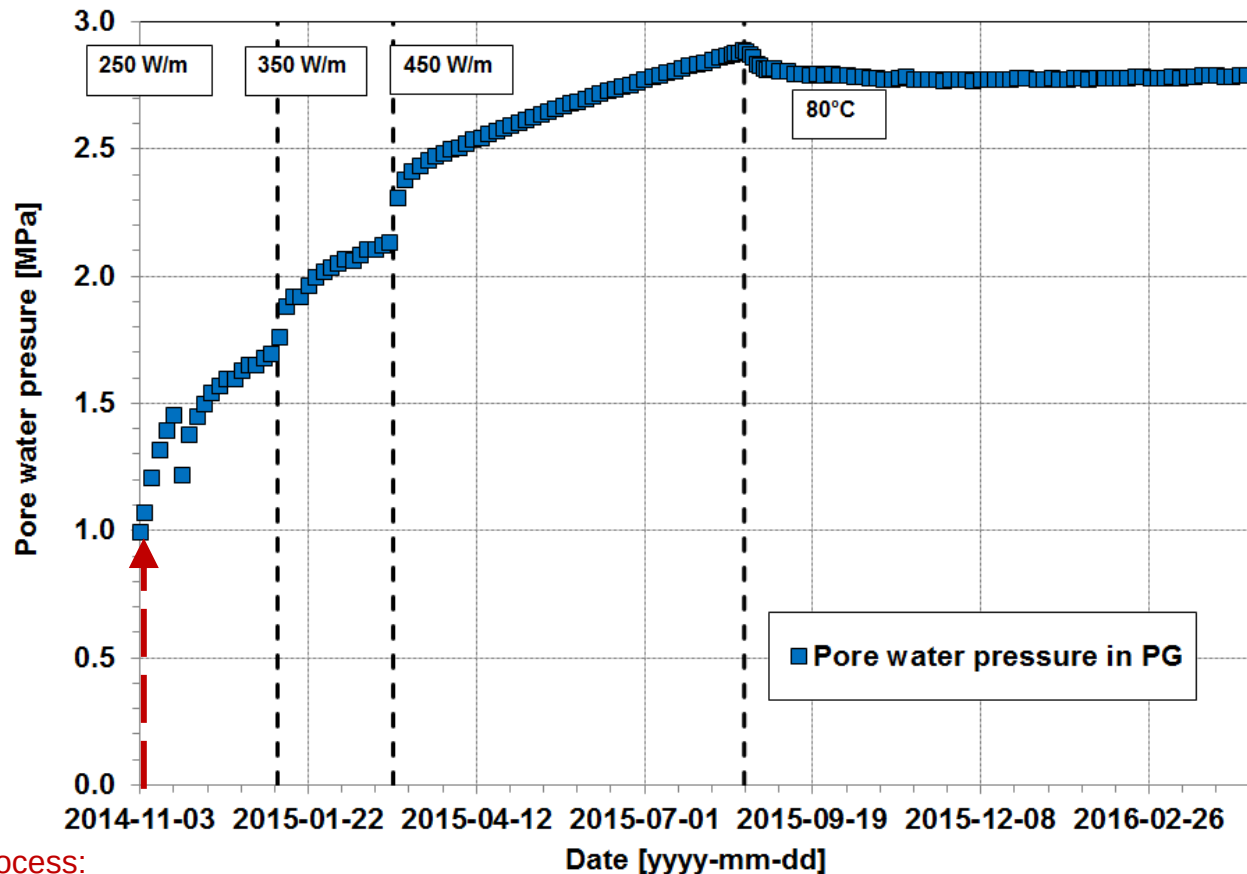
- Increase of the temperature in the concrete lining
- Current situation: 80°C at Boom Clay/ lining interface



The PRACLAY Heater test

□ PRACLAY thermal loading:

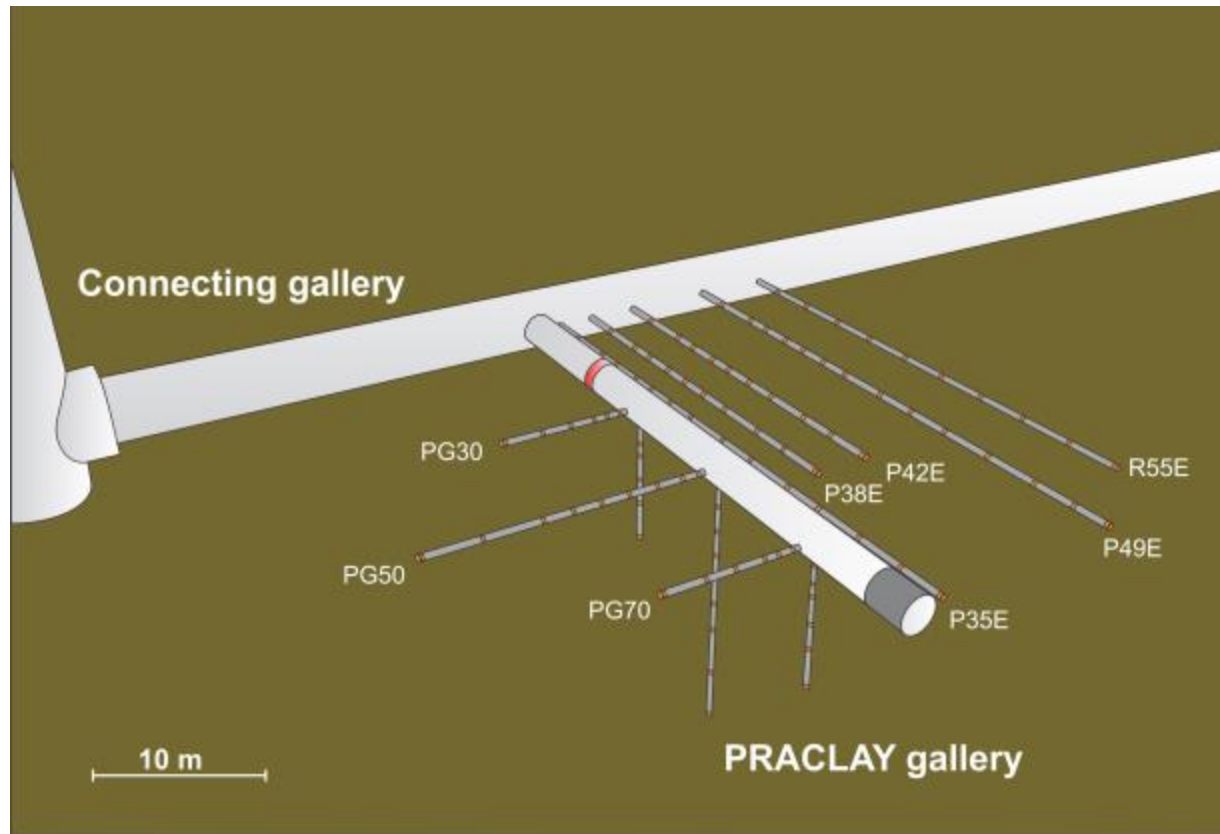
- Increase of the pore water pressure inside PG



Pressurization process:
Initial pore pressure in PG = 1 MPa

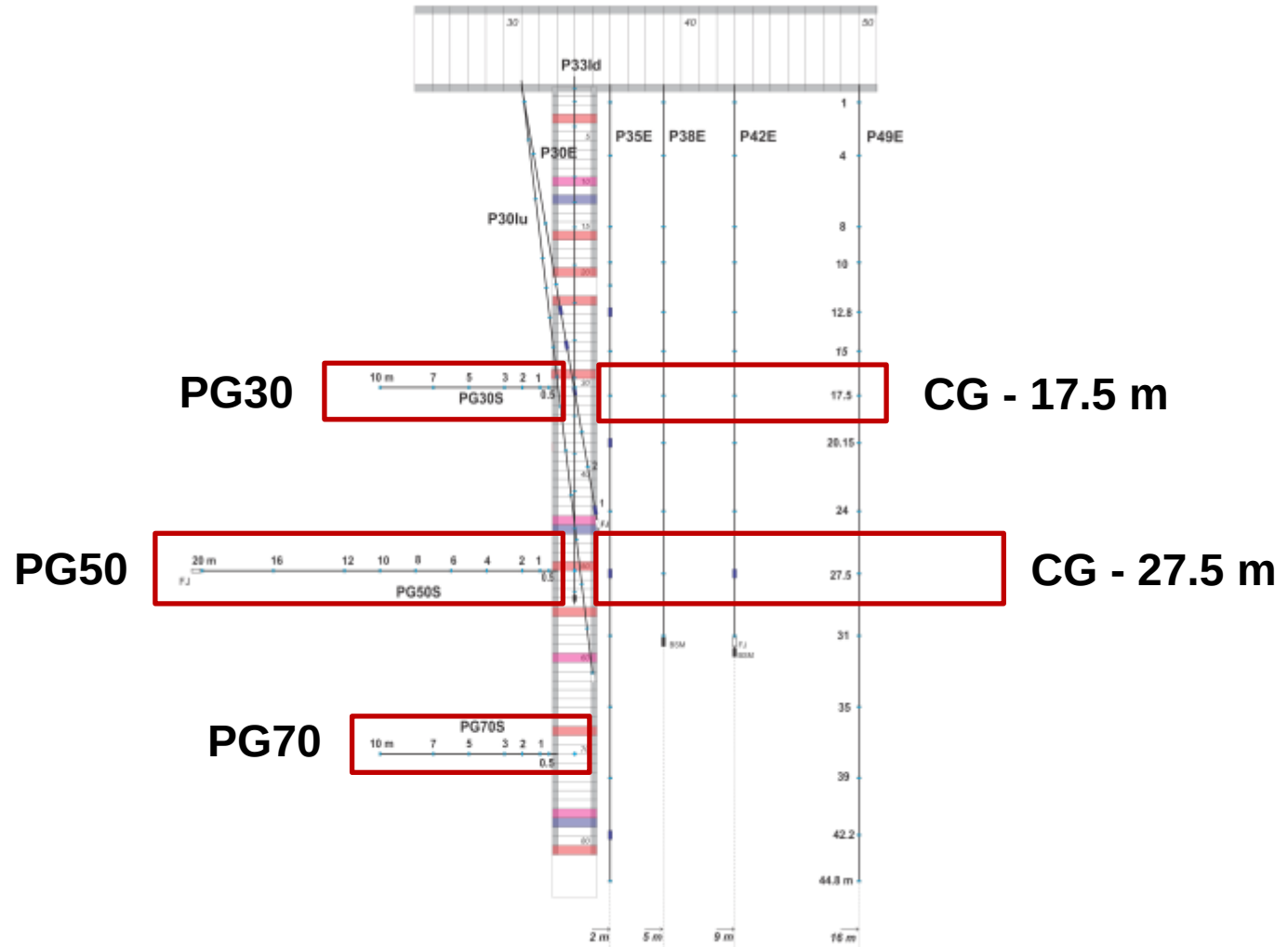
The PRACLAY Heater test - Observations

- ❑ What do we observe in the Boom Clay?



The PRACLAY Heater test - Observations

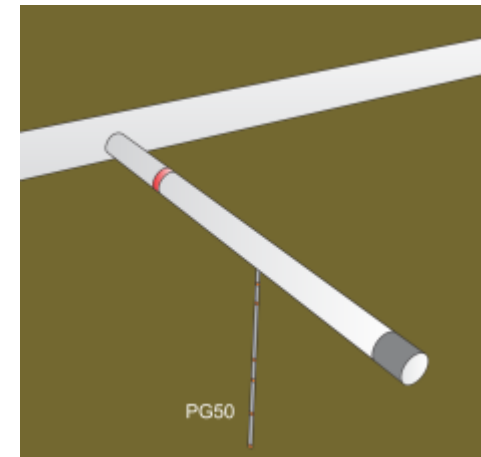
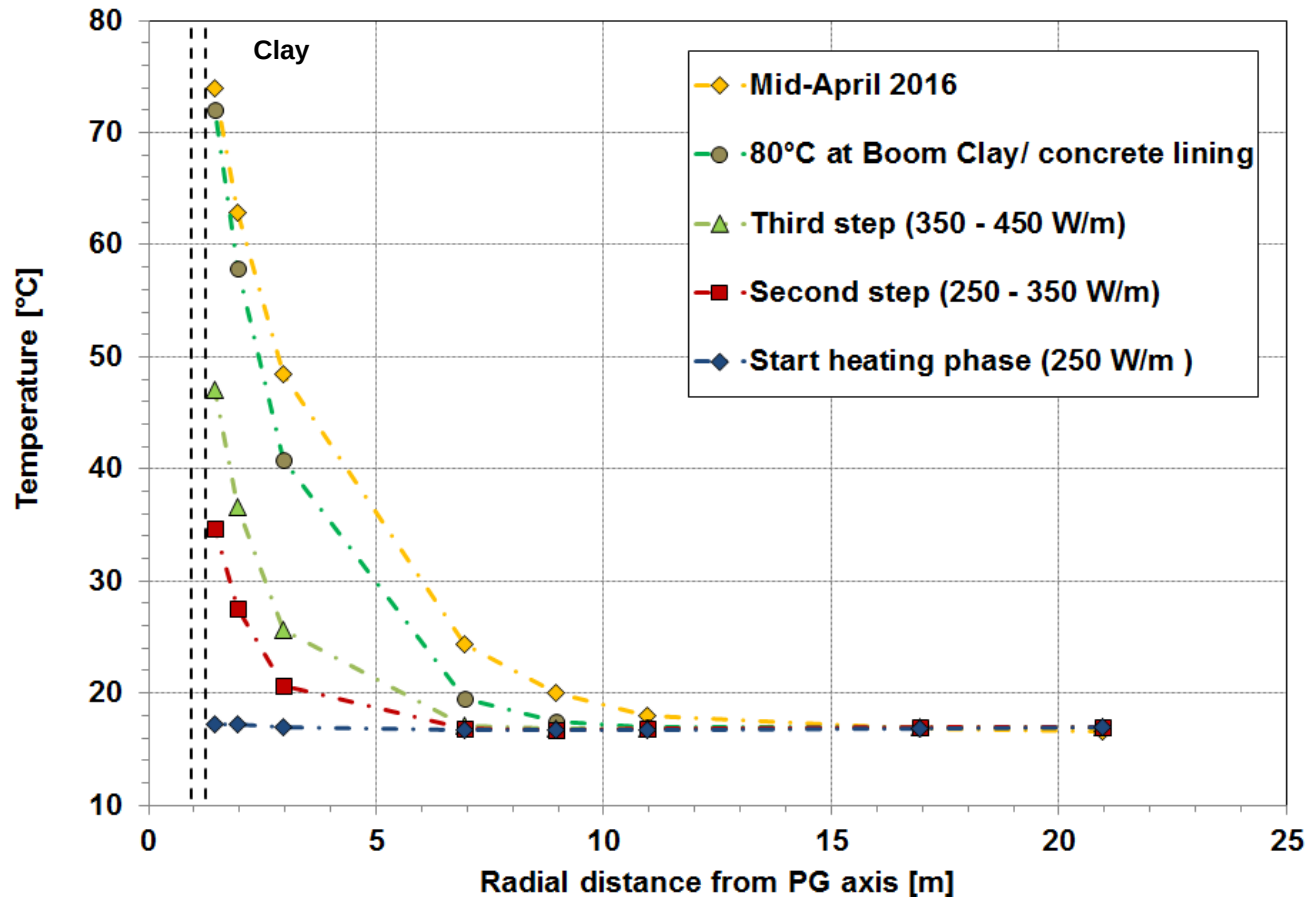
❑ What do we observe in the Boom Clay?



The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

- Temperature profiles in the clay (PG50D)

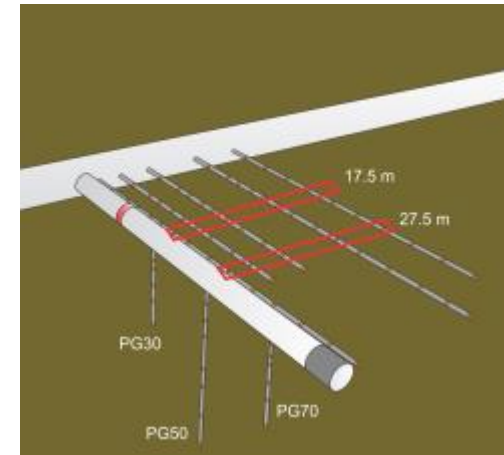
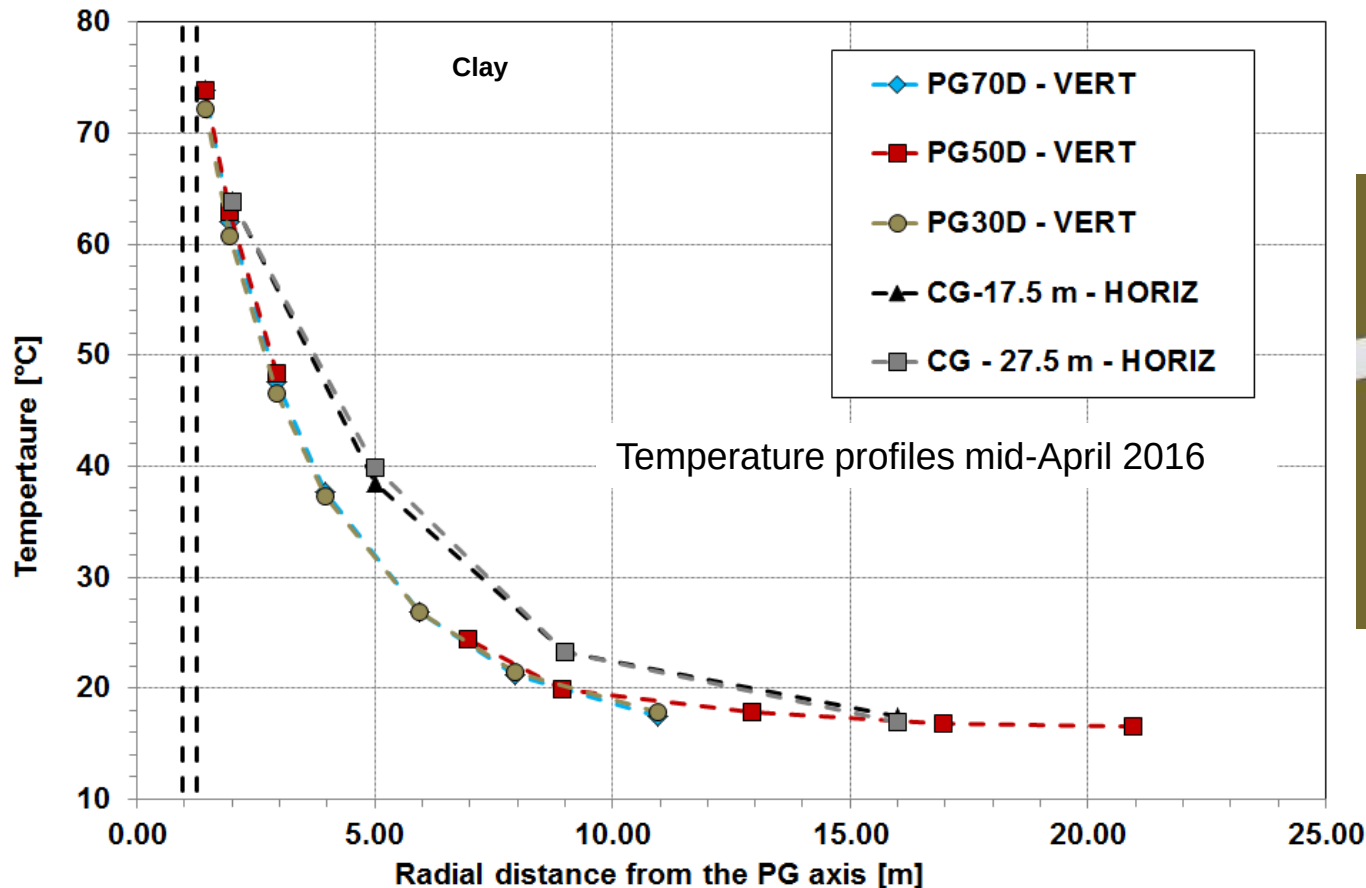


Extension of the thermally affected zone : around 10 m

The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

- Temperature profiles in the clay (Vertical/ horizontal)

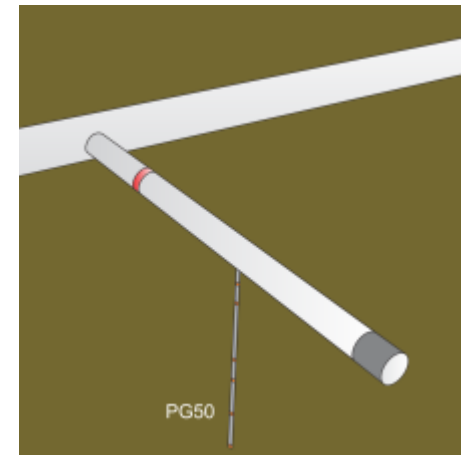
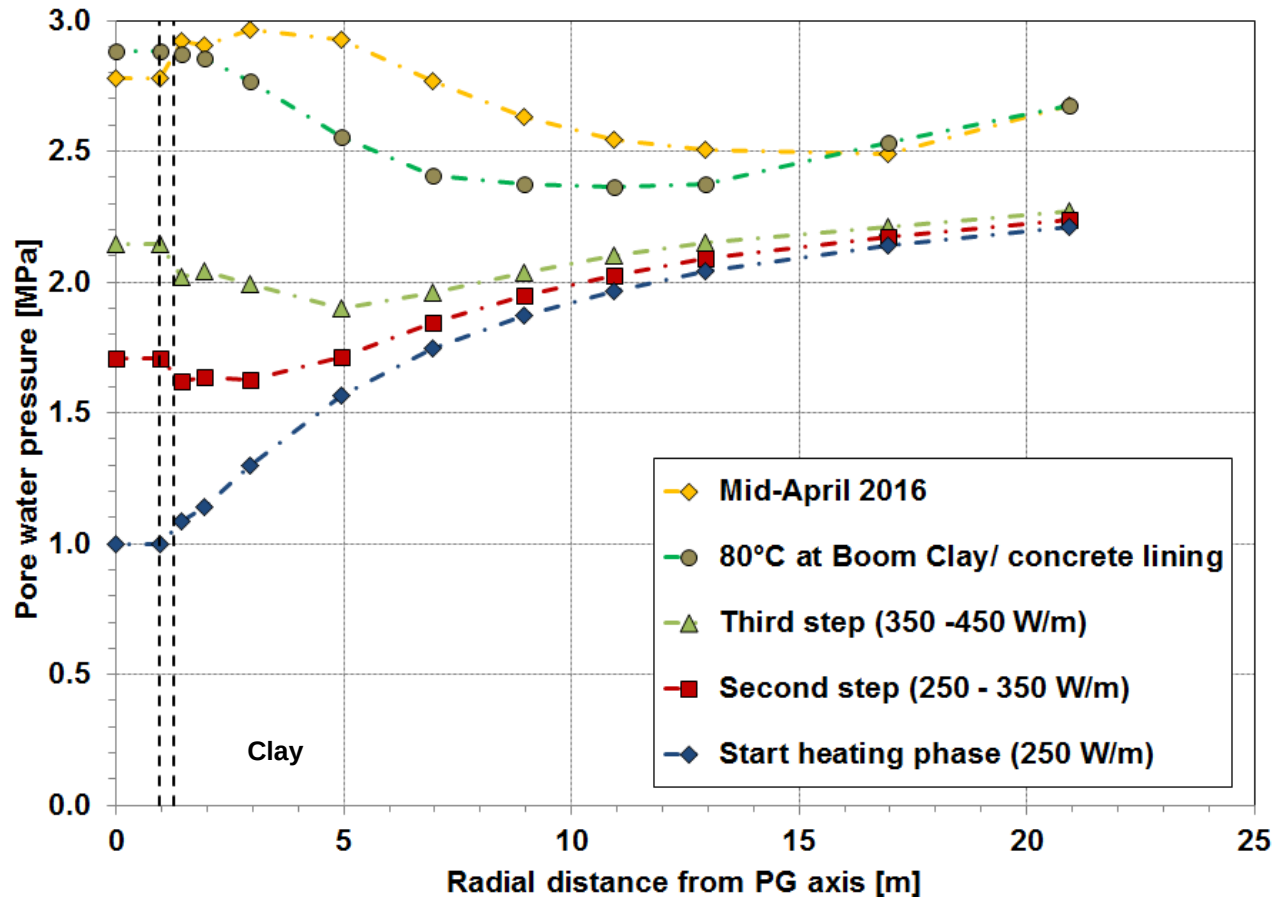


Extension of the thermally affected zone : around 10 m

The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

- Pore water pressure profiles in the clay (Vertical direction, PG50D)

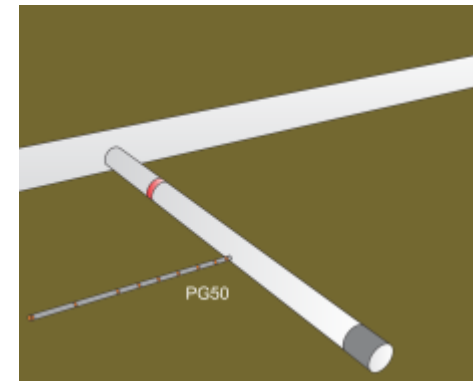
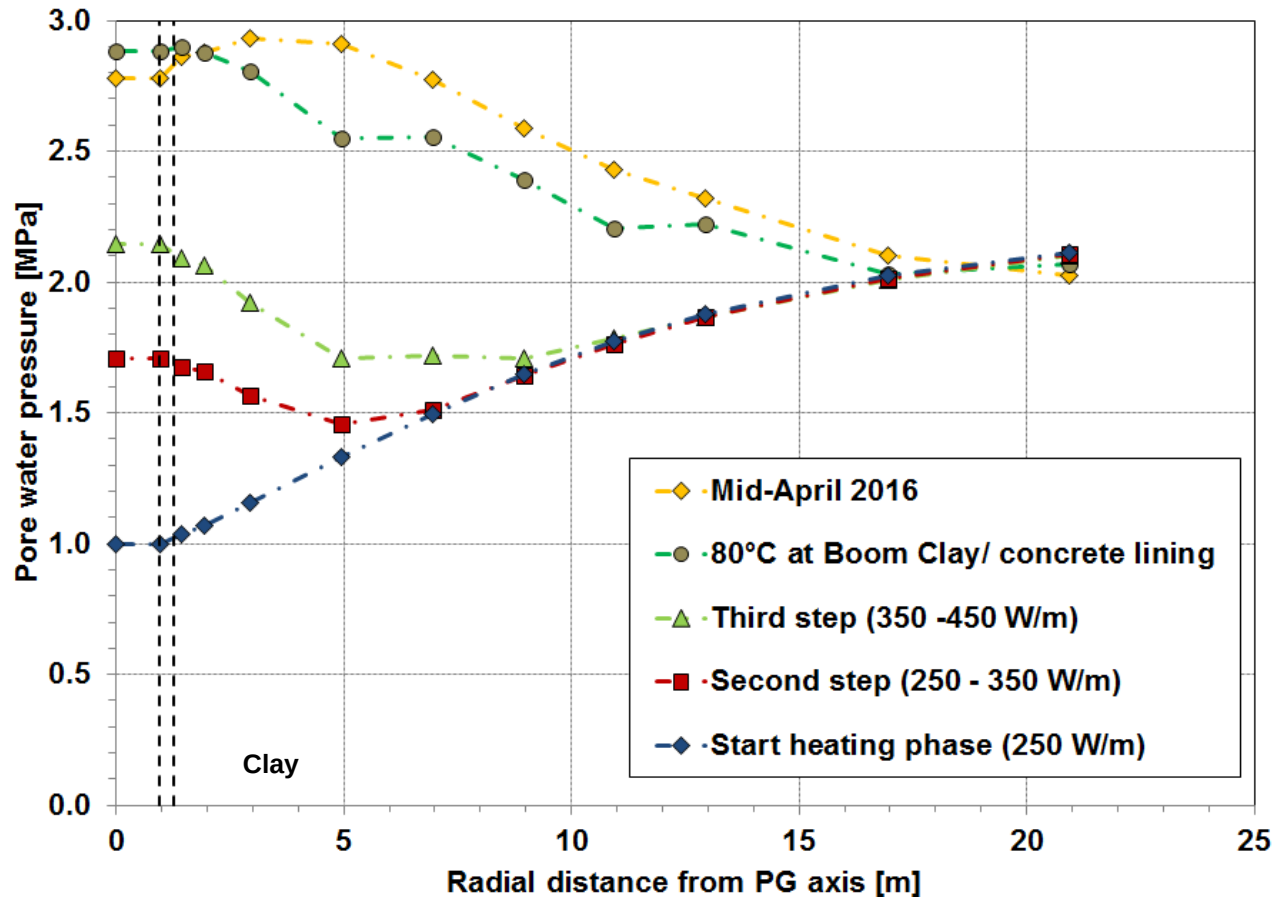


Extension of the hydraulic affected zone : around 15 m

The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

- Pore water pressure profiles in the clay (Horizontal direction, PG50S)

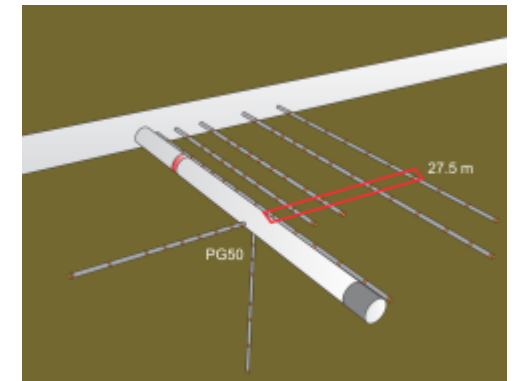
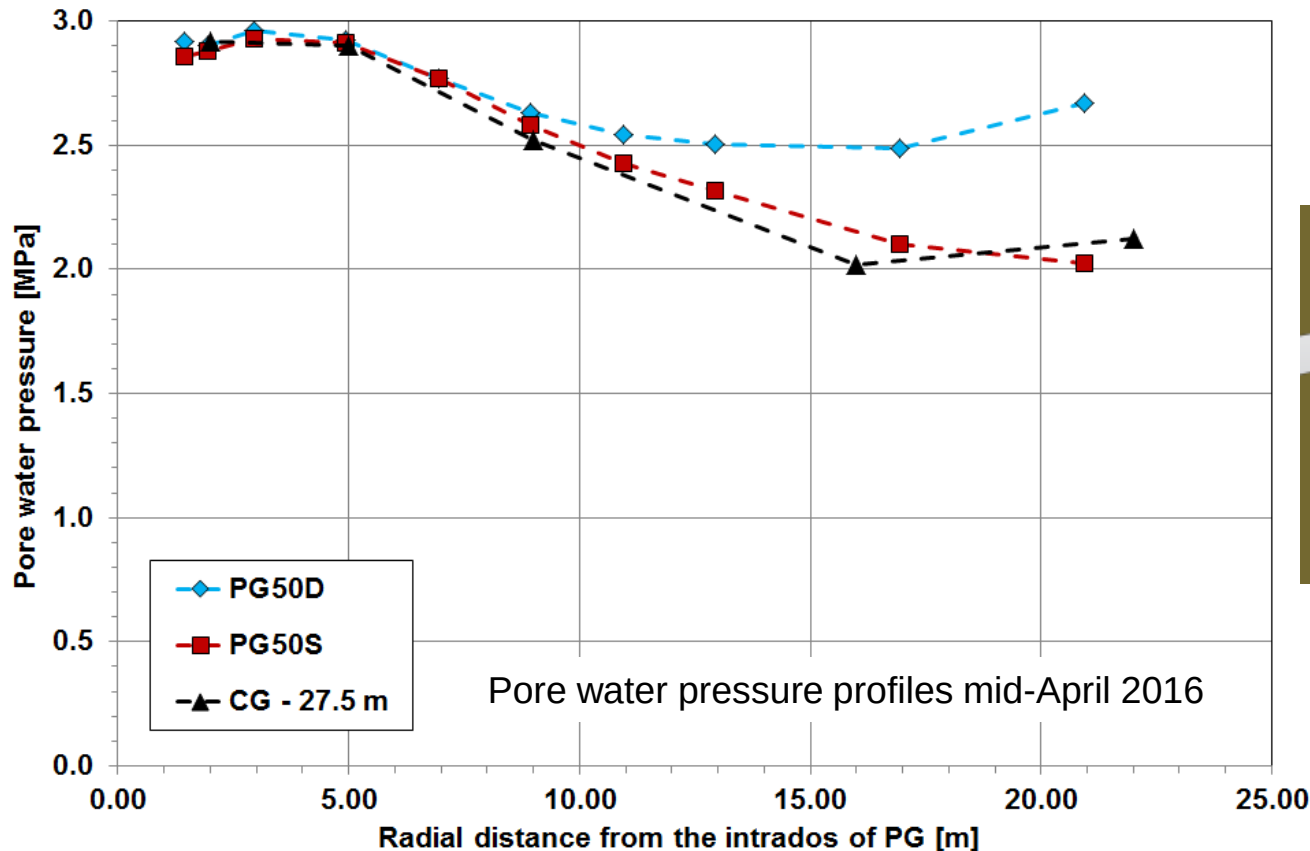


Extension of the hydraulic affected zone : around 15 m

The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

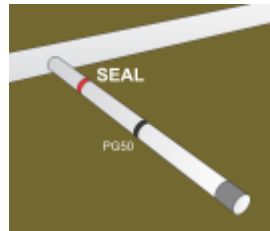
- Pore water pressure profiles in the clay (Vertical/ Horizontal)



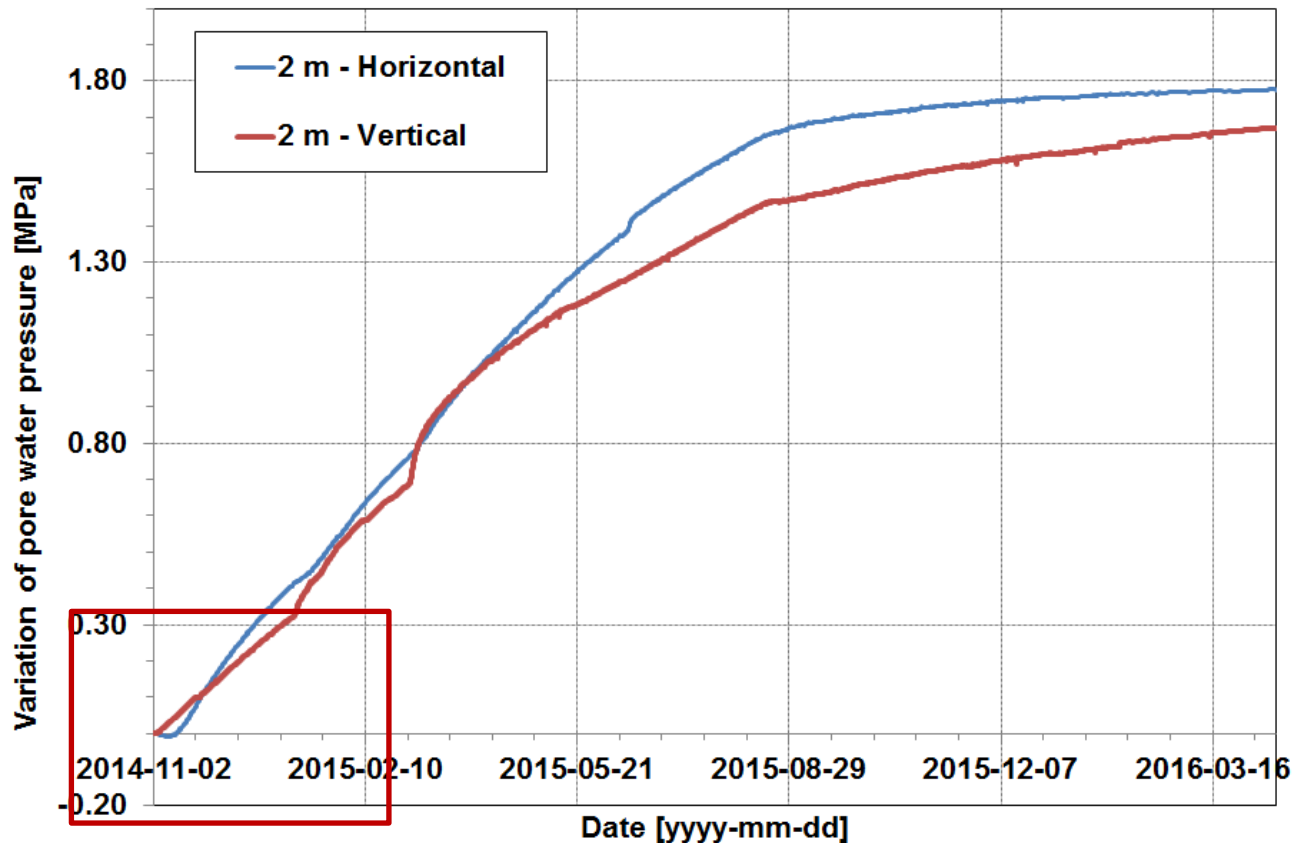
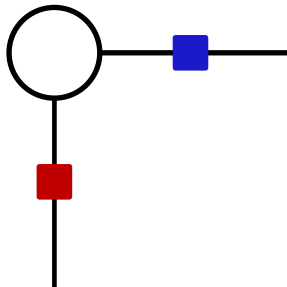
The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

- Pore water pressure variation in the clay (vertical vs horizontal)



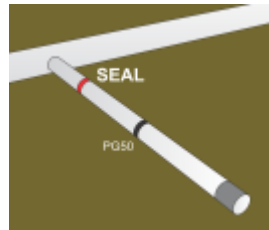
PG50



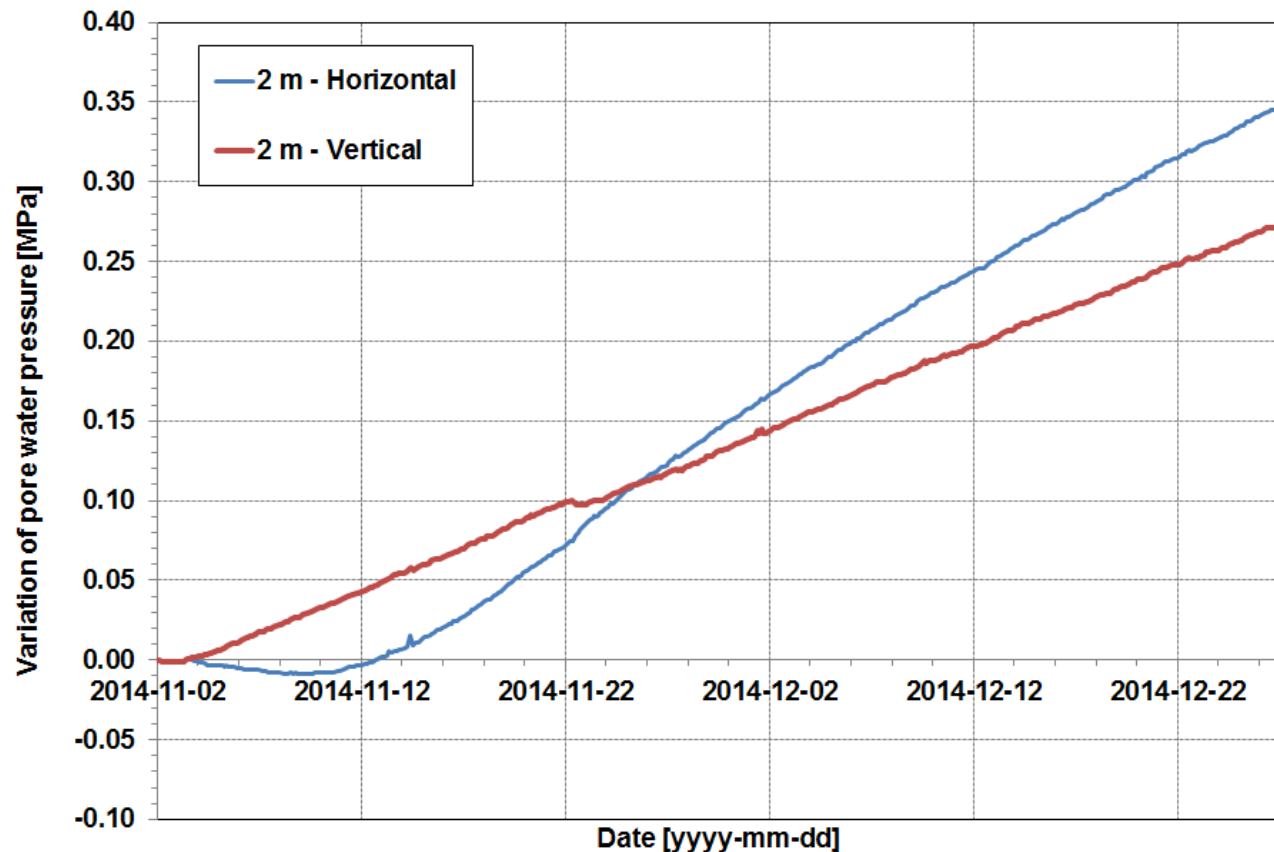
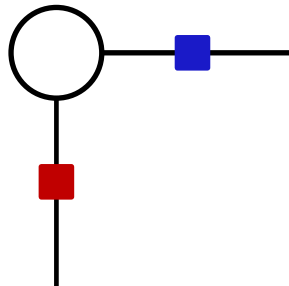
The PRACLAY Heater test - Observations

□ What do we observe in the Boom Clay?

- Pore water pressure variation in the clay (vertical vs horizontal)



PG50

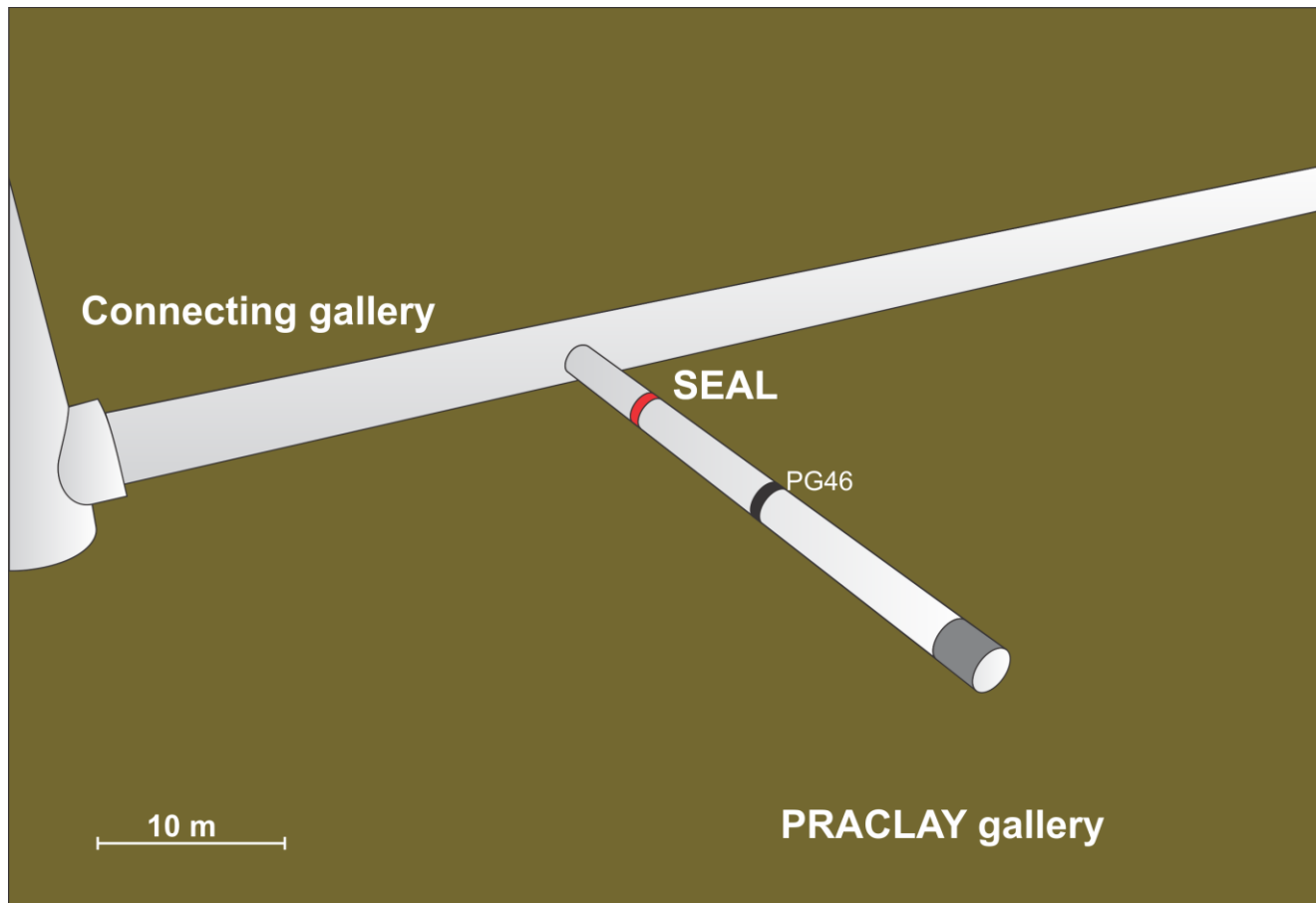


Phenomenon already observed during ATLAS experiment

The PRACLAY Heater test - Observations

❑ What do we observe in the seal/ concrete lining?

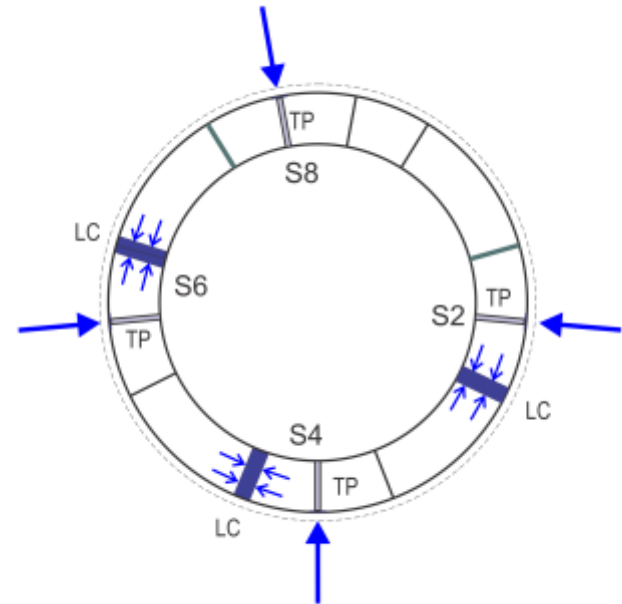
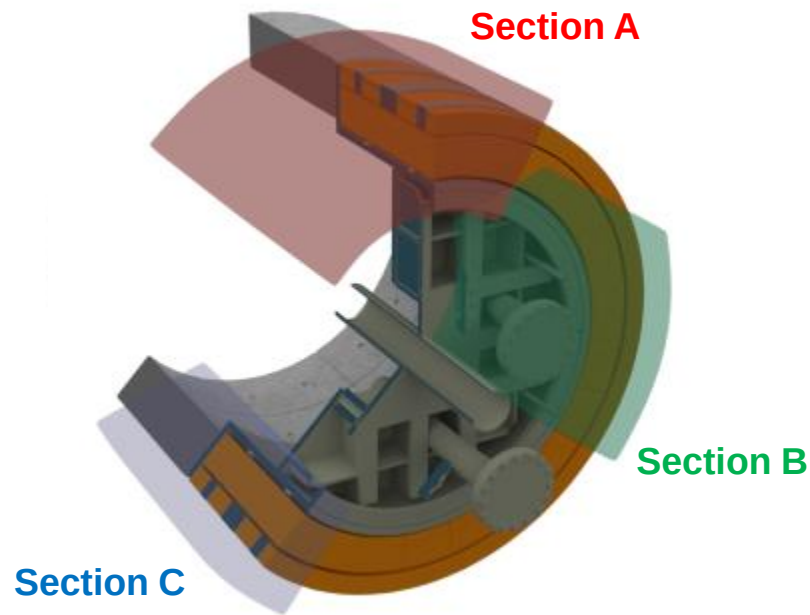
- Pore water pressure, total stress and displacement



The PRACLAY Heater test - Observations

❑ What do we observe in the seal/ concrete lining?

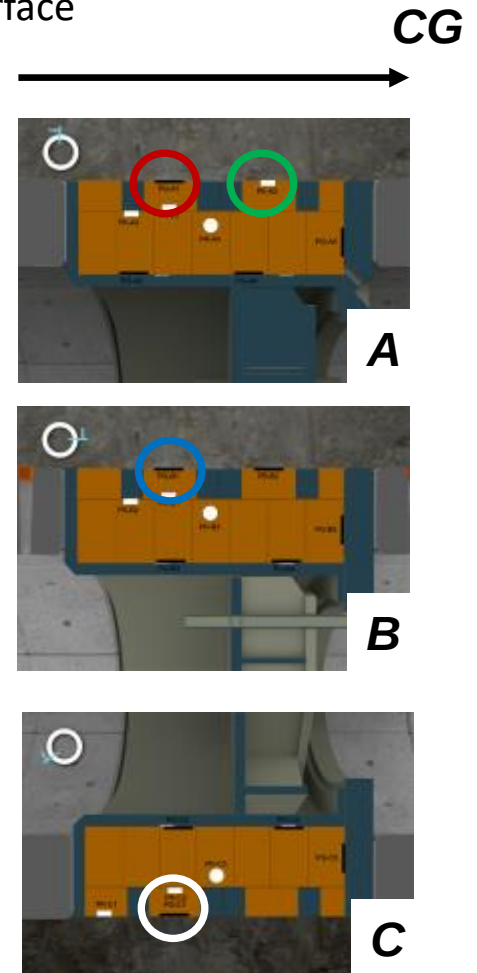
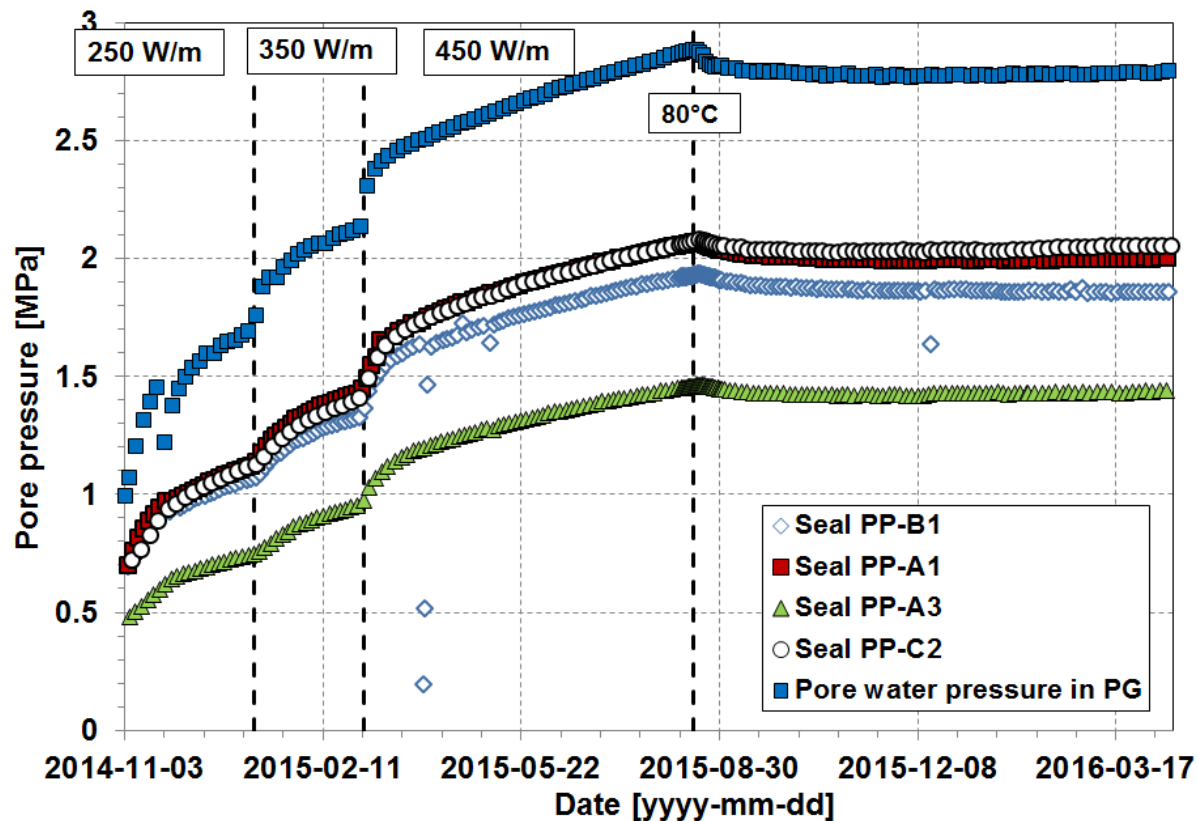
- Pore water pressure, total stress and displacement



The PRACLAY Heater test - Observations

□ What do we observe in the seal?

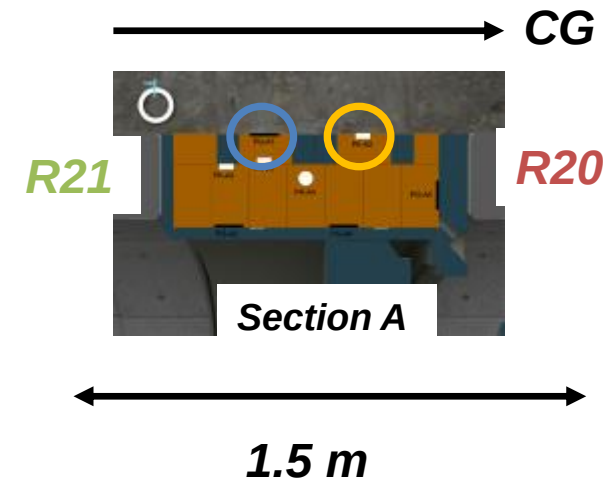
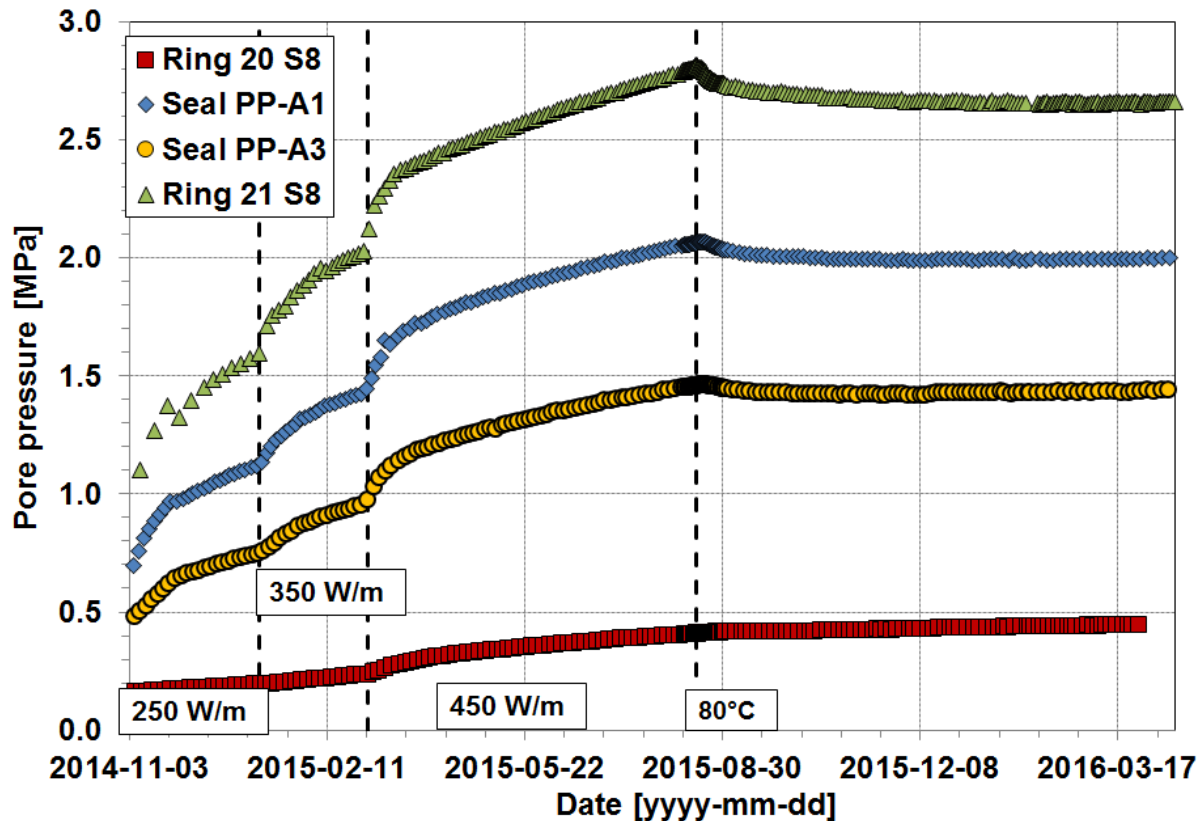
- Pore water pressure evolution at Boom Clay/ bentonite interface



The PRACLAY Heater test - Observations

□ What do we observe in the seal?

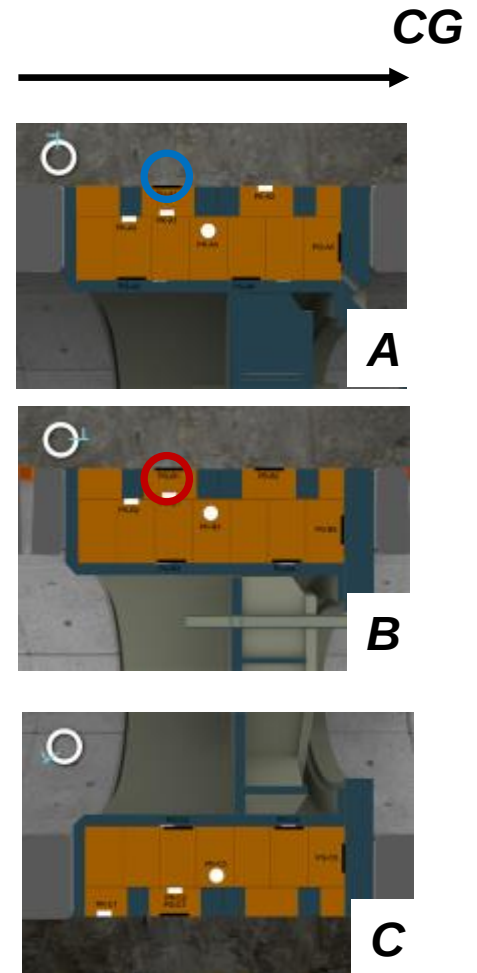
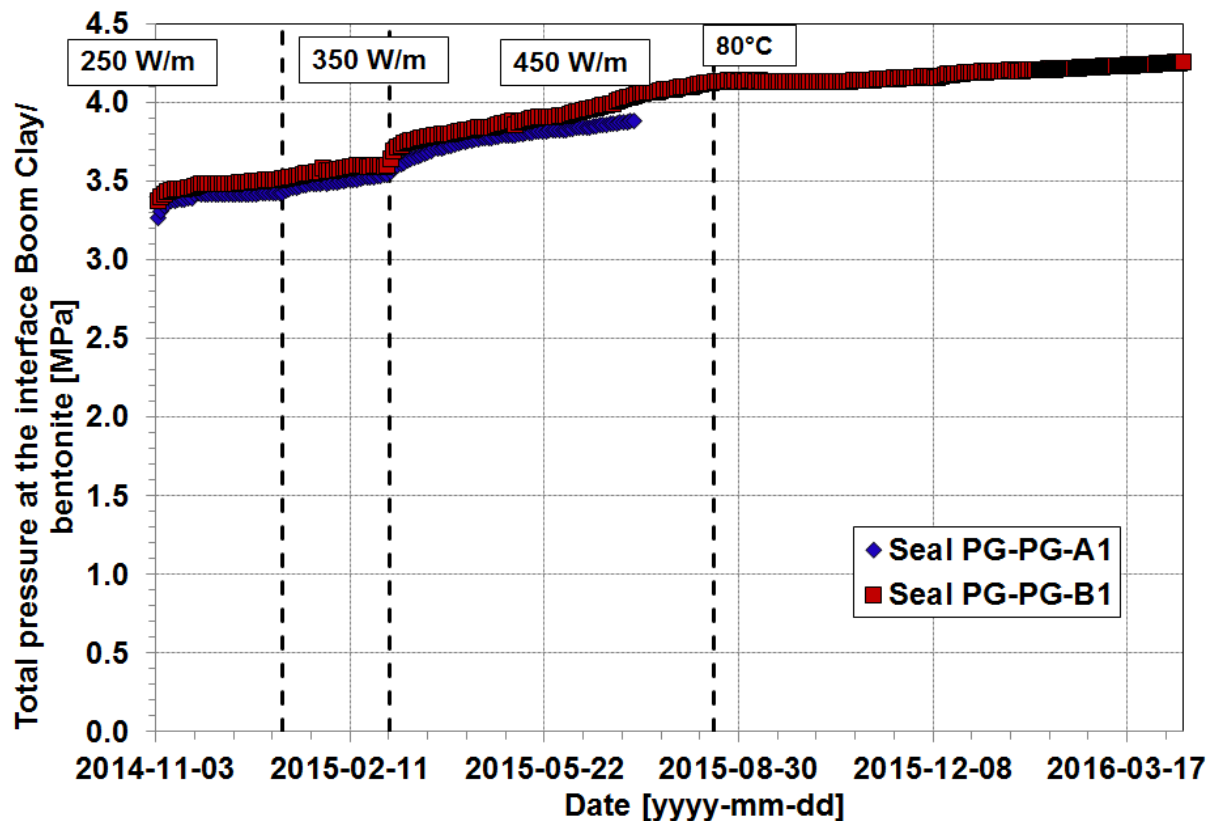
- Pore water pressure evolution at Boom Clay/ bentonite interface



The PRACLAY Heater test - Observations

□ What do we observe in the seal?

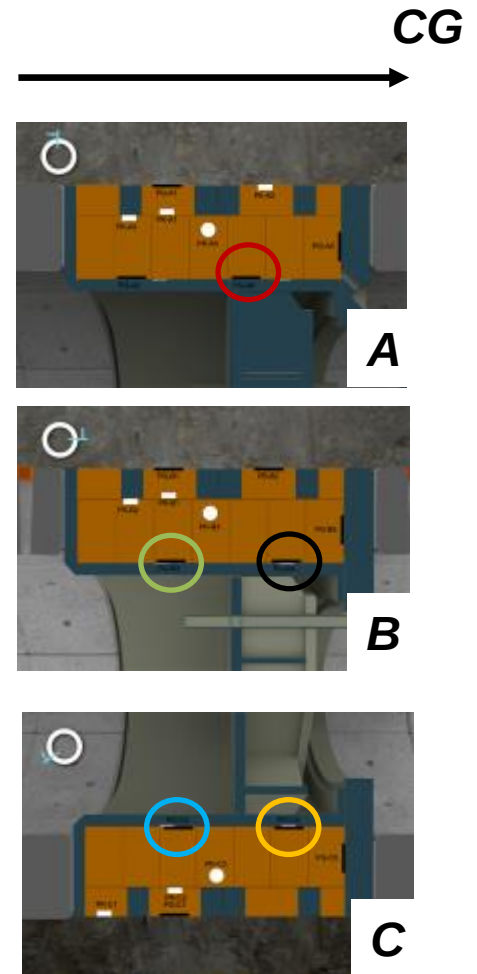
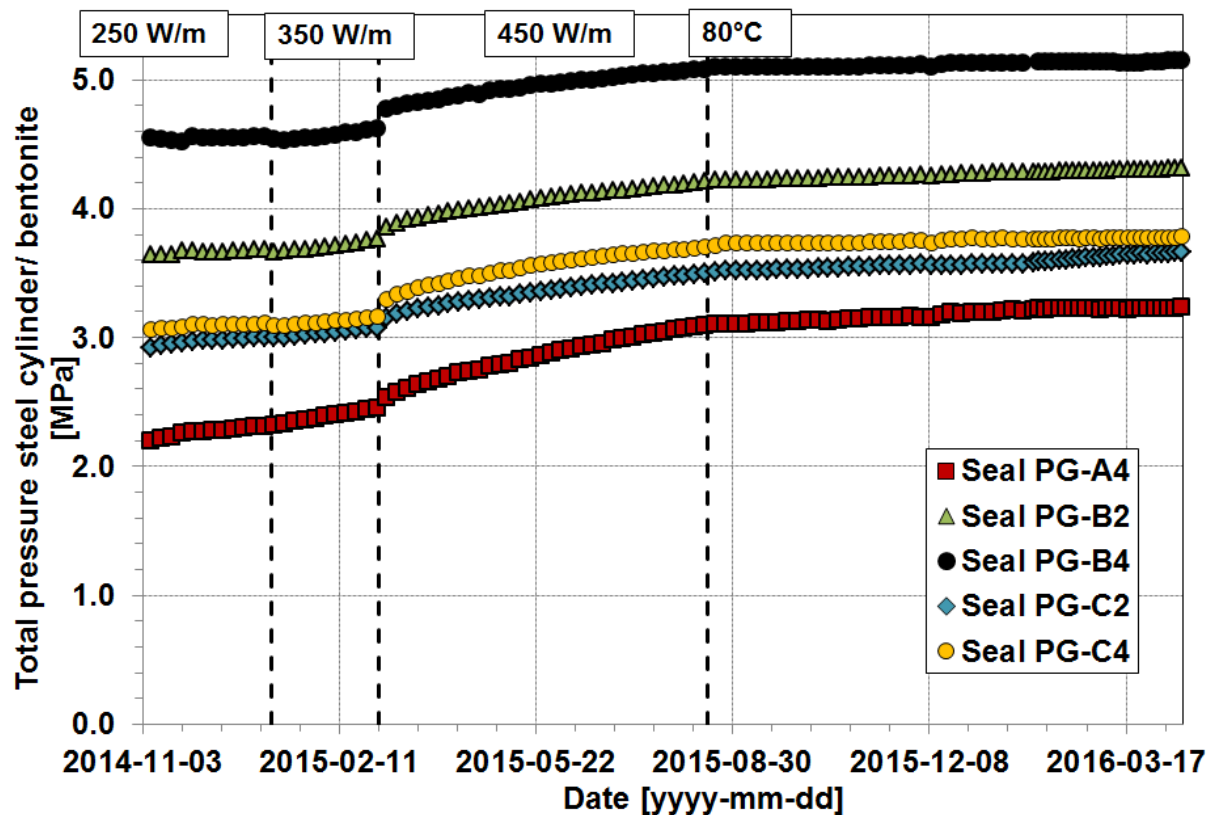
- Total pressure at Boom Clay/ bentonite interface



The PRACLAY Heater test - Observations

□ What do we observe in the seal?

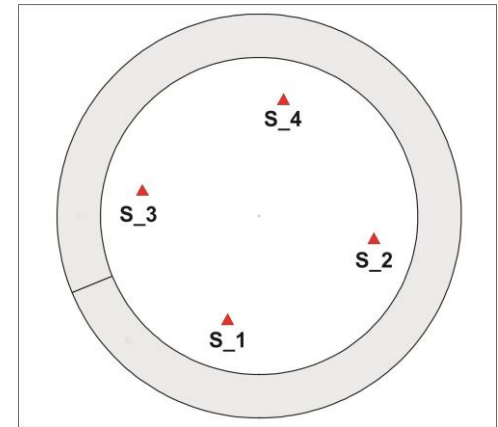
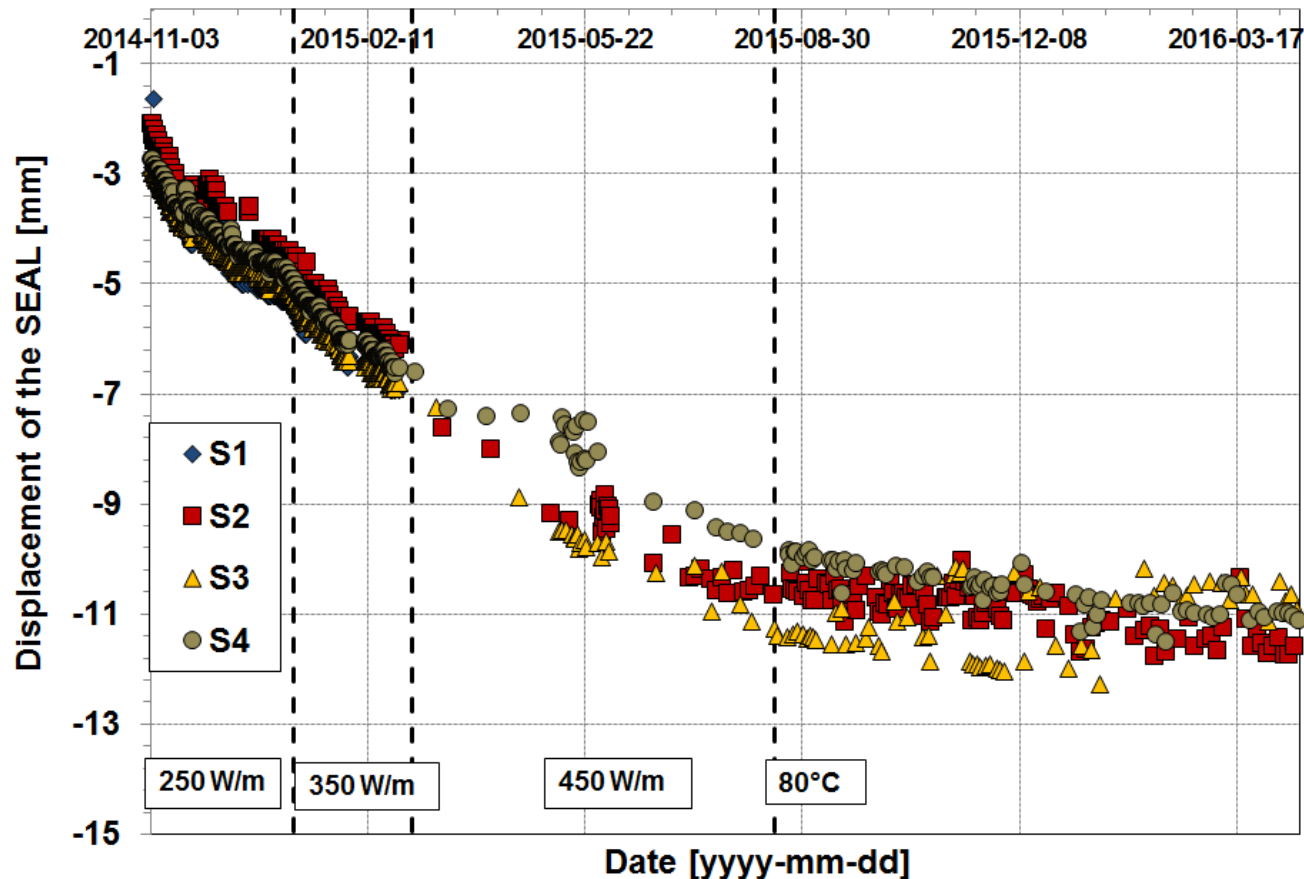
- Total pressure at bentonite/ steel cylinder interface



The PRACLAY Heater test - Observations

□ What do we observe in the seal?

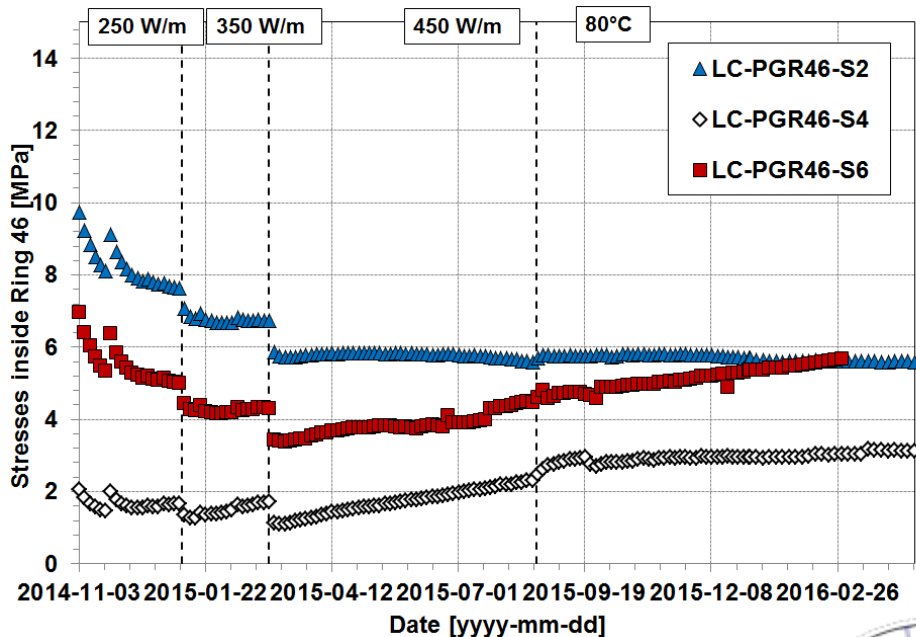
- Displacement of the SEAL towards the Connecting gallery



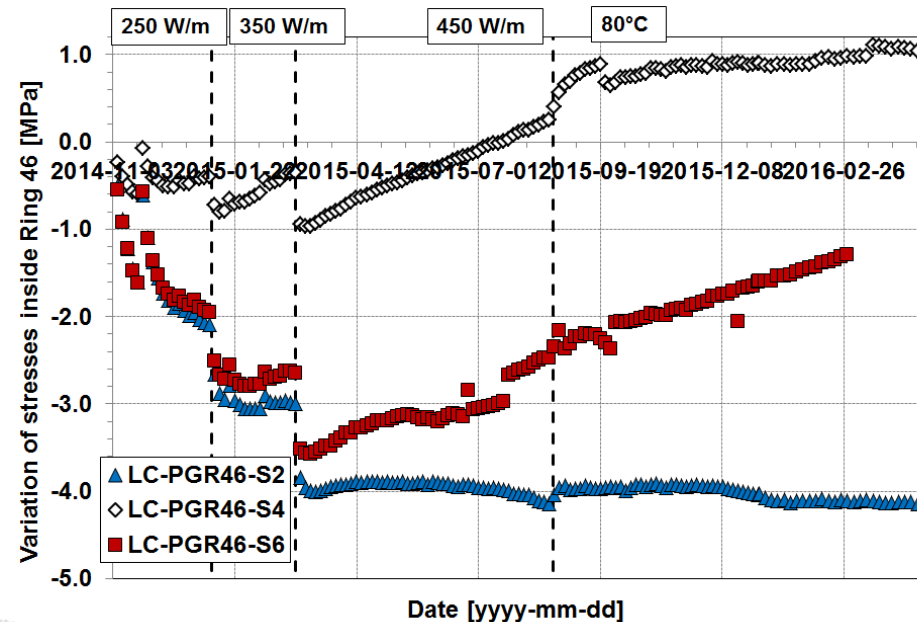
The PRACLAY Heater test - Observations

□ What do we observe in concrete lining?

- Stresses and variation of stresses between the concrete lining segments



Mean circumferential stress



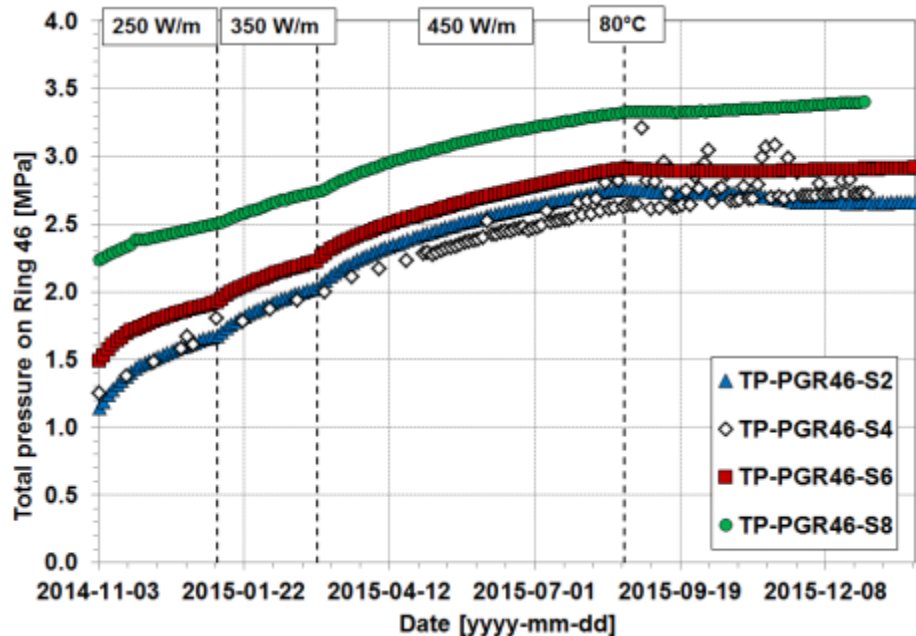
Variation of the mean circumferential stress



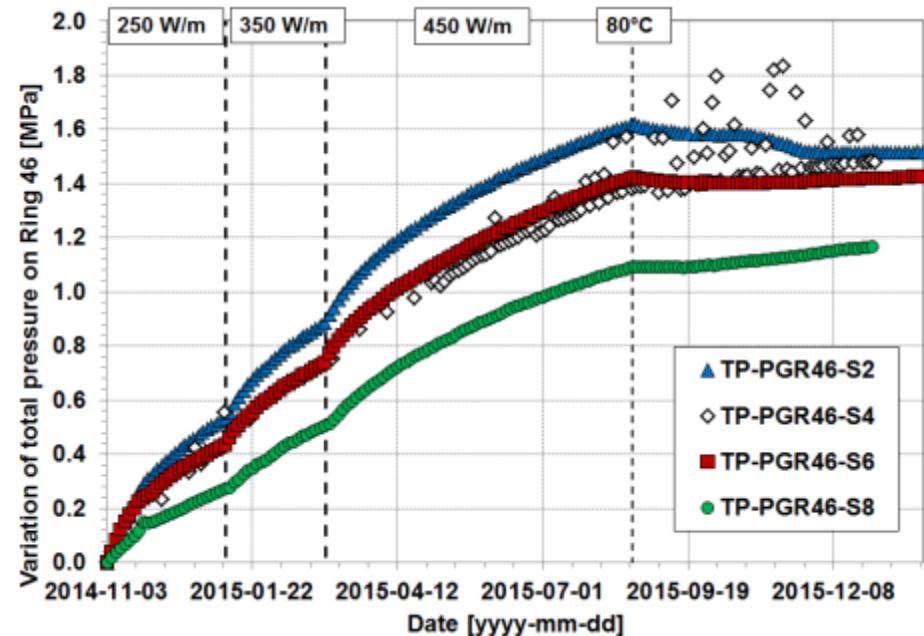
The PRACLAY Heater test - Observations

□ What do we observe in the concrete lining?

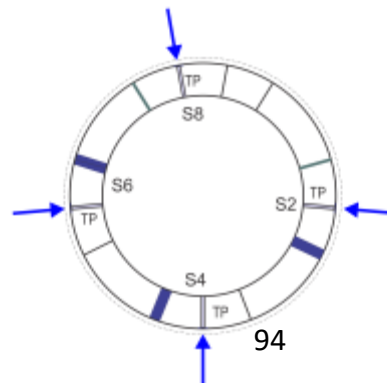
- Pressure and variation of pressure on the concrete lining segments (PG46)



Total pressure on the lining



Variation of the total pressure on the lining



The PRACLAY Heater test - Conclusion

18 months after the switch-on, the experimental set-up and the Boom Clay are generally behaving as expected (start-up phase: 9½ months to reach 80°C)

- **Boom Clay** (after 18 months):
 - Temperatures affected up to a radial distance of about 10 m
 - Pore pressures affected up to a radial distance of about 15 m
 - Anisotropic responses, as expected (vertical vs horizontal profiles)
 - No indication at this point of large displacements, hydraulic fracturing, liquefaction or drastic changes of properties
- **Seal:** plays its role as a hydraulic cut-off
- **Concrete lining:** evolution of the stresses and of total pressure acting on it remains within the expected range (compared with the design value).

20th Exchange Meeting

The PRACLAY Heater test

First results after one and a half years of heating



First results PART 2

Comparison with the blind predictions

20th Exchange Meeting
Mol, 4 May 2016

Guangjing Chen
EIG EURIDICE



ONDRAF/NIRAS



ESV EURIDICE GIE



Content

- ❖ **Numerical models (blind prediction)**
- ❖ **Comparison between measurements and predictions**
 - ☐ Lining temperature
 - ☐ Pore Water Pressure (PWP) in the PRACLAY gallery (PG)
 - ☐ Temperature and PWP in the Boom Clay
 - ☐ Stresses in the lining
 - ☐ PWP and stresses in the Seal
- ❖ **Future expected evolution**
- ❖ **Summary**

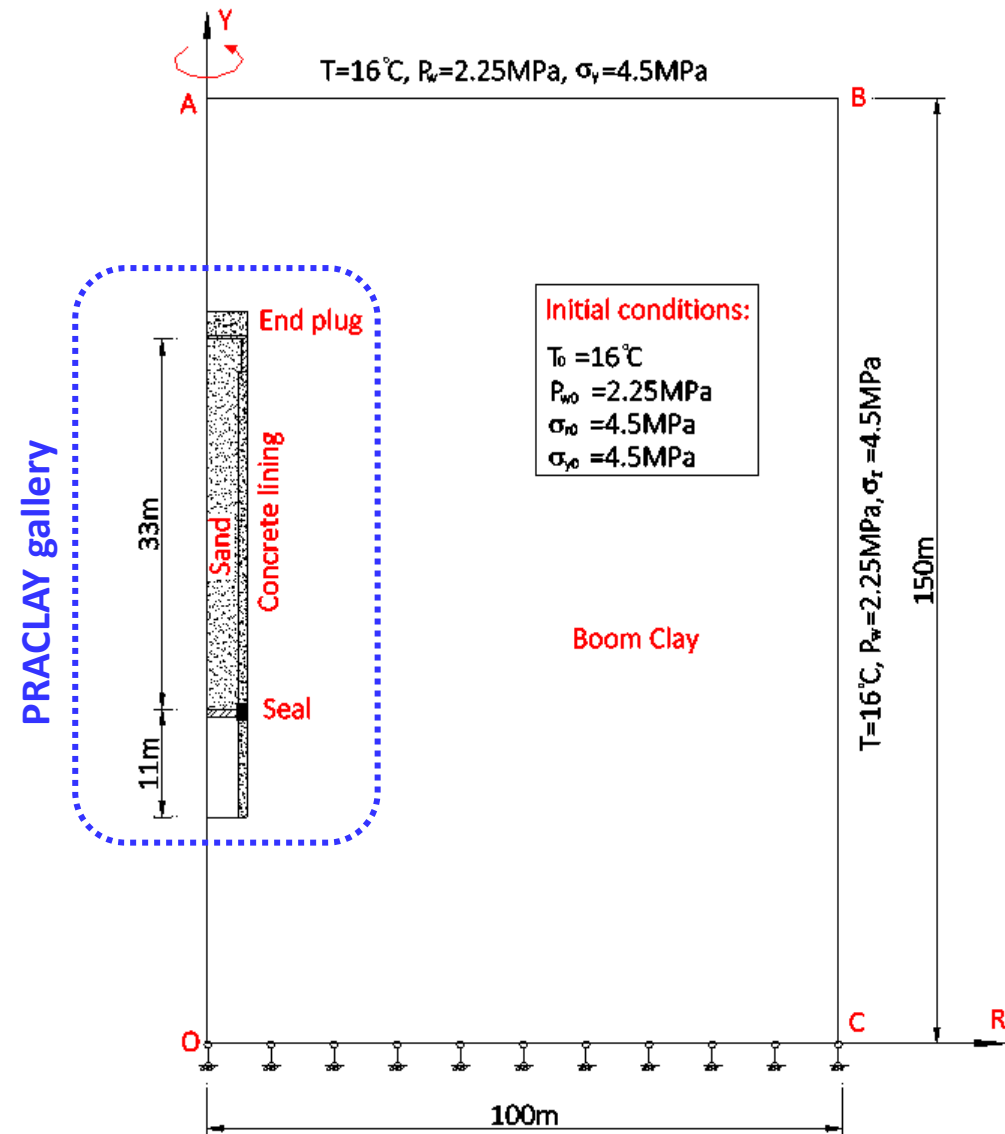
Content

- ❖ **Numerical models (blind prediction)**
- ❖ Comparison between measurements and predictions
 - ☐ Lining temperature
 - ☐ Pore Water Pressure (PWP) in the PRACLAY gallery (PG)
 - ☐ Temperature and PWP in the Boom Clay
 - ☐ Stresses in the lining
 - ☐ PWP and stresses in the Seal
- ❖ Future expected evolution
- ❖ Summary

Numerical models

❑ 2D axisymmetric model (2D-Axis)

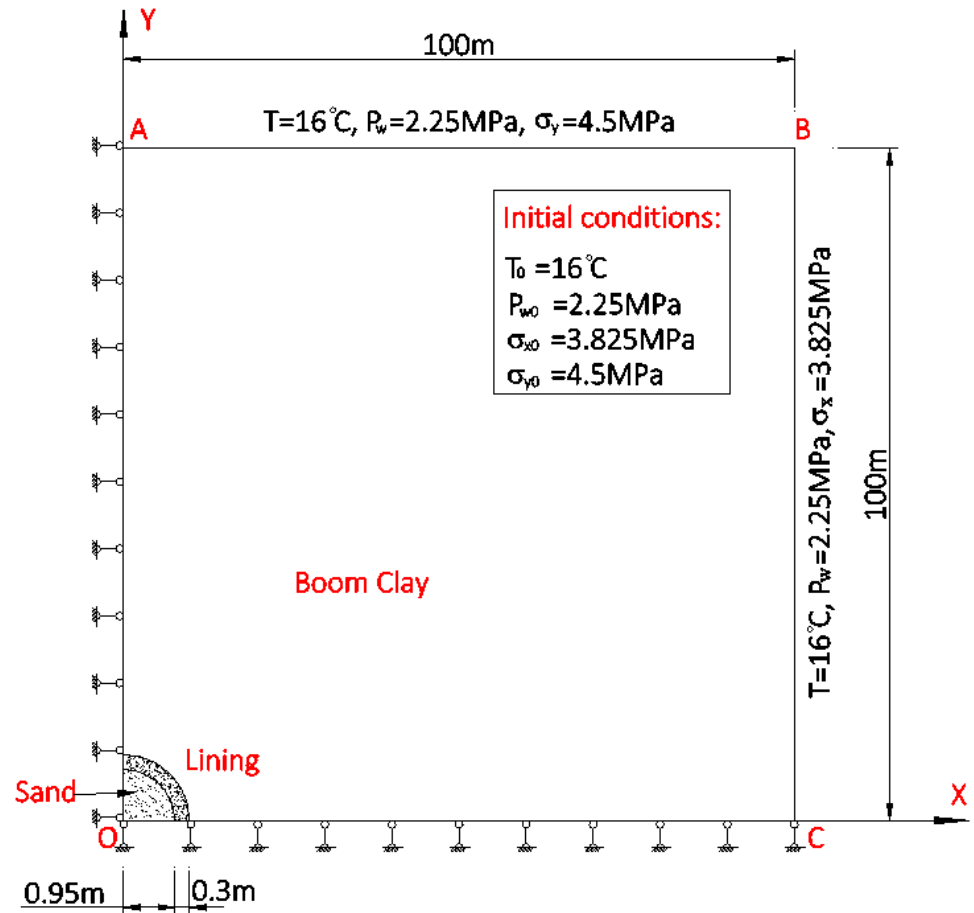
- Geometry is generated around PG axis Y
- Materials:
 - Lining/End plug/Seal/Backfill sand/Boom Clay
- Initial and boundary conditions
- Anisotropy cannot be considered
- Connecting gallery is not considered



Numerical models

□ 2D plane strain model (2D-PS)

- Geometry is a cross section perpendicular to axis of heated PG
- Materials:
Lining/Backfill sand/Boom Clay
- Initial and boundary conditions
- THM anisotropy is considered
- More representative for mid plane of heater test

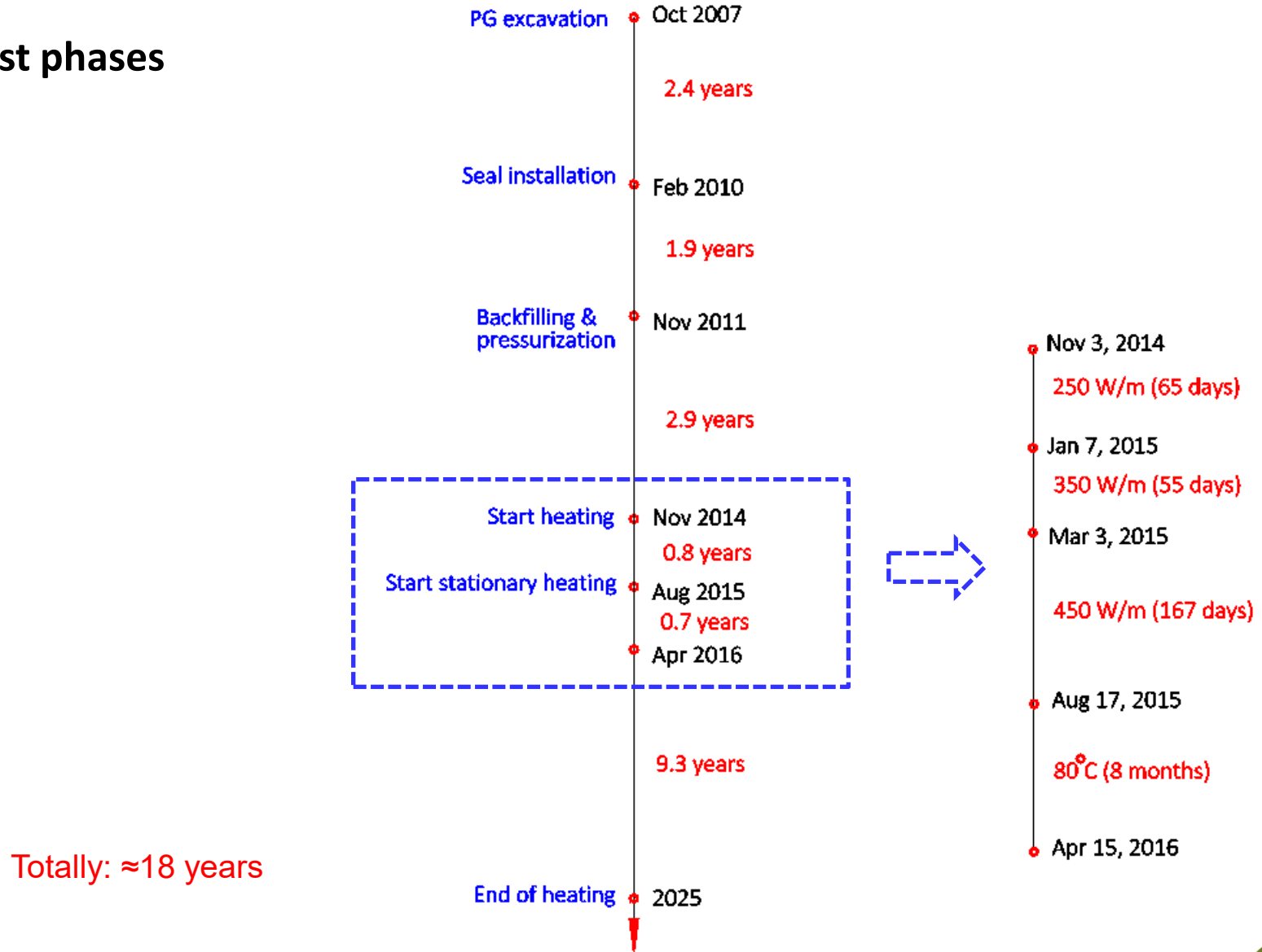


❑ THM parameters

- Interpretation of small scale in-situ heating tests (ATLAS I~IV: 1993-2012)
- Back analysis of in-situ measured PWP around PG (2007-2014)
- In-situ permeability tests
- Lab tests
- Literature review

Numerical models

☐ Test phases

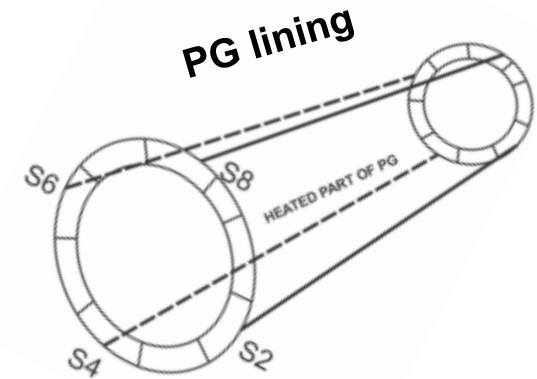
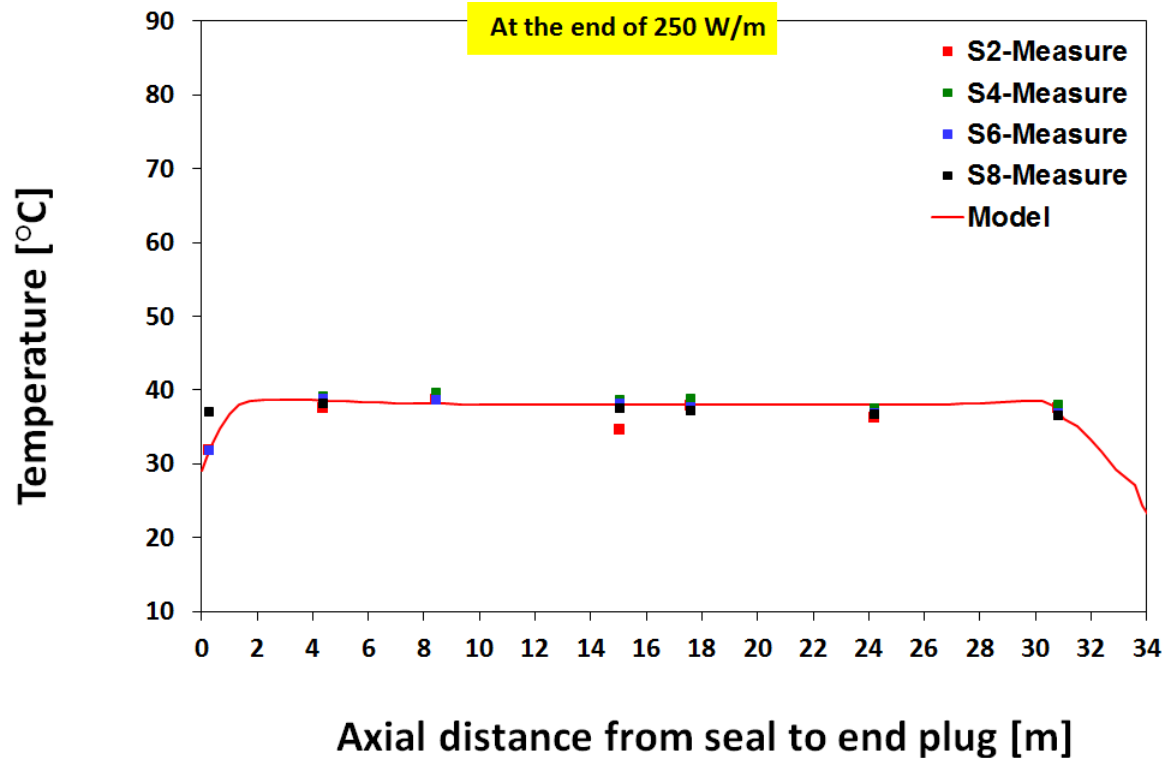


Content

- ❖ Numerical models (blind prediction)
- ❖ **Comparison between measurement and prediction**
 - ☐ Lining temperature
 - ☐ Pore water pressure in the PRACLAY gallery
 - ☐ Temperature and pore water pressure in the Boom Clay
 - ☐ Stresses in the lining
 - ☐ Pore water pressure and stresses in the Seal
- ❖ Future expected evolution
- ❖ Summary

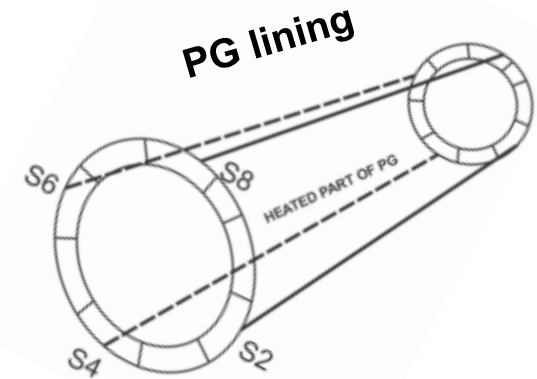
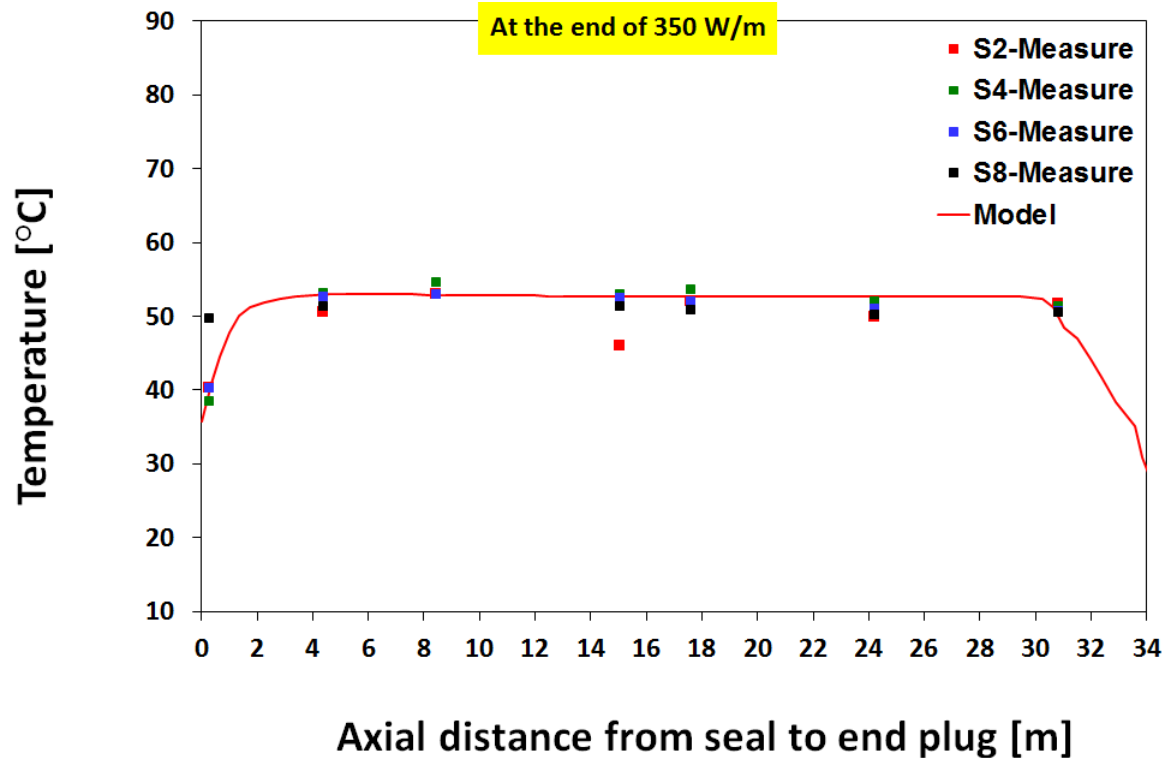
Comparison between measurements and predictions

□ Lining temperature



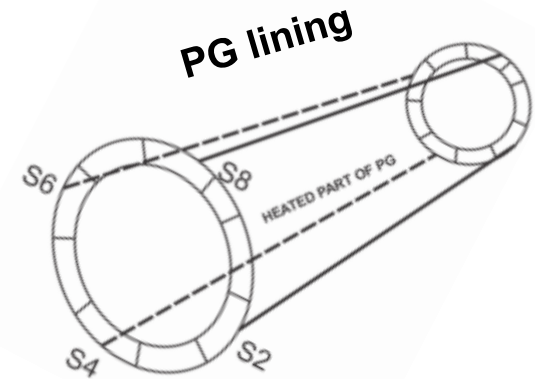
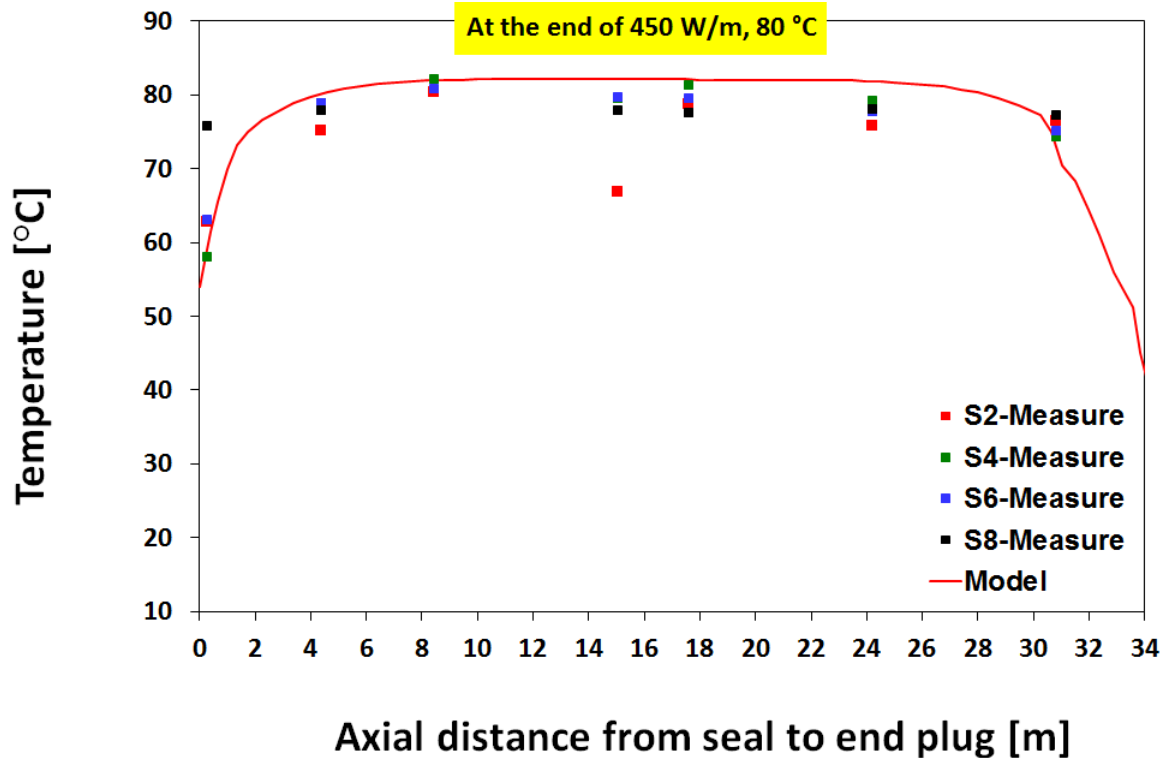
Comparison between measurements and predictions

□ Lining temperature



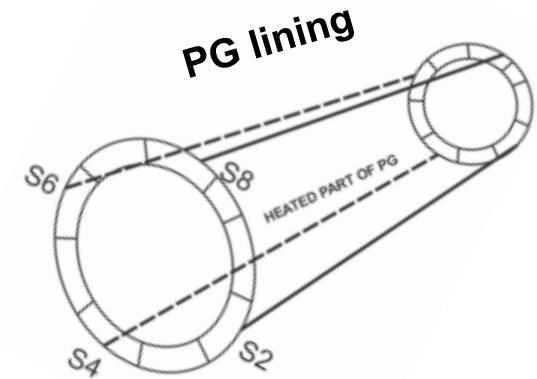
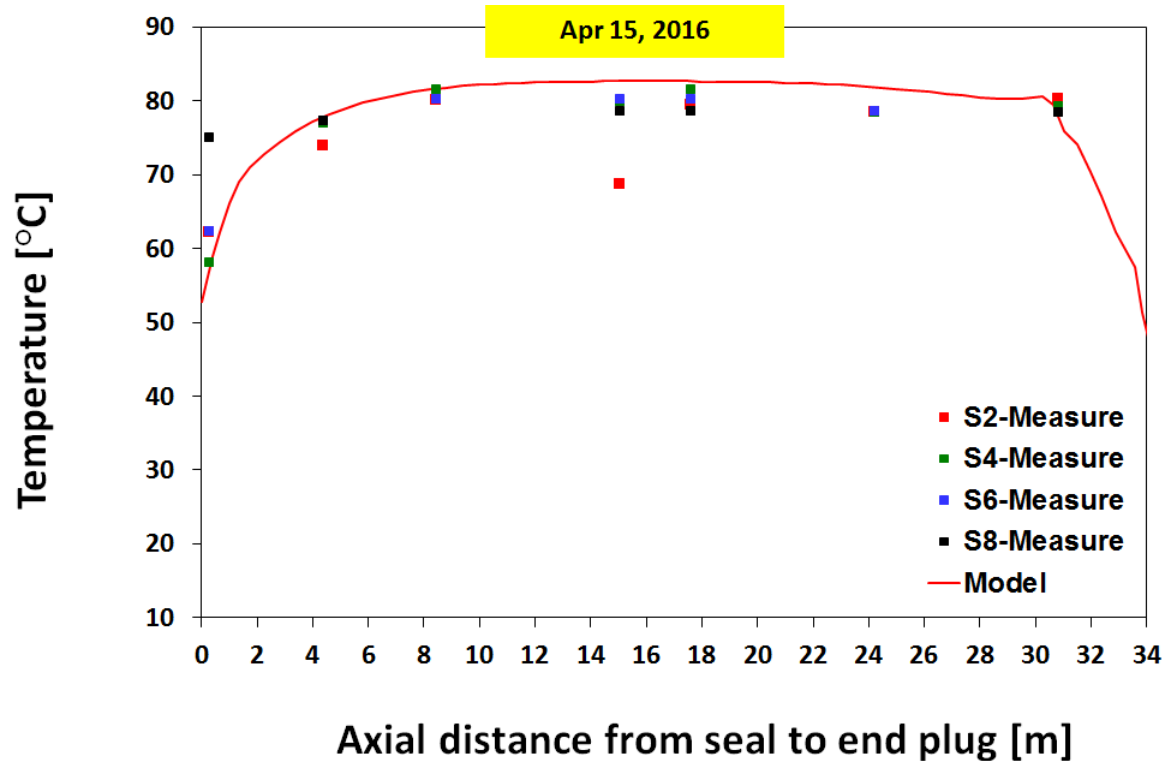
Comparison between measurements and predictions

□ Lining temperature



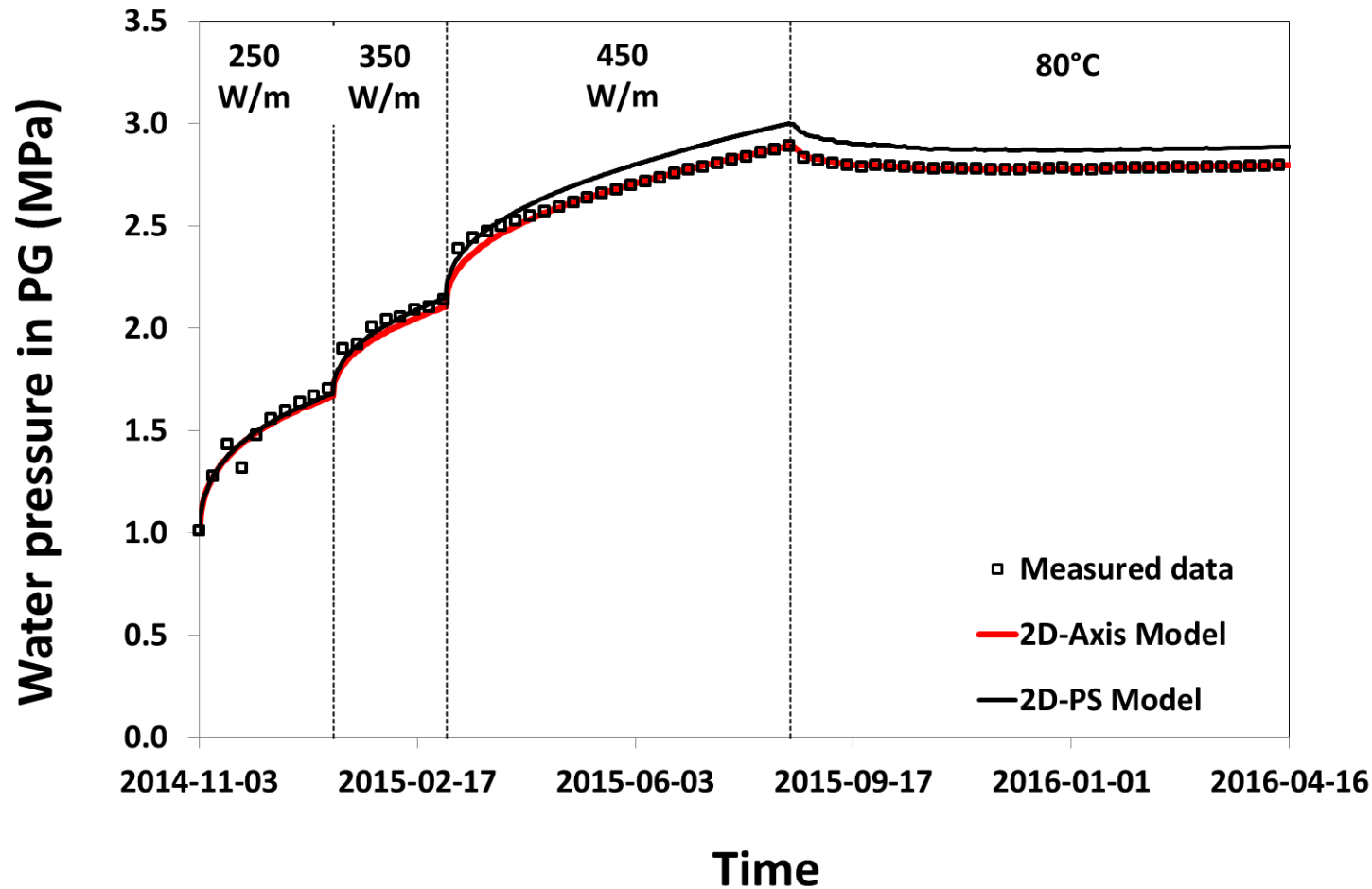
Comparison between measurements and predictions

□ Lining temperature



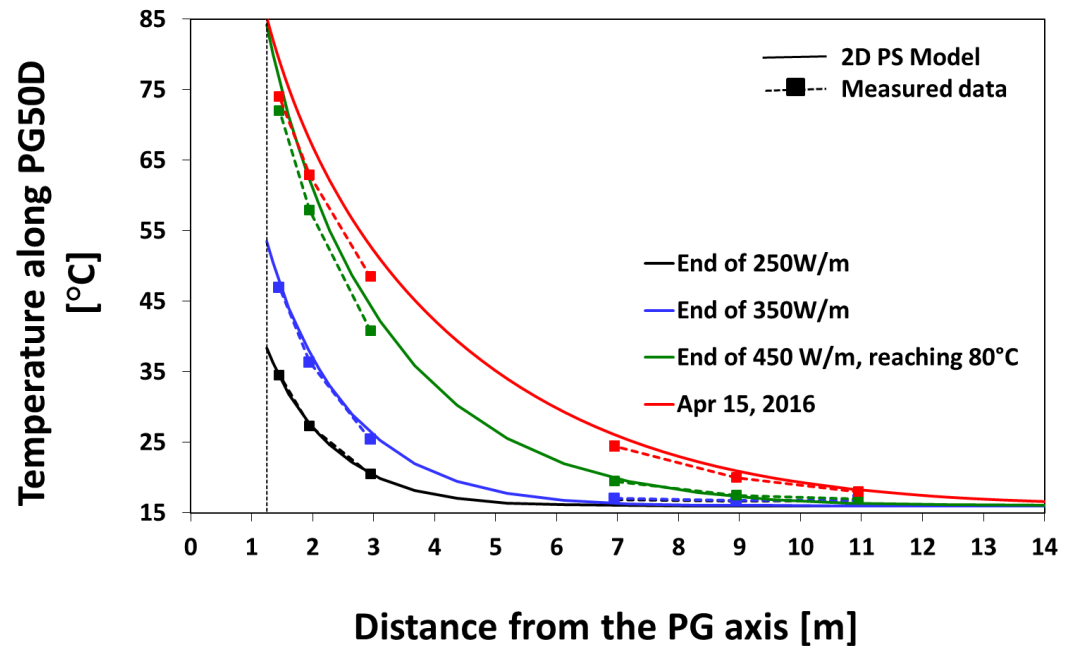
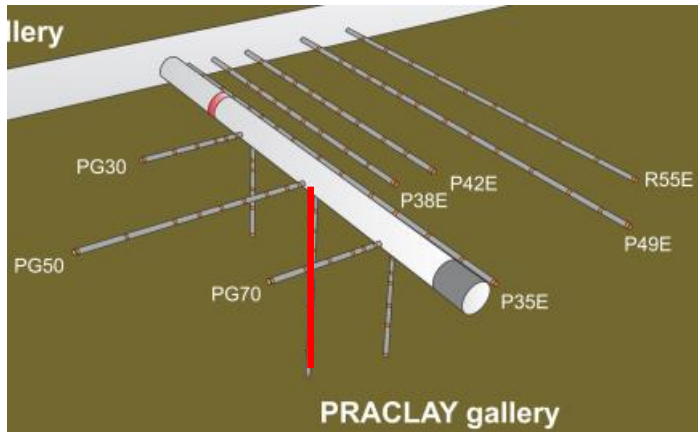
Comparison between measurements and predictions

□ Pore water pressure in PG



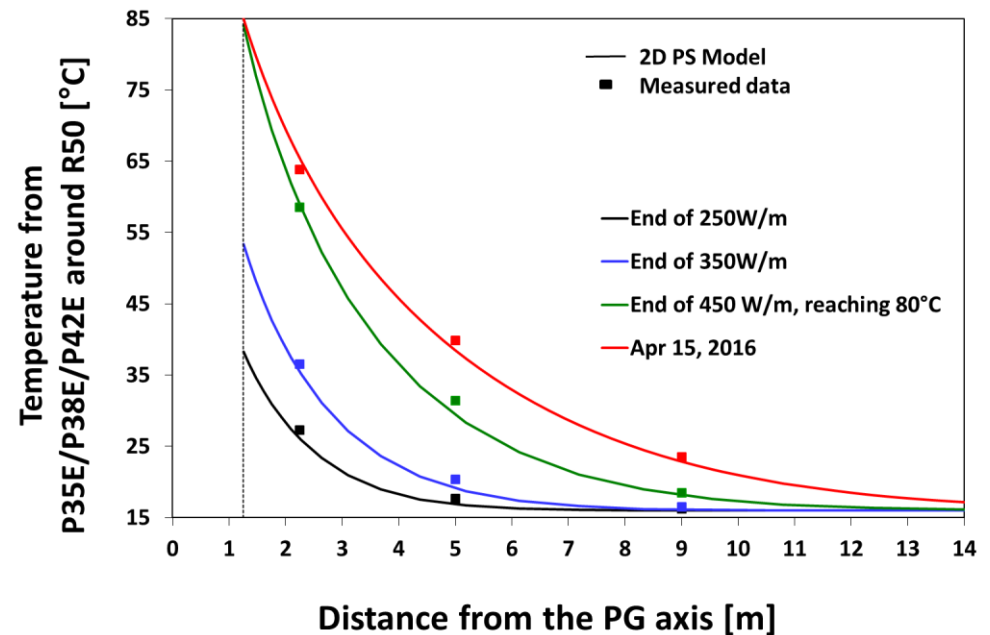
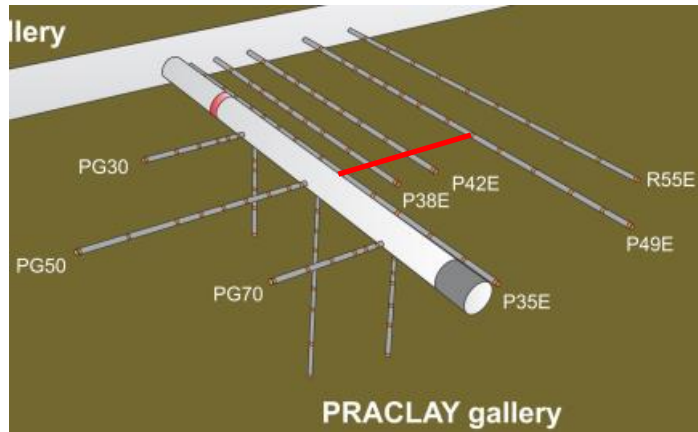
Comparison between measurements and predictions

- ❑ Temperature around R50
- ❑ Middle and vertical



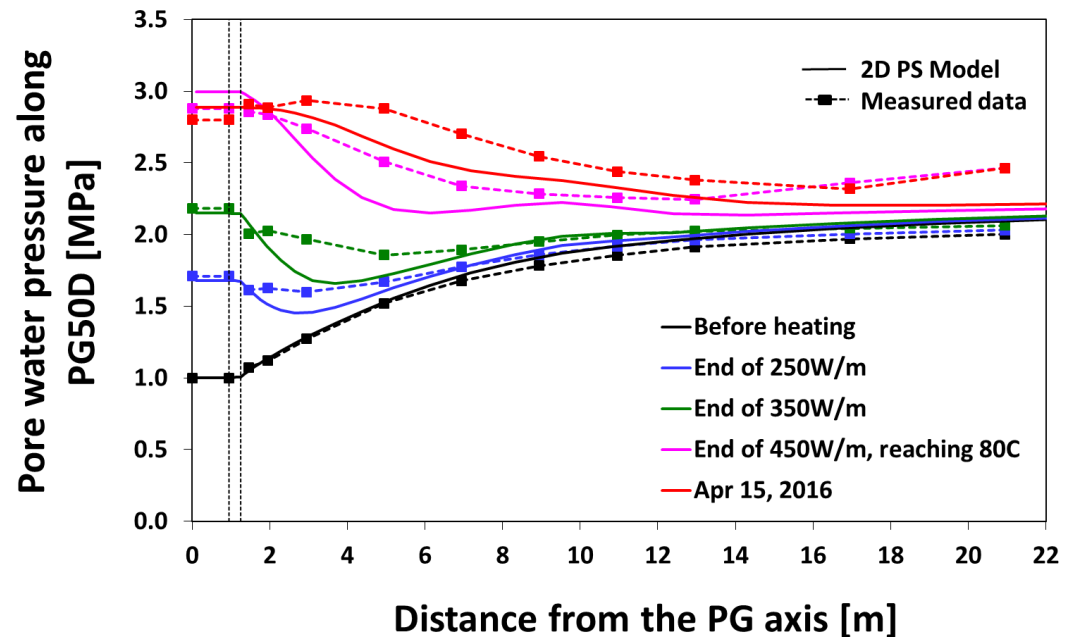
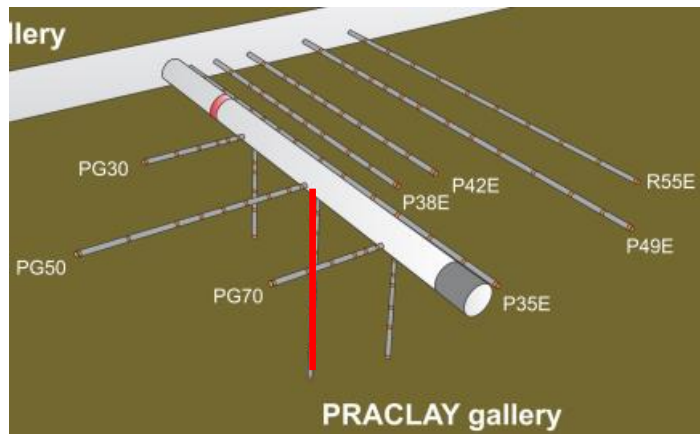
Comparison between measurements and predictions

- ❑ Temperature around R50
- ❑ Middle and horizontal



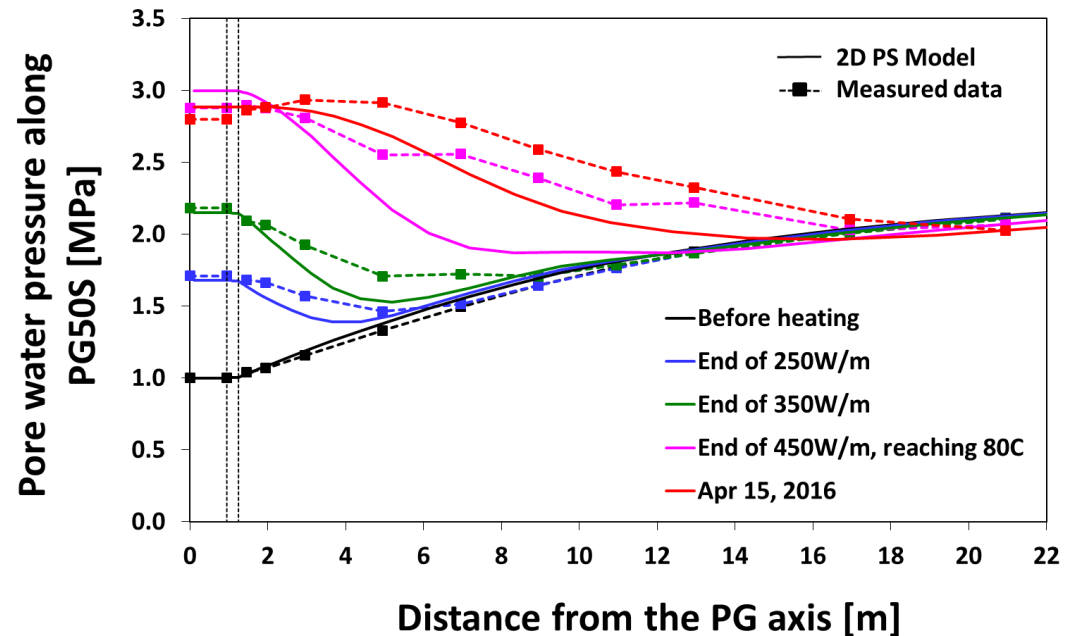
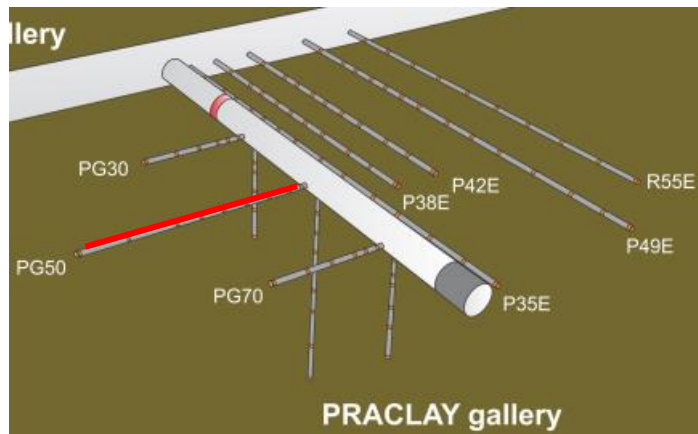
Comparison between measurements and predictions

- ❑ PWP around R50
- ❑ Middle and vertical
- ❑ Capture the trend, but still some difference



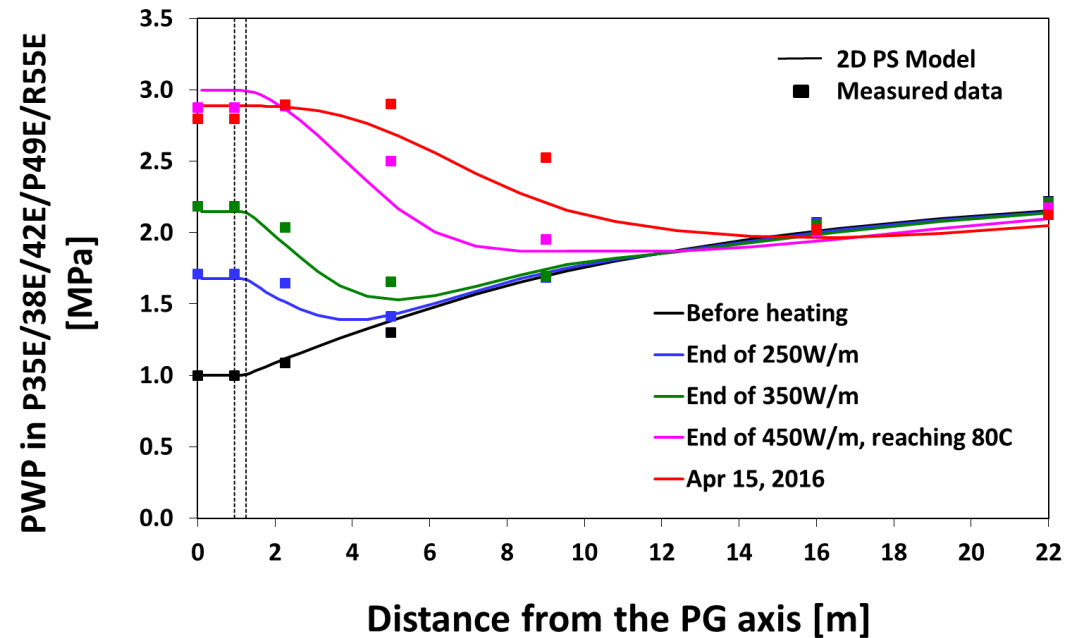
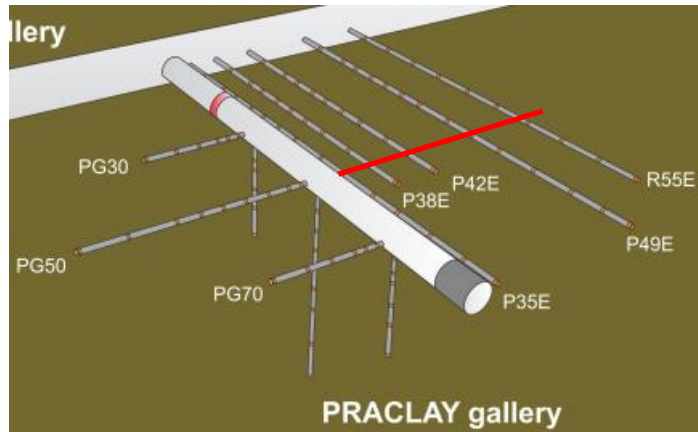
Comparison between measurements and predictions

- ❑ PWP around R50
- ❑ Middle and horizontal
- ❑ Capture the trend, but still some difference



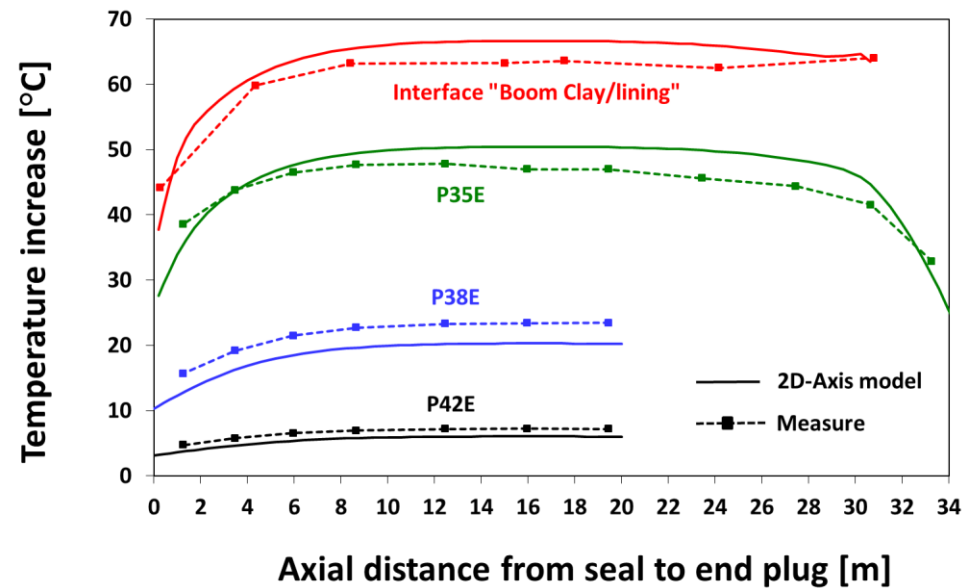
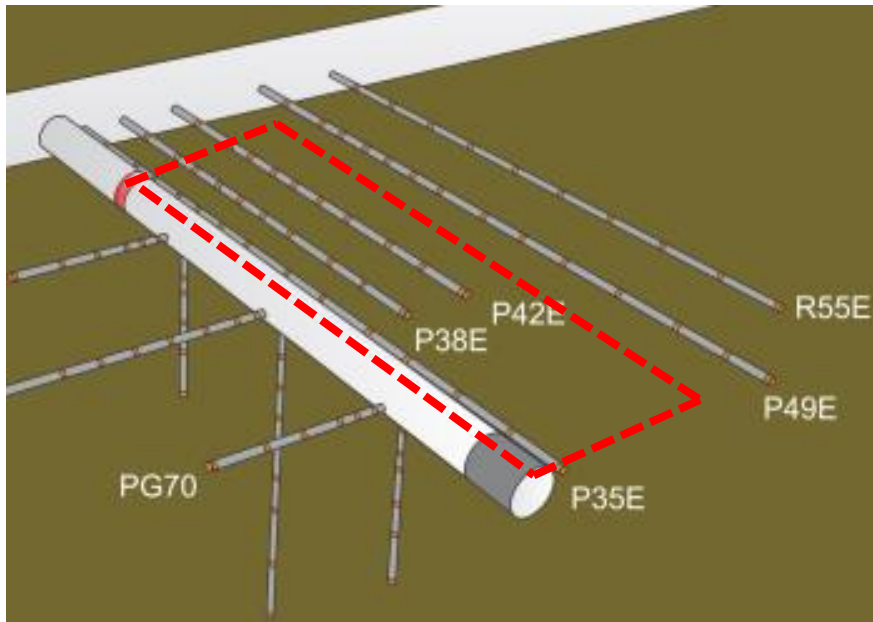
Comparison between measurements and predictions

- ❑ PWP around R50
- ❑ Middle and horizontal



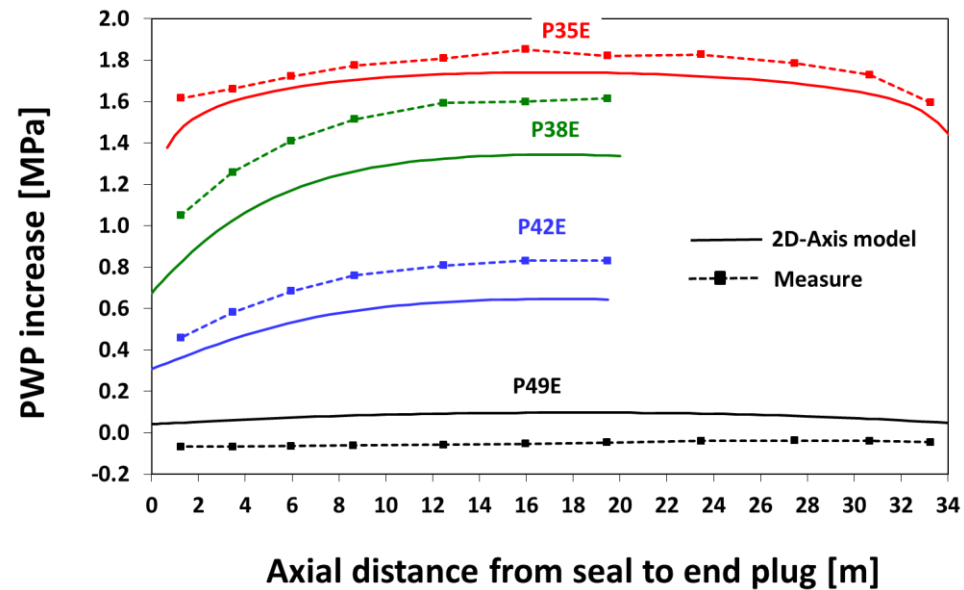
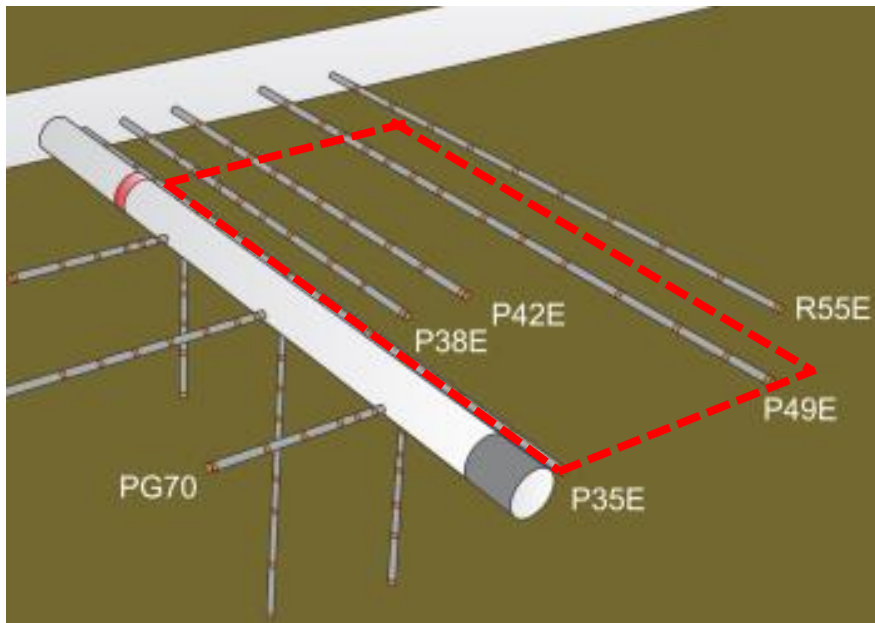
Comparison between measurements and predictions

- ❑ Temperature around heated PG
- ❑ In the axial direction



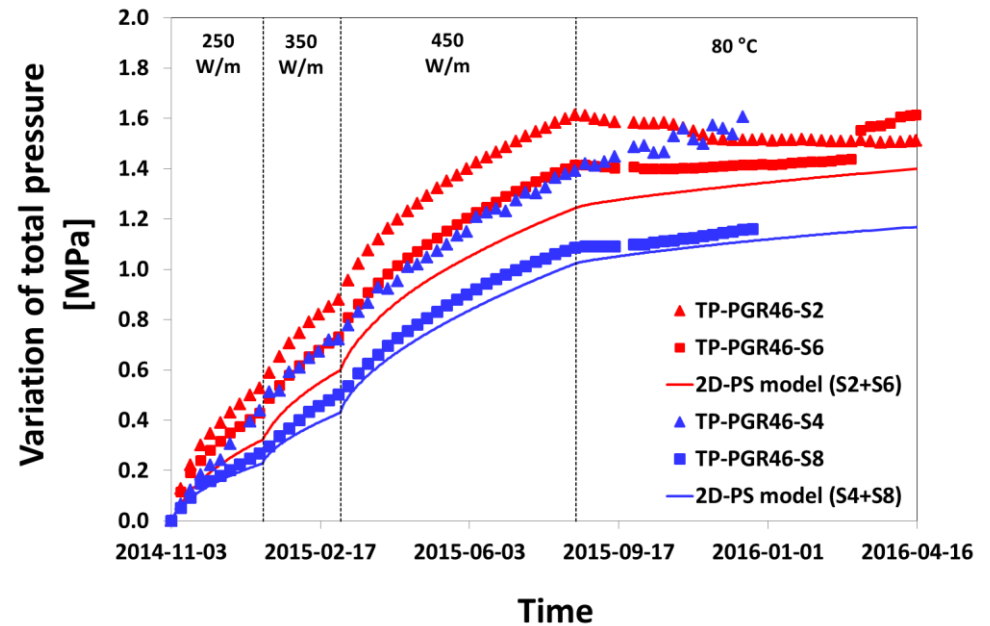
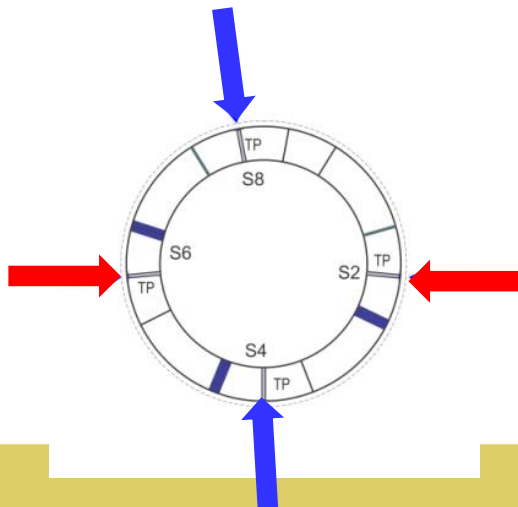
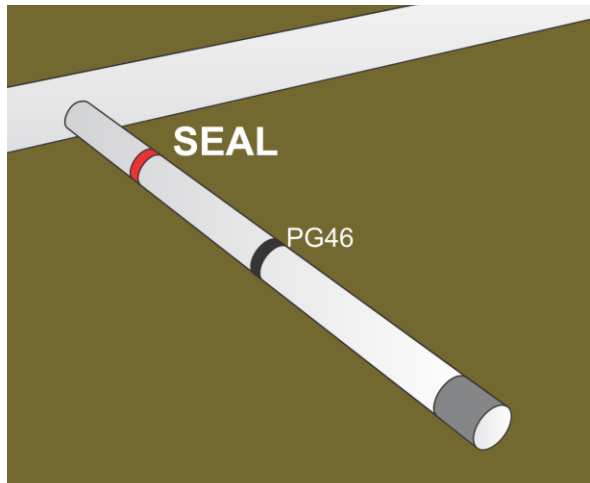
Comparison between measurements and predictions

- ❑ PWP around heated PG
- ❑ In the axial direction



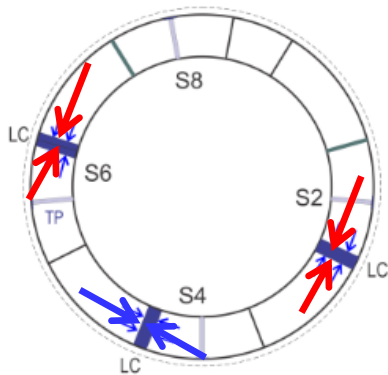
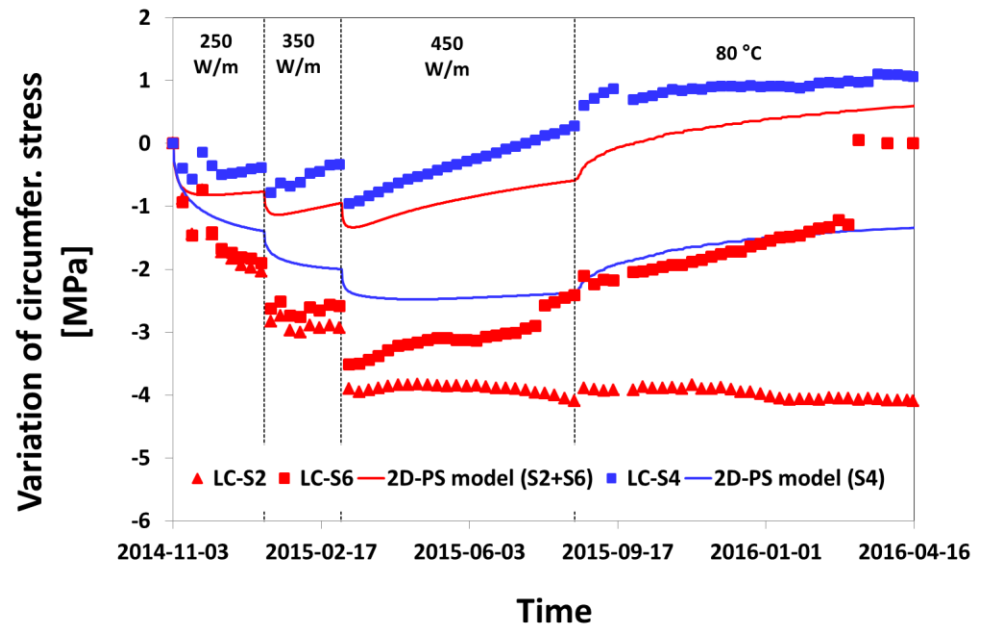
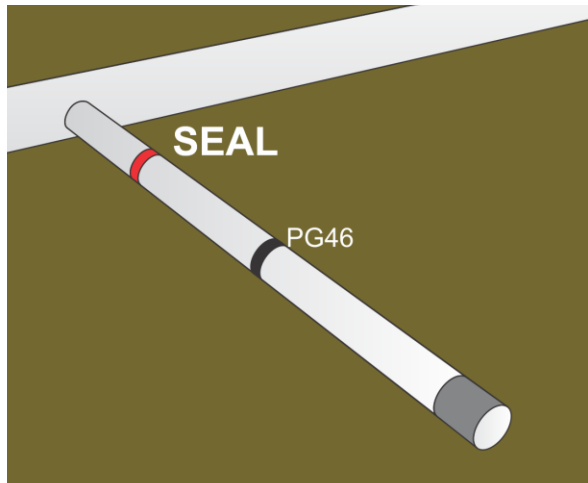
Comparison between measurements and predictions

Clay pressure on lining R46



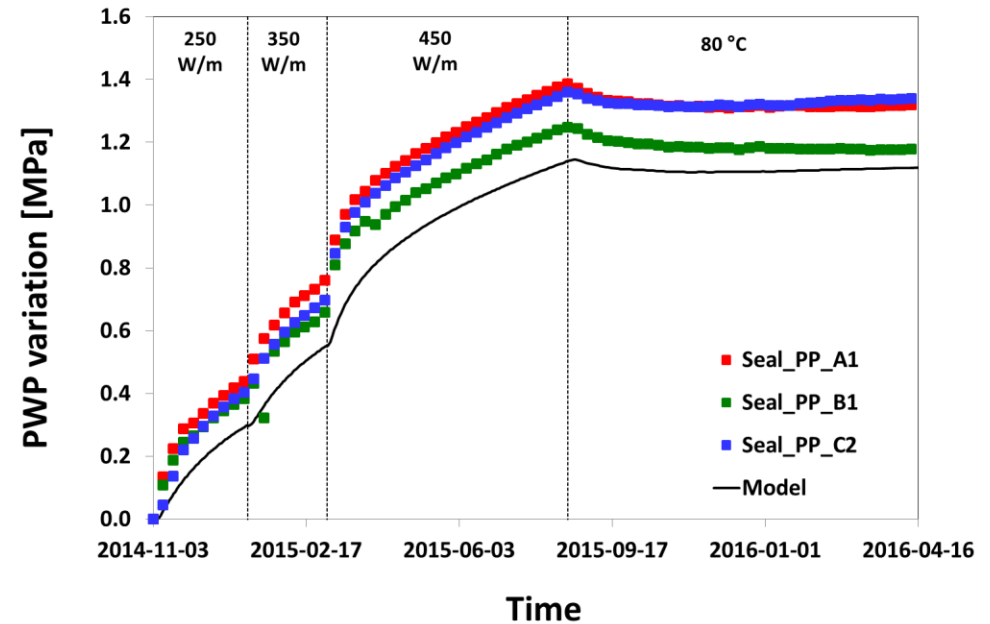
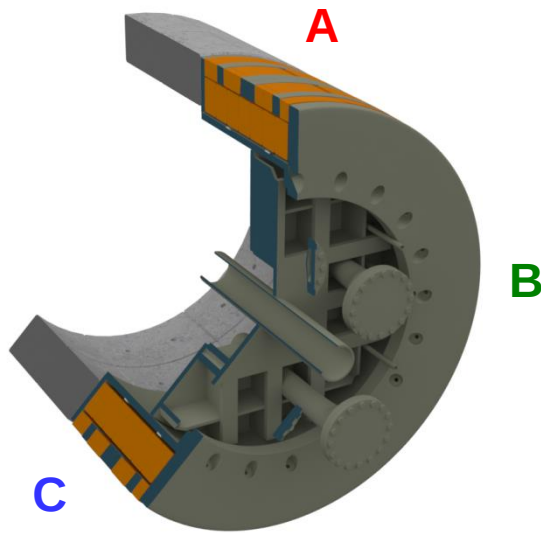
Comparison between measurements and predictions

- ❑ Stress in lining
- ❑ Measurement presents much anisotropy
- ❑ The general trend is captured by prediction, but some difference exists



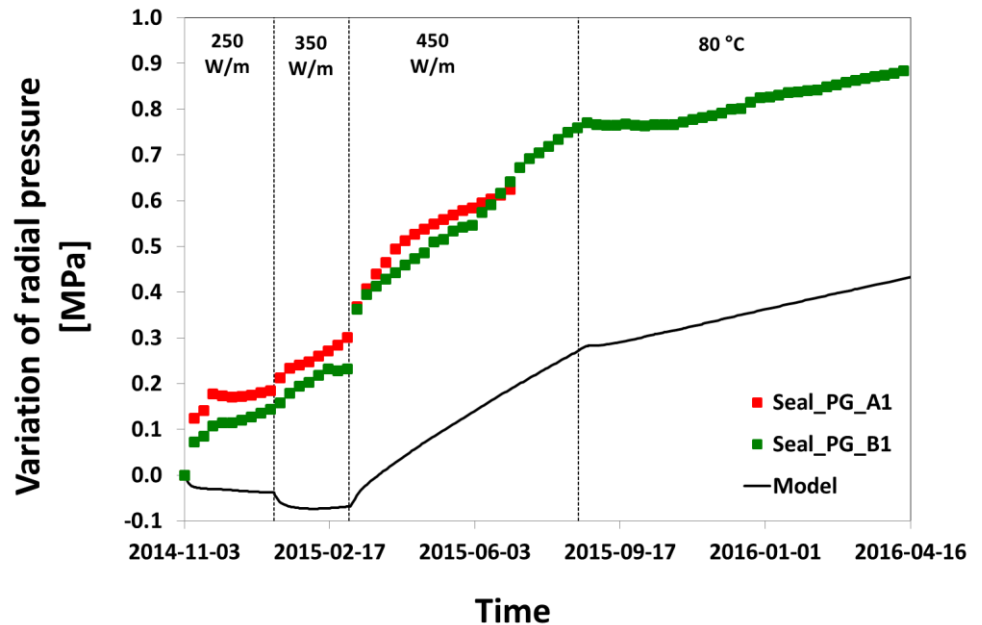
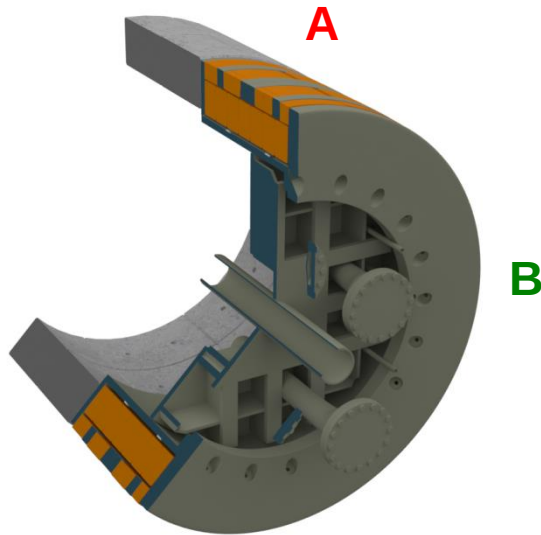
Comparison between measurements and predictions

□ Clay pressure at interface seal/Boom Clay



Comparison between measurements and predictions

- ❑ Radial pressure at interface seal/Boom Clay
- ❑ Modeling underestimates radial total pressure increase at the interface
- ❑ The general trend is now reasonably reproduced

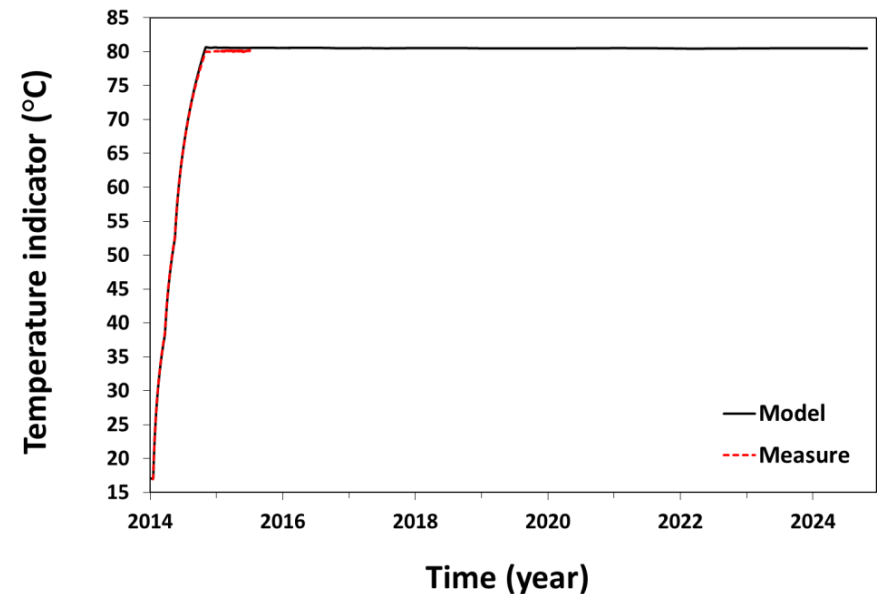
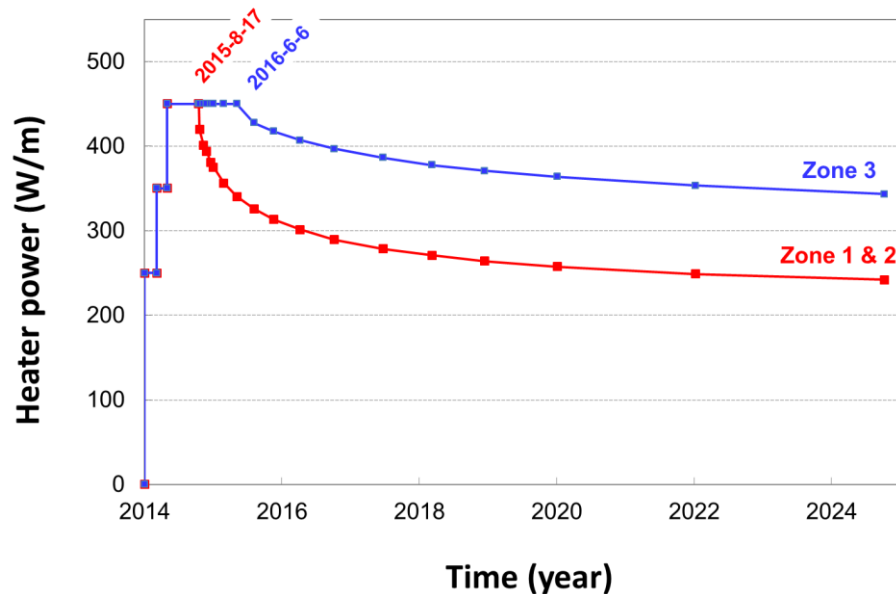


Content

- ❖ Numerical models (blind prediction)
- ❖ Comparison between measurement and prediction
 - ❑ Lining temperature
 - ❑ PWP in PG
 - ❑ Temperature and PWP in Boom Clay
 - ❑ Stresses in lining
 - ❑ PWP and stresses in Seal
- ❖ **Future expected evolution**
- ❖ Summary

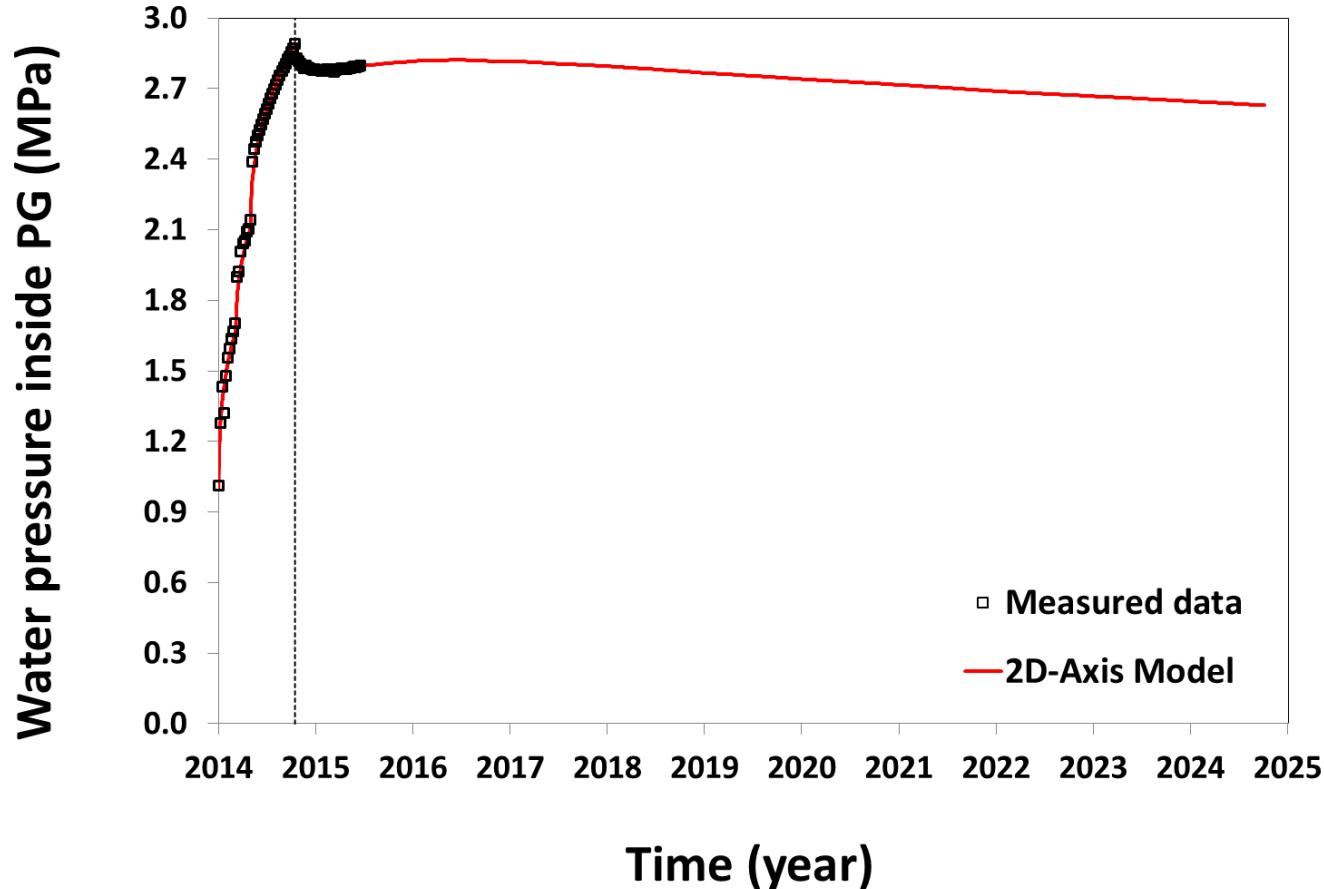
Future expected evolution

- ❑ Control the average temperature at extrados of R37, R50 and R55: 80°C
- ❑ Heater power input is predicted by modeling
- ❑ The measured “temperature indicator” is very close to 80 °C till now



Future expected evolution

- ❑ Modeling excellently predicts the measured PWP in PG till now
- ❑ The future PWP in PG ranges between 28 bar and 26 bar



Future expected evolution

□ Contours of Temperature & PWP around PG

Temperature

30 m

PWP

42 m

(1) Before heating

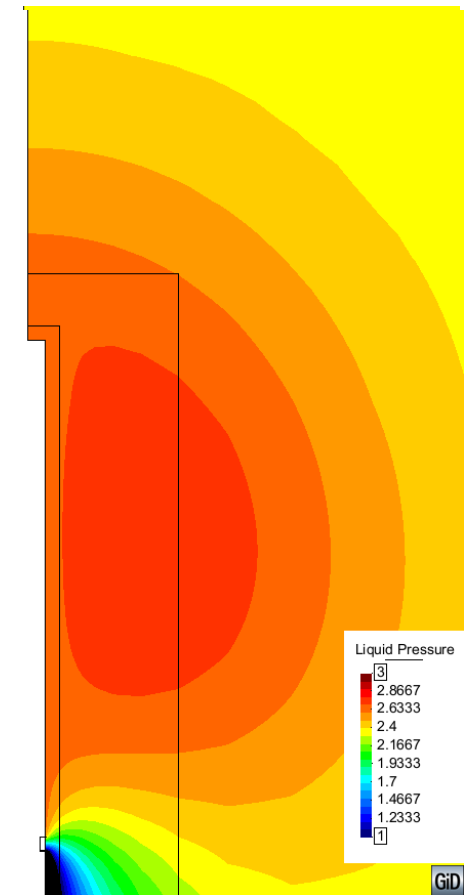
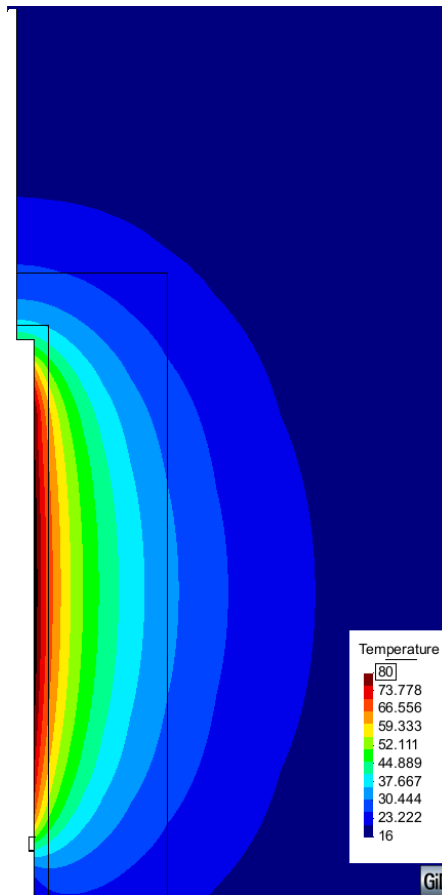
(2) End of startup phase (T_1)

(3) $T_1 + 1y$

(4) $T_1 + 2y$

(5) $T_1 + 5y$

(6) $T_1 + 10y$



Summary

- ❑ The **major THM behavior** of the test components of the PRACLAY Heater test is **in good agreement with the blind predictions** (PG/lining/seal/Boom Clay)
 - In Boom Clay, the temperatures and PWP are well predicted
 - In the lining, the temperatures are well predicted, the estimation of stresses fall in the range of measurement
 - In the seal, a variable degree of agreement for pressures is obtained

- ❑ Improvement is still possible by
 - Refining THM constitutive laws and parameters (e.g. EDZ)
 - Refining initial/boundary conditions
 - Including results of additional in-situ testing (e.g. permeability test)

20th Exchange Meeting

The PRACLAY Heater test

First results after one and a half years of heating



Possible impact of T on chemical characteristics of Boom Clay

20th Exchange Meeting
Mol, 4 May 2016

L. Wang, M. Honty, N. Maes



STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Boom clay geochemical characteristics



- Clay minerals (30-60 %)
→ **Sorption capacity**
- Quartz (20-60 %)
- Feldspars (5-10 %)
- Carbonates (1-5 %)
→ **pH buffering capacity (8.2-8.6)**
→ **Potential source of CO₂**
- Pyrite (1-5 %)
→ **Reducing environment (< -270mV)**
- Organic matter – *Kerogen* (1-5 %)
→ **Source of CO₂**
→ **Source of dissolved organic matter**

Boom Clay geochemistry

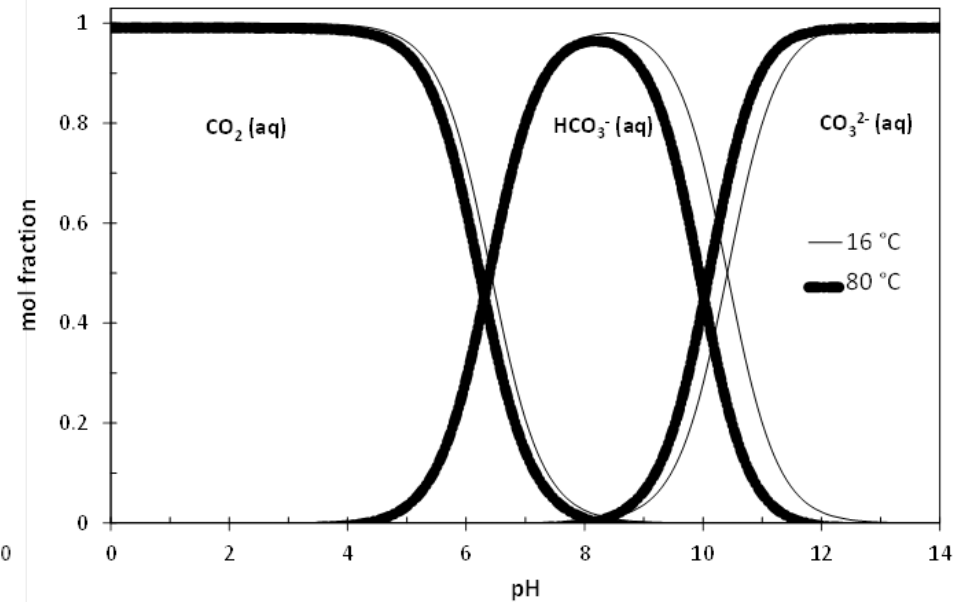
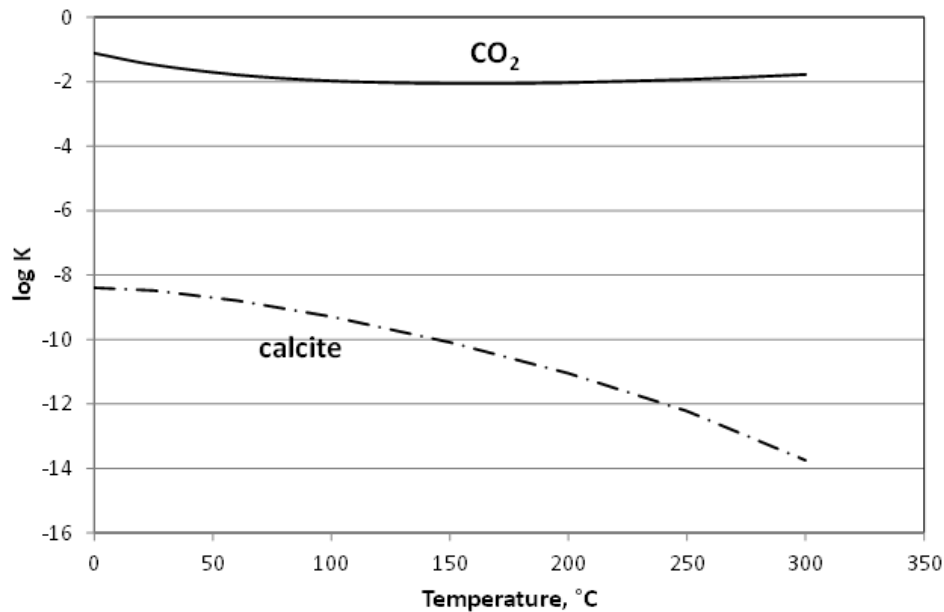
- Boom Clay Pore water ~ 0.015 M NaHCO_3 , $p\text{CO}_2 \sim 10^{-2.62}$ atm
 - Controlled by equilibrium reactions with minerals and ion-exchange reactions
- Equilibrium between pH and dissolved inorganic carbon (and $p\text{CO}_2$) is explained by the **Coudrain-Ribstein (1993, 1989) model**
 - Based on numerous observations in natural systems: $p\text{CO}_2$ seems constrained by several mineral assemblages and depends only on T and to lesser extend P.
 - Mineral assemblages relevant for Boom Clay:



$$\text{Log}K = -5\log(f\text{CO}_2) \quad (\text{K is T dependent})$$

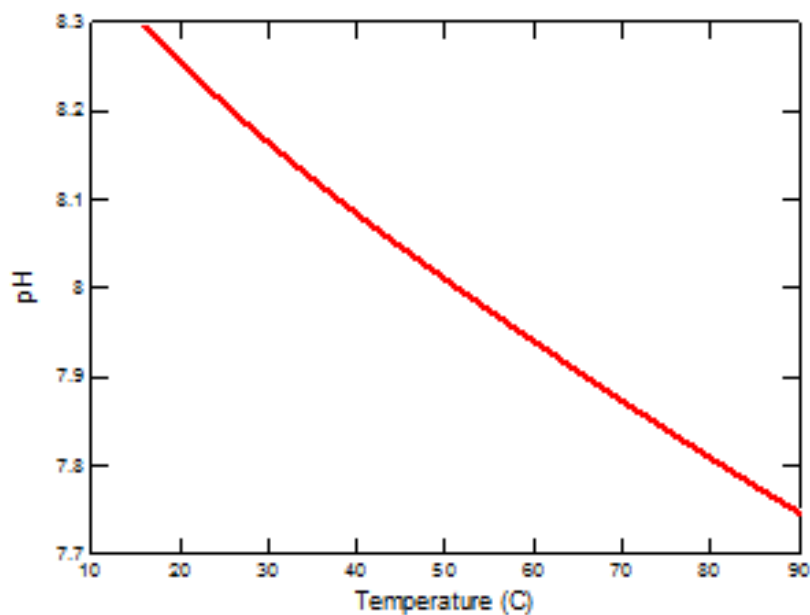
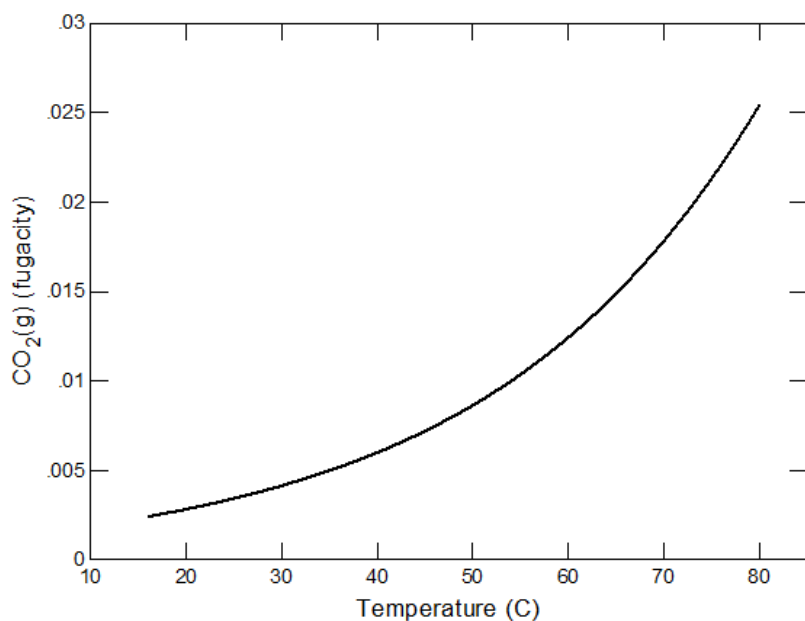
What happens chemically at increased T? - General

- Calcite (CaCO_3) dissolution decreases with T (opposite to most other minerals)
- $\text{CO}_2(\text{g})$ dissolution decreases with T when $T < 100^\circ\text{C}$
- Dissolved inorganic C speciation changes with T and pH



What happens chemically at increased T? - Pore water

- $p\text{CO}_2$ increases with T (0.015 M NaHCO_3 @ pH=8.5)
- pH decreases with T (0.015 M NaHCO_3)

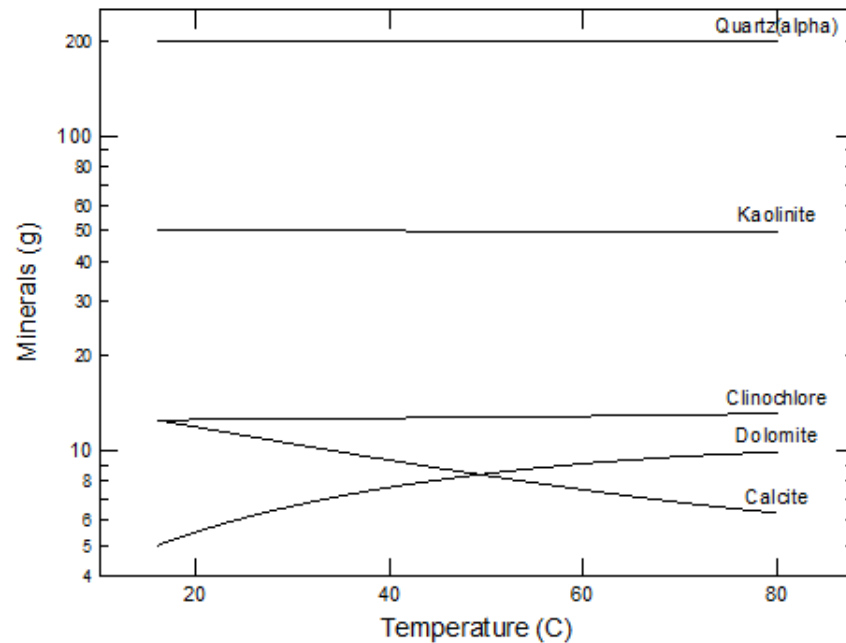
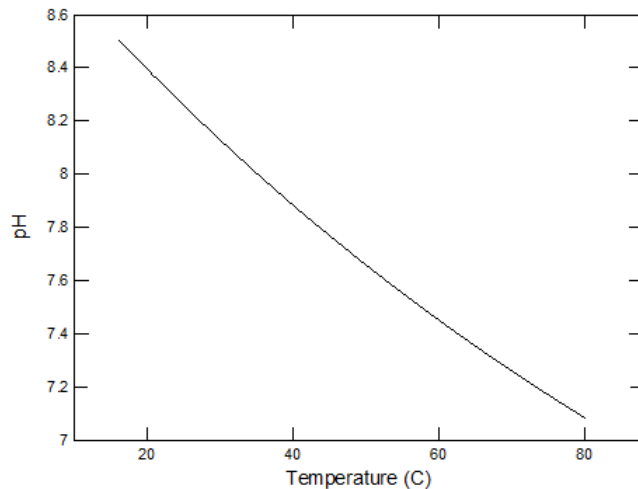
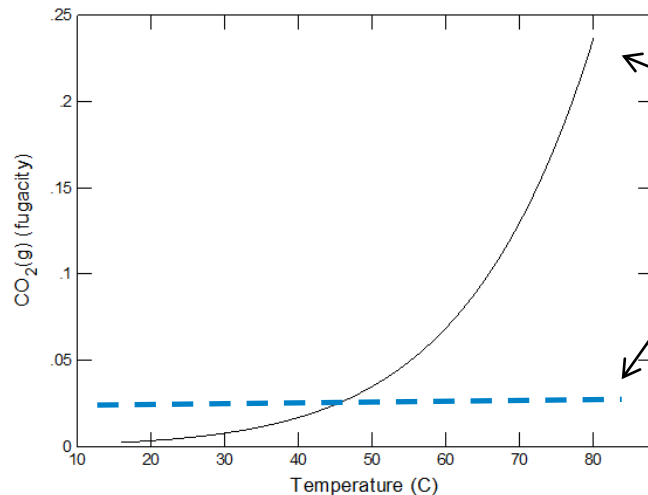


What happens chemically at increased T? – Boom Clay

● Mineral assemblage model

10 times higher $p\text{CO}_2$ is reached at 80°C if minerals are present

- decreased solubility of CO_2
- reaction of minerals produces CO_2



But what about the Kerogen and its importance at higher T?

- Kerogen: insoluble sedimentary Organic Matter, precursor of petroleum and natural gas.
- **Kerogen decomposes under thermal stress into CO₂ and small organic molecules**

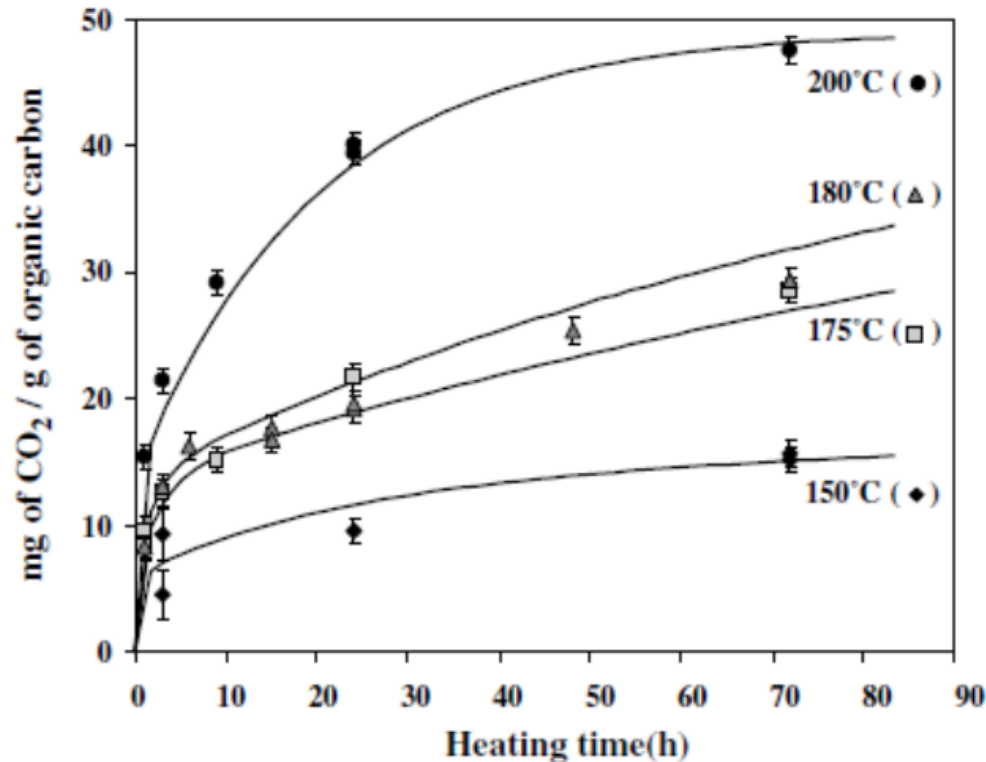
→ increase in pCO₂ may lead to an acidification (lowering of pH)

→ the formed small organic molecules may form soluble complexes with RN, hence promote their mobility not further discussed

- IFP (PhD I. Deniau, Lorant): Rock-eval pyrolysis on dry isolated kerogen – *kinetic model (2000-2008)*
- University of Nancy-Crégu (R. Michels): Rock-eval pyrolysis on “whole rock” Boom Clay – *role of water and minerals (2009-2010)*
- SCK•CEN (M. Honty): Batch studies, suspensions of BC in BCPW at 80°C for longer time periods – *more realistic conditions (2009-on-going)*
- SCK•CEN/EURIDICE: PRACLAY large heater experiment: follow up of porewater composition as function of time and temperature *(2011-on-going)*

Kerogen CO₂ production potential (1)

- Rock-Eval pyrolysis on isolated *dry* Boom Clay Kerogen
Deniau et al. (2001,2004,2005), and Lorant et al. (2008)
→ Kinetic model: total potential of ~50 mg CO₂/g organic carbon
→ 10 mg CO₂/g organic carbon at 80°C predicted



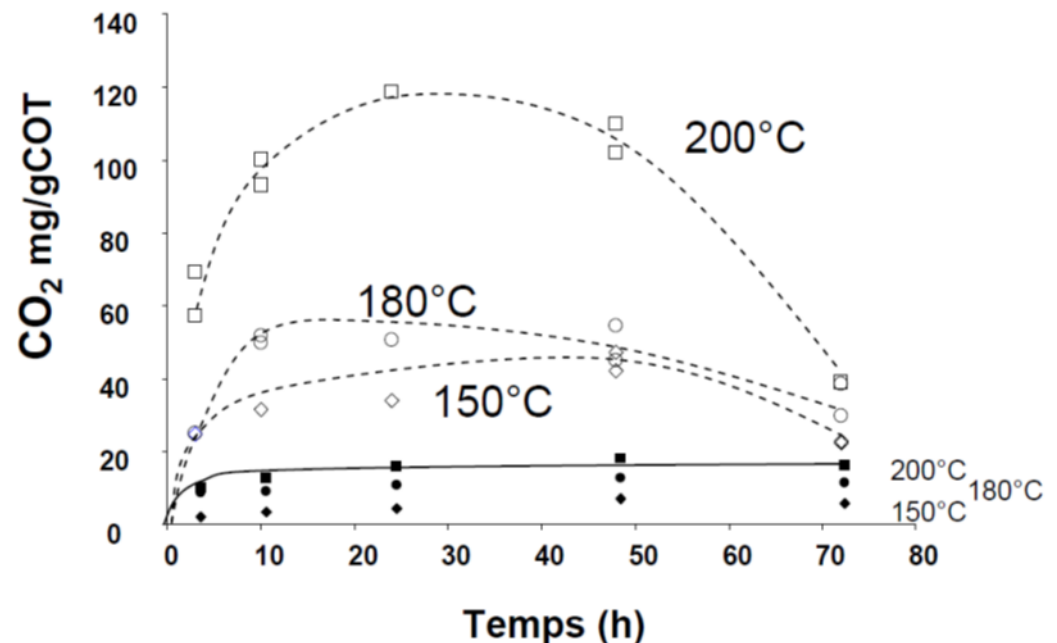
Kerogen CO₂ production potential (2)

- Rock-Eval pyrolysis on kerogen + water and Rock-Eval pyrolysis on Boom Clay (Michels et al., 2010)
 - Water did not seem to have a significant oxidizing effect that may lead to higher CO₂
 - Presence of minerals (acting as catalyst) leads to enhanced CO₂

→ total potential of ~118 mg CO₂/g organic carbon

→ Initial high production attributed to reaction of carbonate minerals

→ carbonate minerals are important contributor to CO₂ release at elevated T

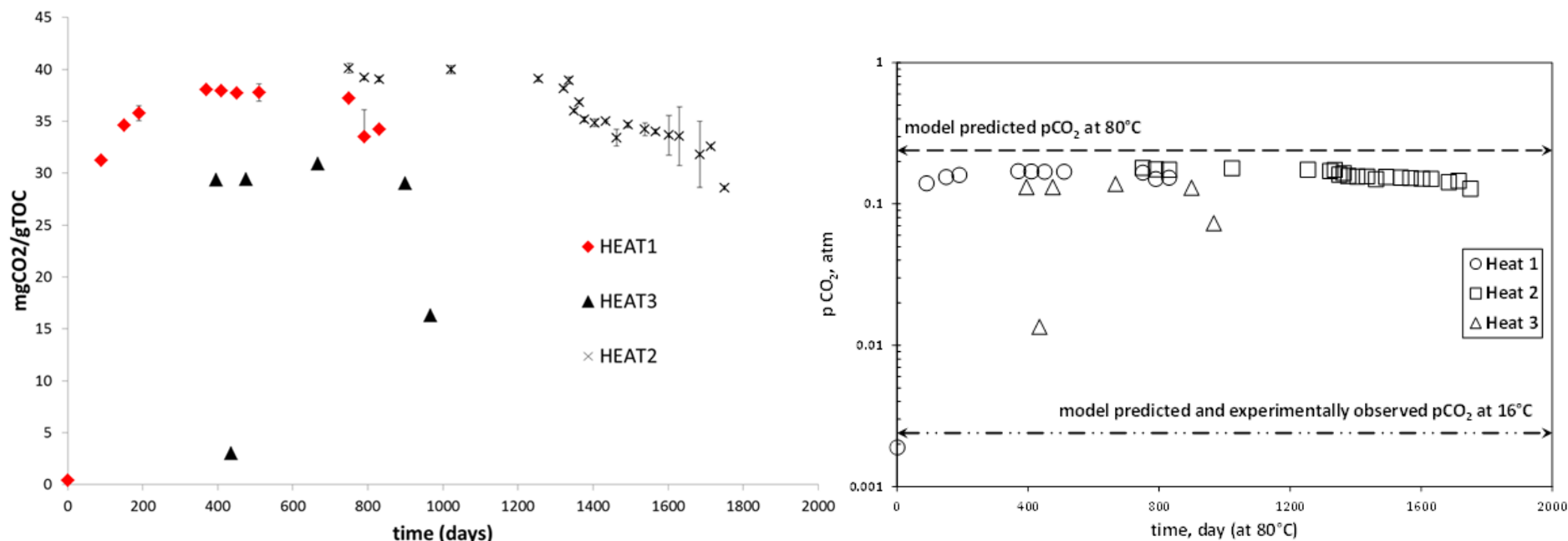


Long term batch heating experiments at 80°C (1)



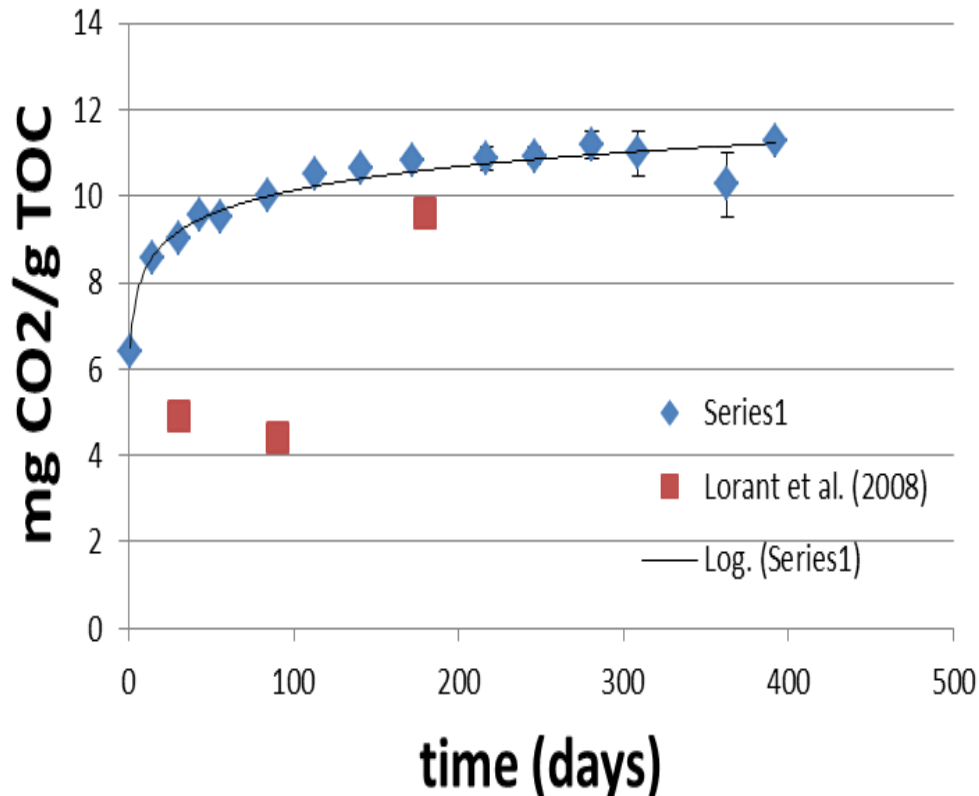
- More realistic conditions
- Boom Clay suspensions in milli-Q water (0.5kg/l)
- 80°C
- 2-5 years
- Ar (20bar) atmosphere
- 3 vessels with untreated BC
- 1 vessel with decarbonated BC
- Evolution of gas phase monitored by μ GC
- Post mortem analysis of water and solid fraction
- Reversibility (heating followed by cooling cycle)

Long term batch heating experiments at 80°C (2)



- Max CO₂ production of ~40 mgC/gTOC
 - Higher than for pure kerogen @80°C (10mg/g TOC): carbonates
 - Mineral assemblage model (no kerogen) represents well both T situations but slightly overpredicts at 80°C
- Any extra release of CO₂ is buffered acc. to mineral assemblage model

Long term batch heating experiments at 80°C (3)



Decarbonated clay

→ Only kerogen should contribute to CO₂

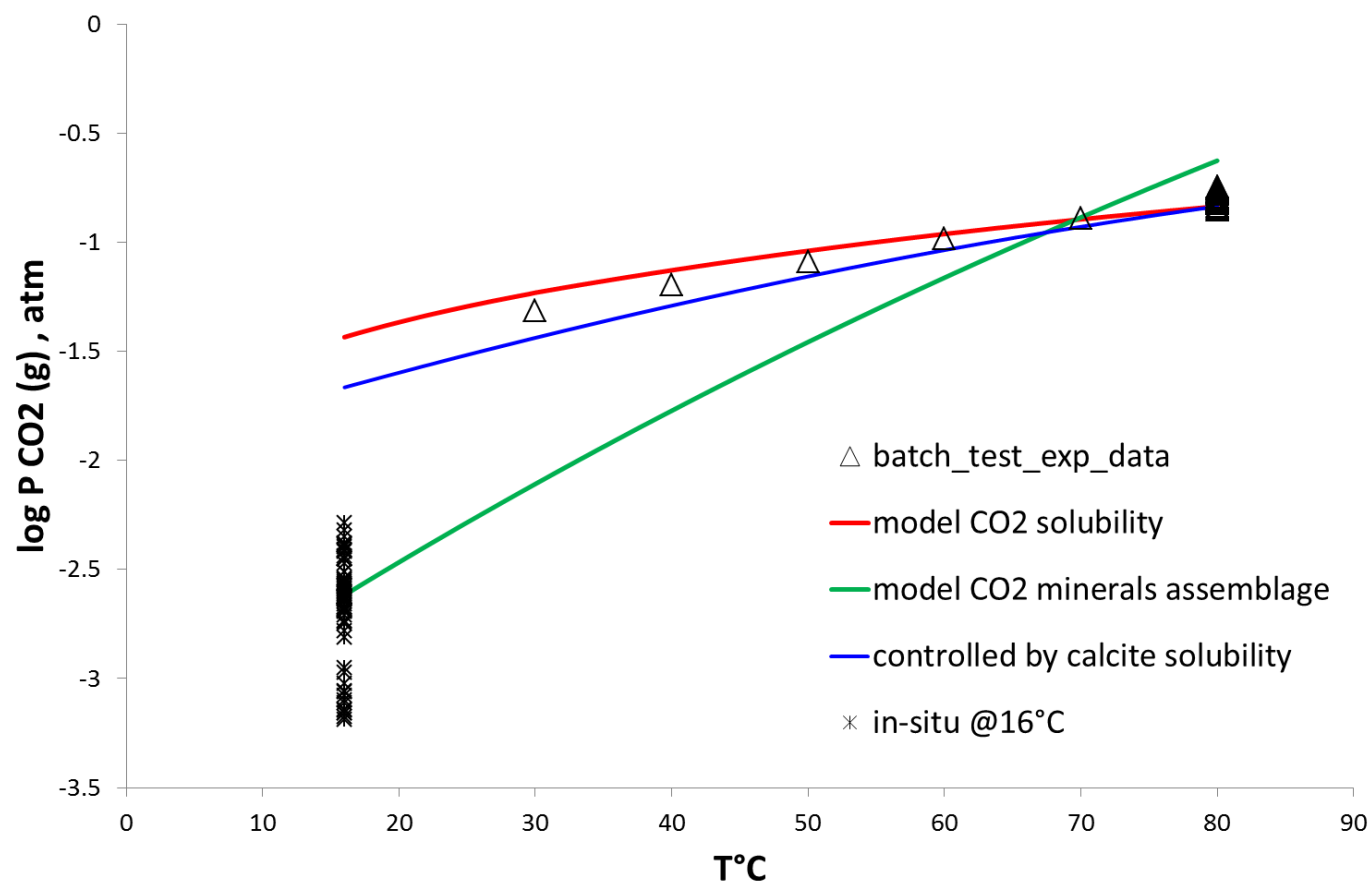
Comparable values are obtained for Kerogen heated for 180 days (Lorant et al.)

Large difference with unaltered Boom Clay

→ Role of inorganic carbonates is relatively more important in CO₂ control

Long term batch heating experiments at 80°C (4)

Reversibility of the reactions: step-wise_(10°C/month) cooling



→ Work in Progress!

- $p\text{CO}_2$ at 16°C and 80°C is well predicted by the mineral assemblage model and related equilibrium reaction

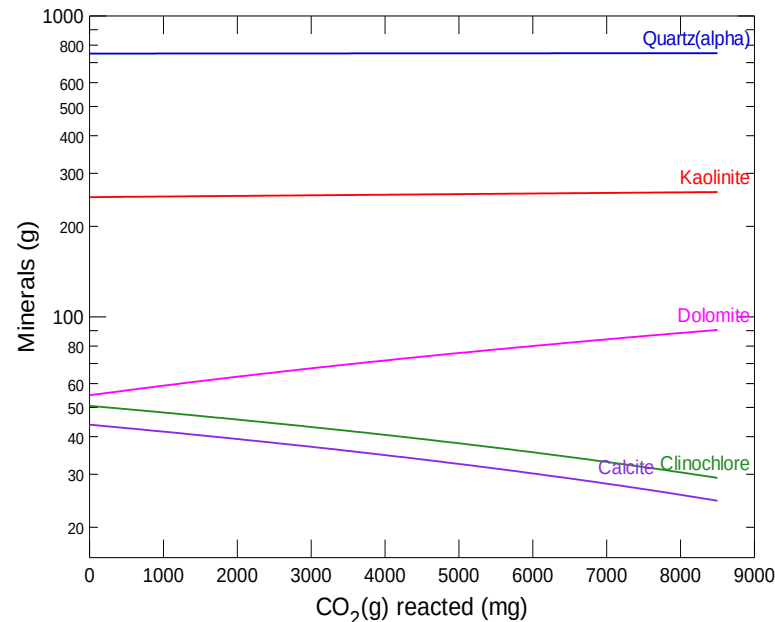
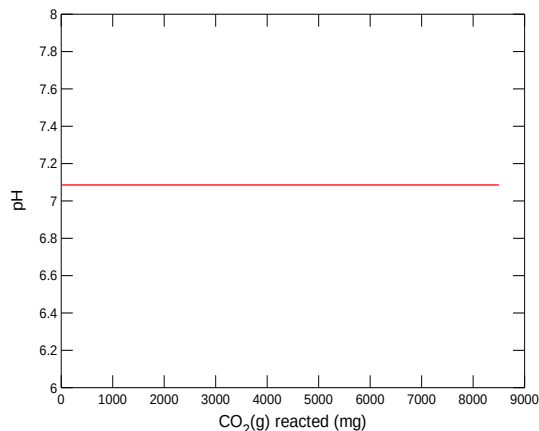
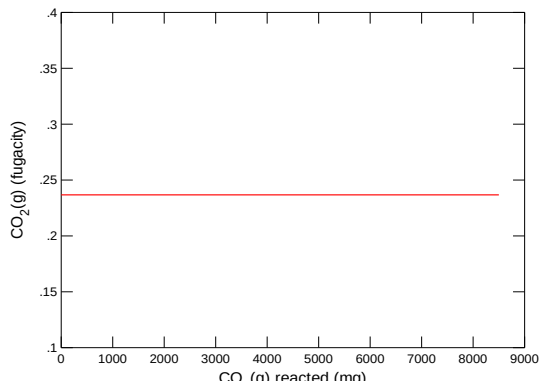


→ Any CO_2 production due to decomposition of kerogen will be buffered as long as the buffering materials (chlorite and calcite) are present

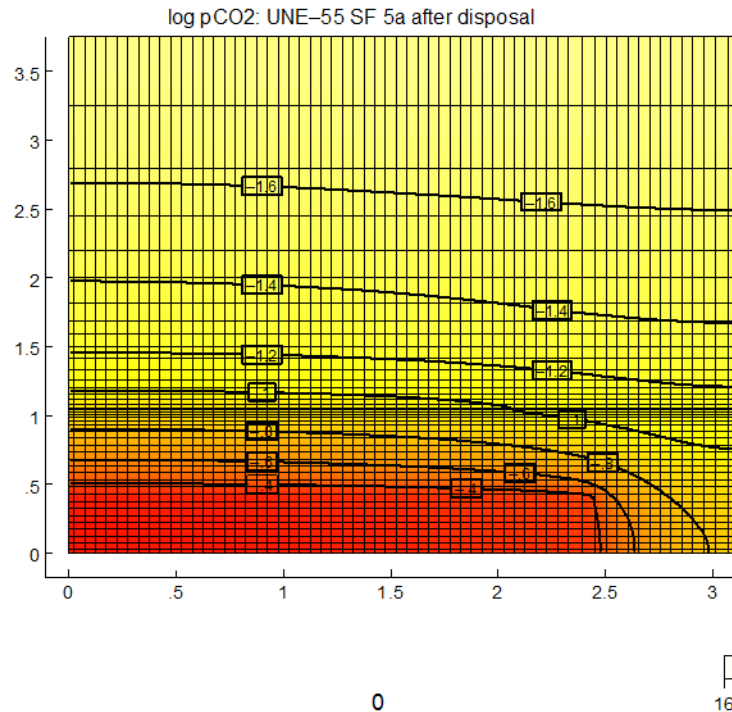
Demonstration of the mineral assemblage model

- 5Wt% kerogen
- 1Wt% dolomite and chlorite

→ Effective buffering of pH and pCO₂ during kerogen decomposition at elevated T



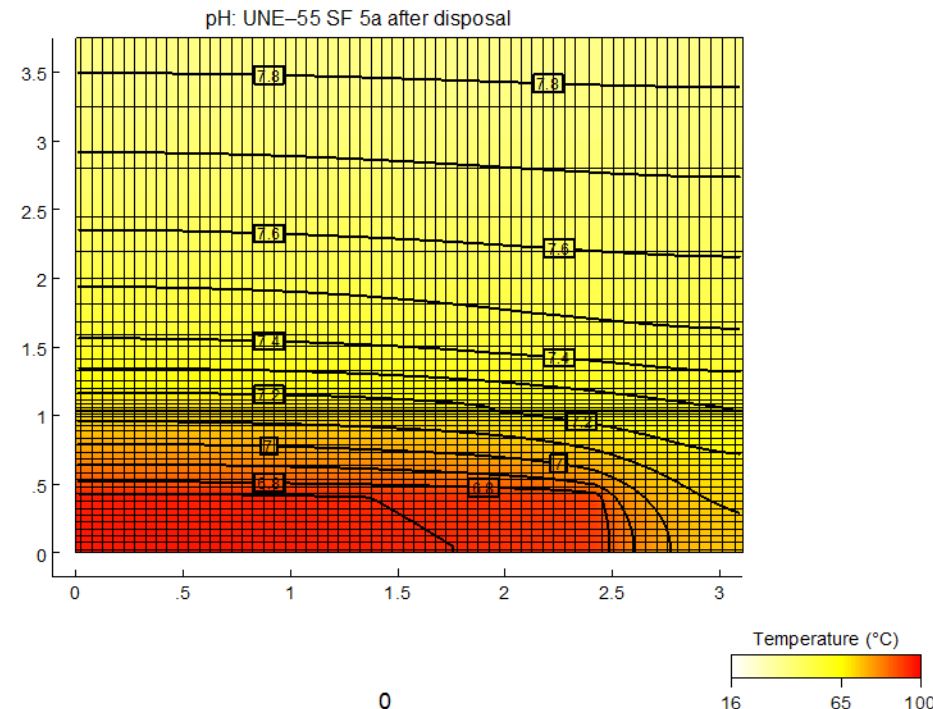
Demonstration of the mineral assemblage model for larger spatial scales



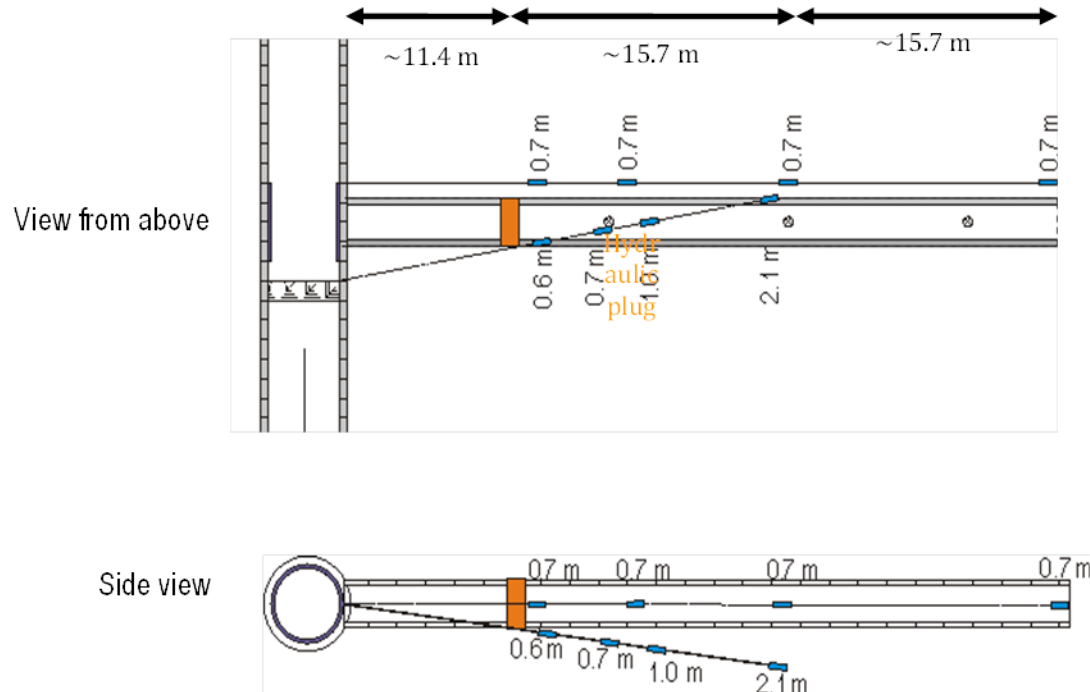
Can be used to simulate
PRACLAY Heater test

Calculations made for disposal of Spent Fuel
UNE-55 waste type after 5 y of disposal.

- Code: Geochemical workbench
- Temperature field imported from Weetjens et al. 2009.
- (kerogen decomposition not included)

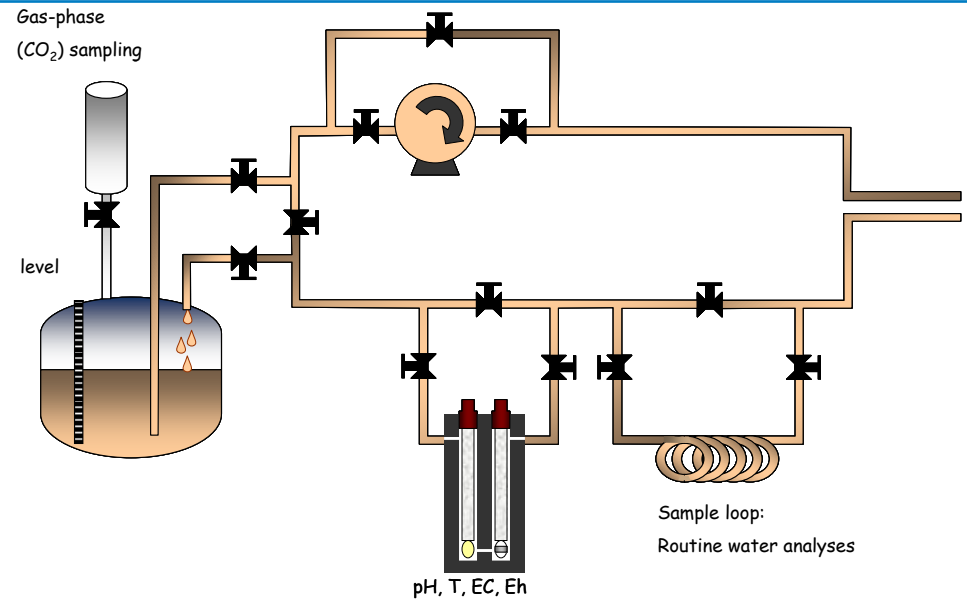


PRACLAY large-scale Heater test – Geochemical part



- 2 piezometers: inclined and parallel are used
- 3 out of 4 filters of each piezometer is connected to an on-line sampling station for monitoring the chemistry during the heating phase

PRACLAY large-scale Heater test – Pore water monitoring



Pore water
monitoring system:
On-line pH +
water/gas sampling

PRACLAY large-scale Heater test – Pore water monitoring

- The pore water monitoring set-ups from PRACLAY have enabled us to acquire a vast number of good datasets to fine-tune our understanding of the pore water chemistry of Boom Clay @ 16°C
- We have been given green light to start pore water sampling under heated conditions.
 - During first phase of heating, any possible artefact caused by sampling had to be avoided – all samplings for PW chemistry were suspended since priority is on THM behaviour.
 - Sampling protocol needed some adaptation + approval prior to restart of sampling (*current situation*)

Summary and Conclusions

- The heating of the Boom Clay changes chemical equilibria affecting the pH, $p\text{CO}_2$ and mineral composition – *reversible processes*
 - Well explained by the mineral assemblage model
- Heating of the Boom Clay also leads to decomposition of Kerogen – *irreversible process*, producing extra CO_2 and liberation of small organic molecules

But any CO_2 production due to kerogen decomposition will be buffered as long as the buffering materials are present.

The PRACLAY Heater test and further lab experiments will be used to further underbuild these conclusions.

- Coudrain-Ribstein et al. (1993) App. Geochem. 8, 495-506
- Coudrain-Ribstein et al. (1998) Chem. Geol. 145, 73-89
- Deniau et al. (2001) Org. Geochem. 32, 1343-1356
- Deniau et al. (2004) Org. Geochem. 35, 91-107
- Deniau et al. (2005) App. Geochem. 20, 587-597 & 2097-2107
- Lorant et al. (2008) Org. Geochem. 39, 1294-1301
- Michels et al. (2010) Rapport Crégu n°2009-31
- Weetjens et al. (2009) SCK•CEN-ER-86
- Wang et al. (2013) SCK•CEN-TN-14 + updated version under review

20th Exchange Meeting

The PRACLAY Heater test

First results after one and a half years of heating



Concluding remarks

20th Exchange Meeting

Mol, 4 May 2016

Peter De Preter

Director - EIG EURIDICE



ONDRAF/NIRAS



ESV EURIDICE GIE



Successful launching of the Heater test

- One and a half years of heating since switch-on
- Nine months on target temperature of 80°C
- Seal structure and bentonite play their role

Almost 30 bar water pressure inside the PRACLAY gallery

- Heater system functions perfectly well
- Data acquisition system and visualisation of data allow real-time follow-up

Scientific follow-up and interpretation

- **General evolution in line with our scientific understanding and blind predictions**
 - ⇒ Broad confirmation of our understanding of the key processes in such a complicated system
- **Start-up phase report** already published and available!
- Next 2 – 3 years will provide us with crucial scientific information on the disposal system behaviour under thermal stress
 - Key input for NIRAS/ONDRAFs Safety Case 2020
 - Intensive scientific reporting period ahead of us

Thanks to the PRACLAY project team

... for the rigorous, high quality preparation and launching of the large scale Heater test

... for the intensive daily steering and follow-up of the experiment

20th Exchange Meeting

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First results after one and a half years of heating

