THE FEBEX IN SITU TEST: AN 18-YEAR LONG SIMULATION OF AN ENGINEERED BARRIER

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28 August – 1 September 2023, Liege (BE)

GOBIERNO DE ESPAÑA

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UE 23

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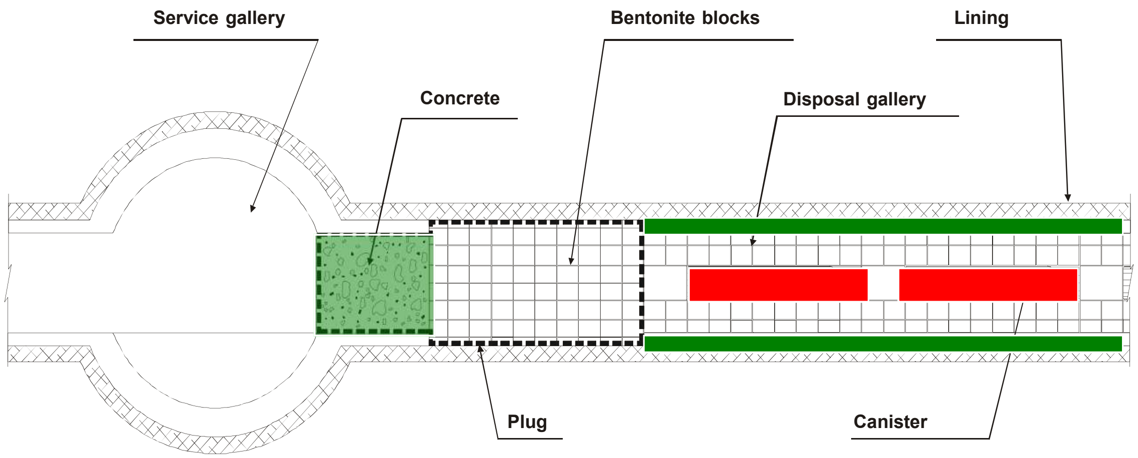
European Joint Programme on Radioactive Waste Management

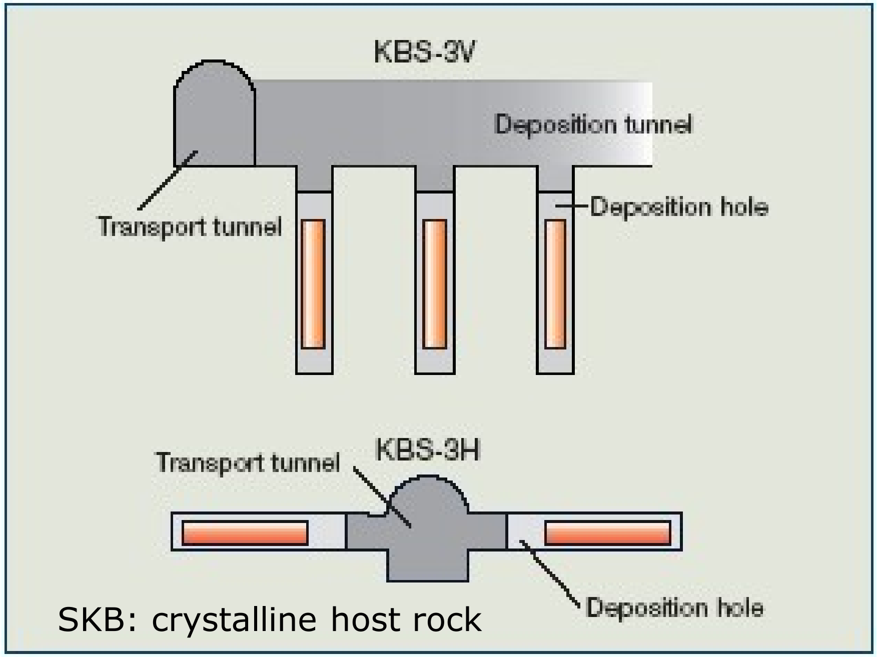
Outline

- Introduction: geological disposal of nuclear waste and engineered barriers
- The FEBEX project and the in situ test
- Partial dismantling of the in situ test after 5 years
- FEBEX-DP: dismantling of the in situ test after 18 years operation
- Postmortem analysis of some THM properties

Buffer/backfill in HLW repositories



ENRESA: clay host rock

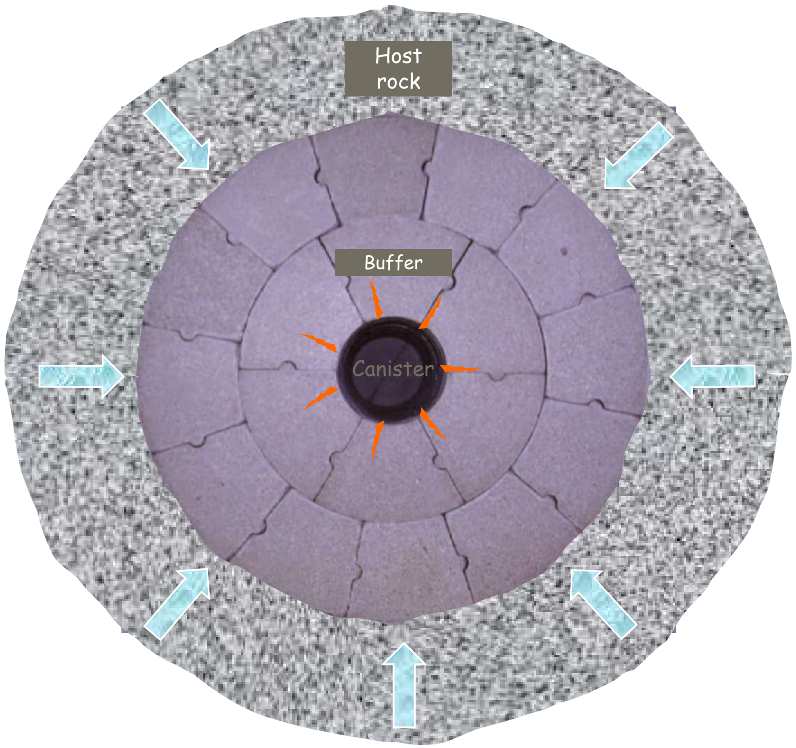


SKB: crystalline host rock

	FUNCTIONS	MATERIALS	
BUFFER	limit the entry of water, contribute to radionuclide retention and heat dissipation, provide mechanical protection for the canisters	Bentonite (expansive, smectite-rich material, can retain elements in its structure) Mixtures of bentonite and aggregates: crushed granite, basalt, quartz, zeolytes, graphite	 

The barrier during the transient stage

PROCESSES: hydration + heating + radiation



Hydration with groundwater:

Development of swelling pressure

Sealing of voids, microstructural reorganisation

Compression of air in pores

Chemical changes

Heating from the canister:

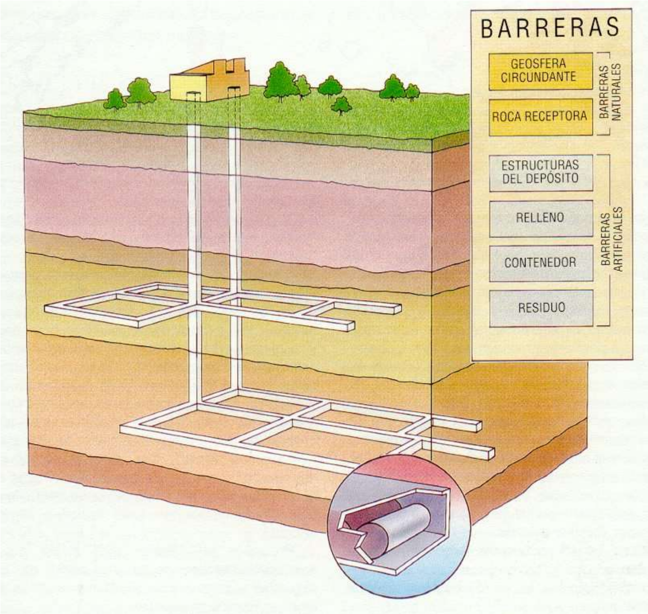
Drying near the heater: cracking?

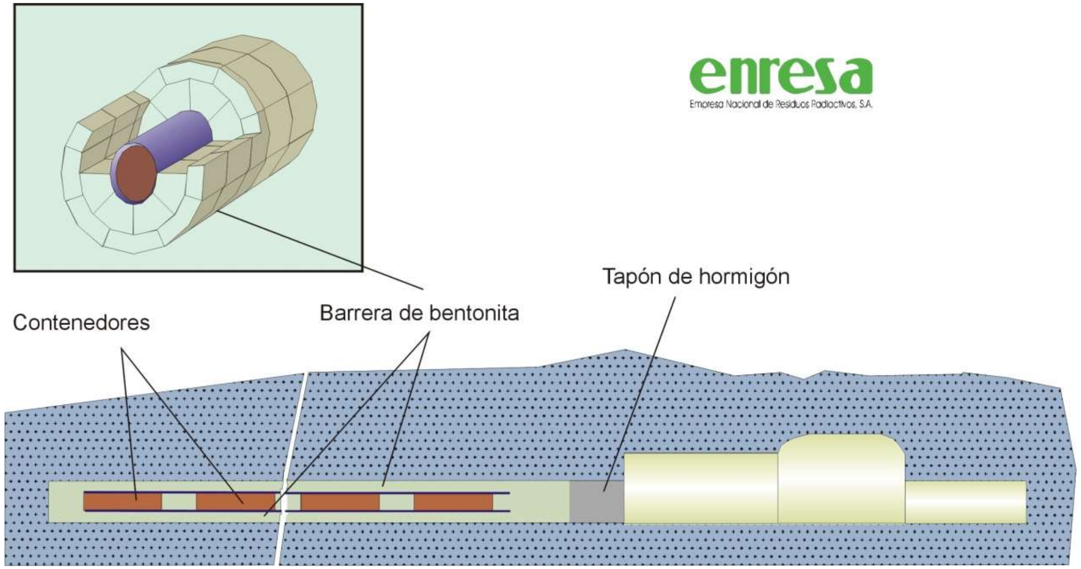
Vapour diffusion/advection

Chemical and mineralogical changes

Gas generation and transport

SPANISH CONCEPT FOR DISPOSAL IN GRANITE





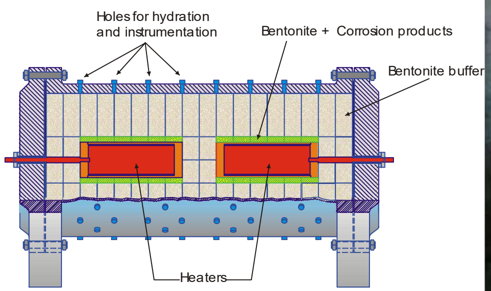
enresa
Empresa Nacional de Residuos Radiactivos, S.A.

- Barrier thickness: 0.75 m
- Barrier dry density: 1.65 g/cm^3, initial water content: hygroscopic
- Initial degree of saturation: 50-60 %
- Maximum temperature at canister surface: 100ºC

FEBEX PROJECT

Study of the behaviour of the near-field components of a high level radioactive waste repository in crystalline rock

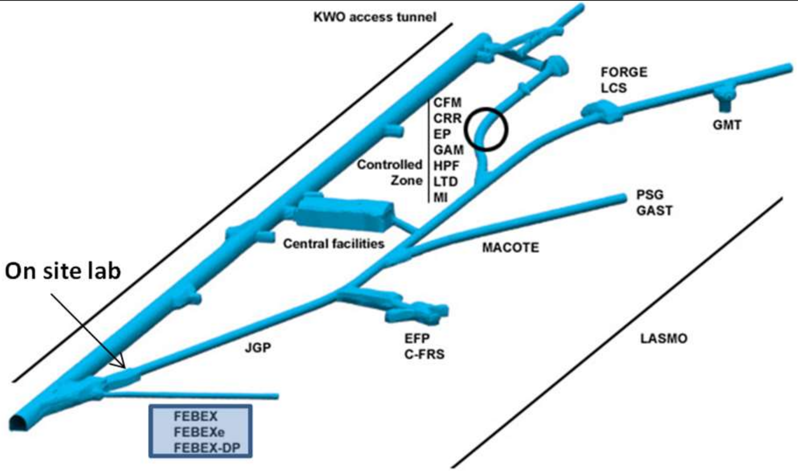
1. *In situ* test under natural conditions and at full scale (Grimsel, Switzerland)



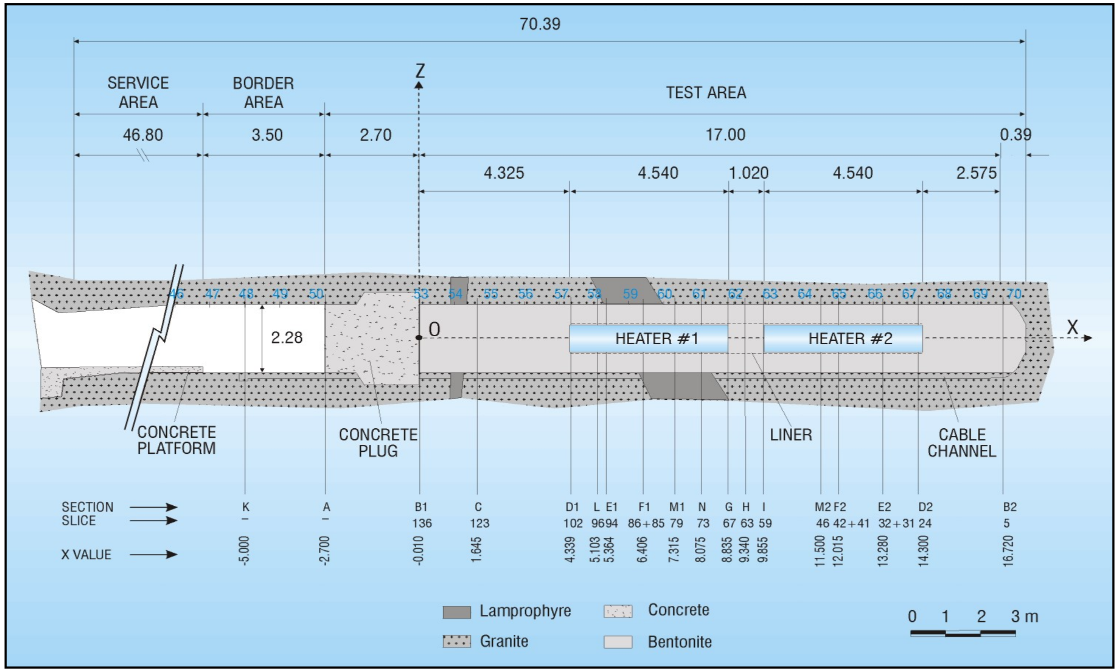
2. Mock-up test at almost full scale (CIEMAT, Madrid)

3. **A series of laboratory tests to complement the information from the two large-scale tests: process understanding, determination of parameters**
4. **THM-THG modelling: model development, data interpretion, prediction**

FEBEX IN SITU TEST AT GRIMSEL UNDERGROUND LABORATORY (GTS)



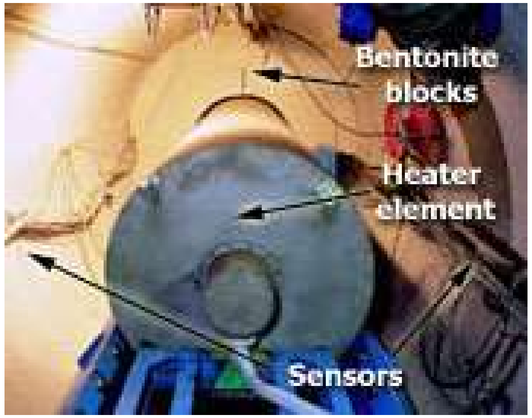
- Underground laboratory excavated in granite at 1730 m.a.s.l. and depth 500 m
- The FEBEX in situ test simulated at a large scale the components of the near field of an underground repository of nuclear waste
- Natural hydration from the host rock and two heaters simulating the waste containers
- Engineered barrier of compacted bentonite blocks

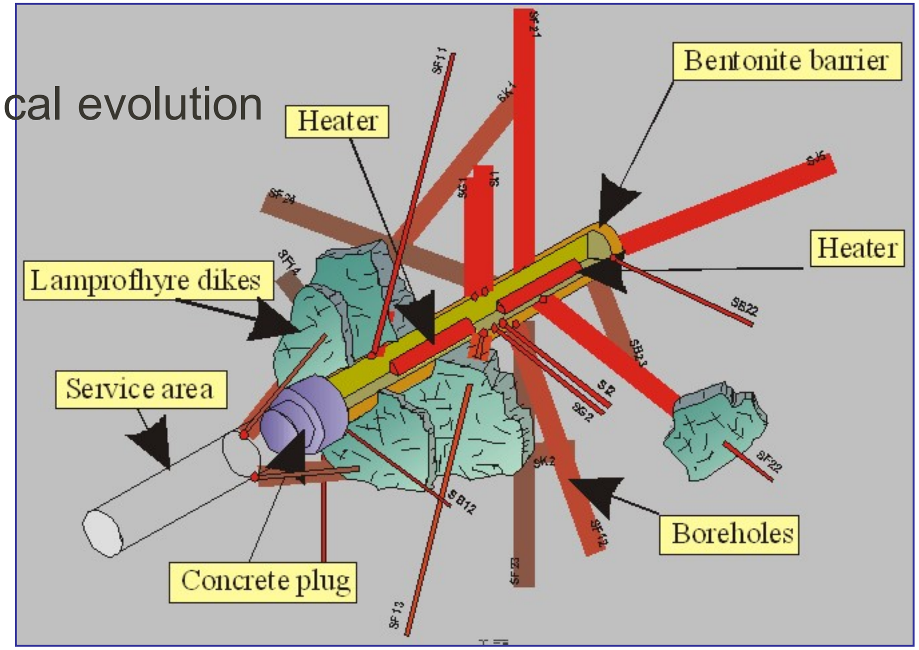


FEBEX IN SITU TEST: INITIAL DESIGN

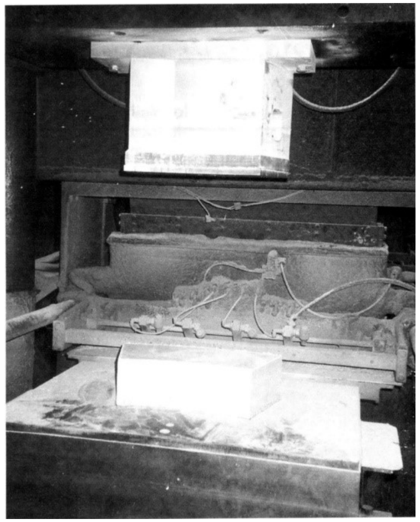
FEBEX

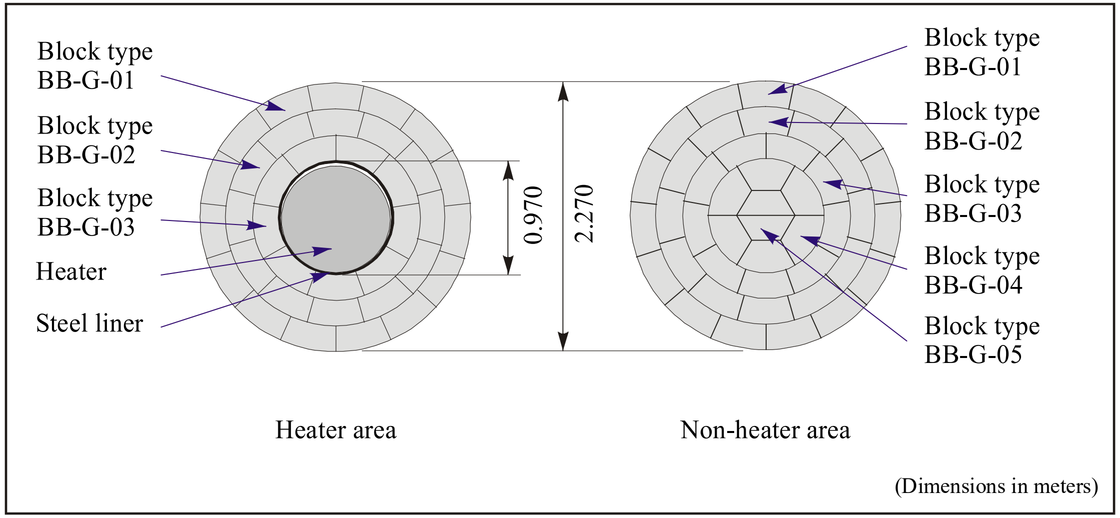
- Full-scale in situ test at GTS
- Barrier of FEBEX bentonite blocks, natural hydration, two heaters at 100°C
- Steal perforated liner to align the heaters along the gallery
- Sensors in bentonite and rock
- Instrumented boreholes in granite to follow hydrogeological evolution
- Tracers
- Concrete plug to close the gallery
- In operation since 1997
- Partial dismantling in 2002
- Final complete dismantling in 2015



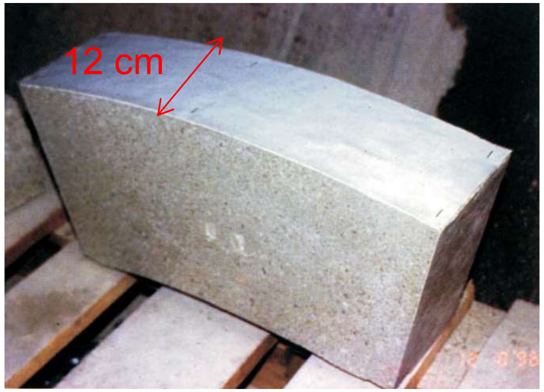


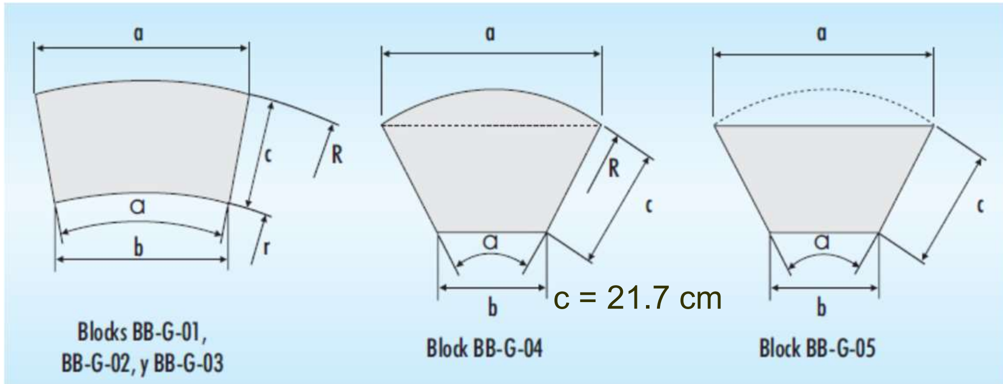
FEBEX IN SITU TEST: PREPARATION AND ASSEMBLY (1996-1997)





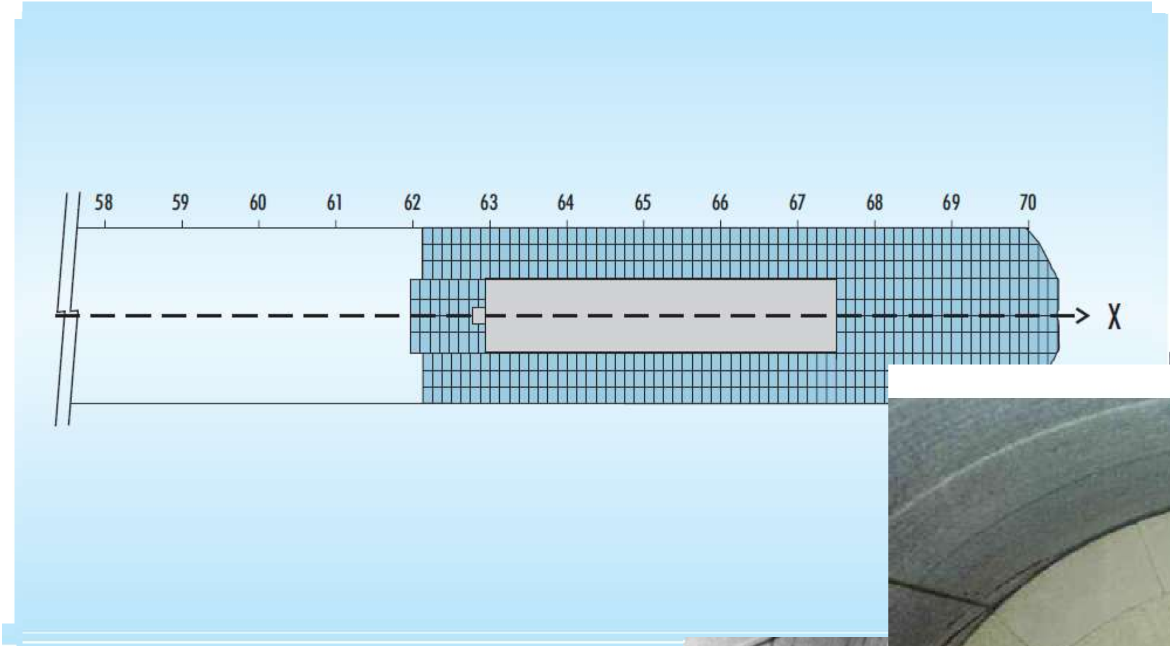
- The FEBEX bentonite came from the Cortijo de Archidona quarry (Almería, SE Spain), it consists of >90% of montmorillonite and Ca, Mg and Na as exchangeable cations

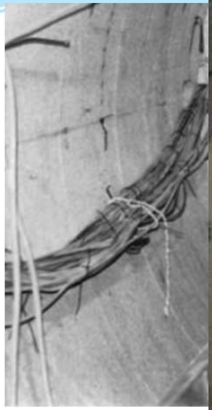




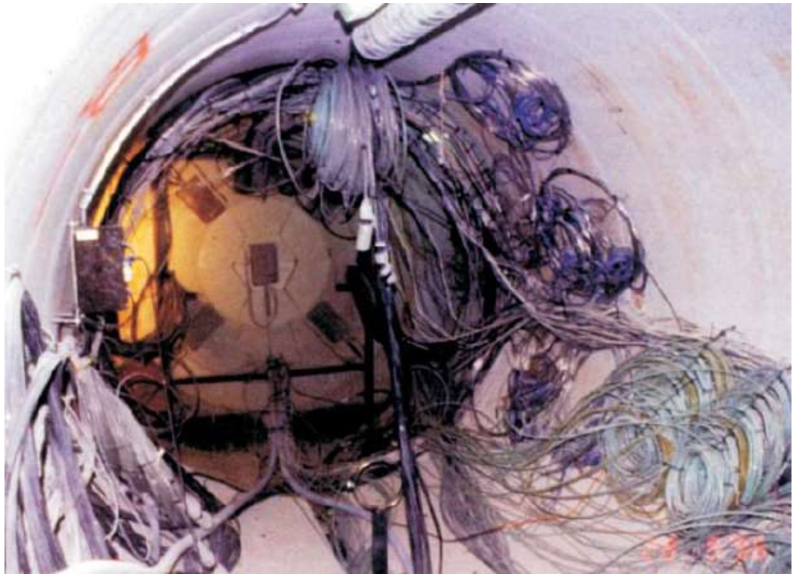
The sealing material was a barrier of bentonite blocks. The bentonite was compacted at a dry density of 1.70 g/cm^3 with its hygroscopic water content (14%): resulting barrier density 1.60 g/cm^3 (gap volume ~6%)

FEBEX IN SITU TEST: PREPARATION AND ASSEMBLY (1996-1997)



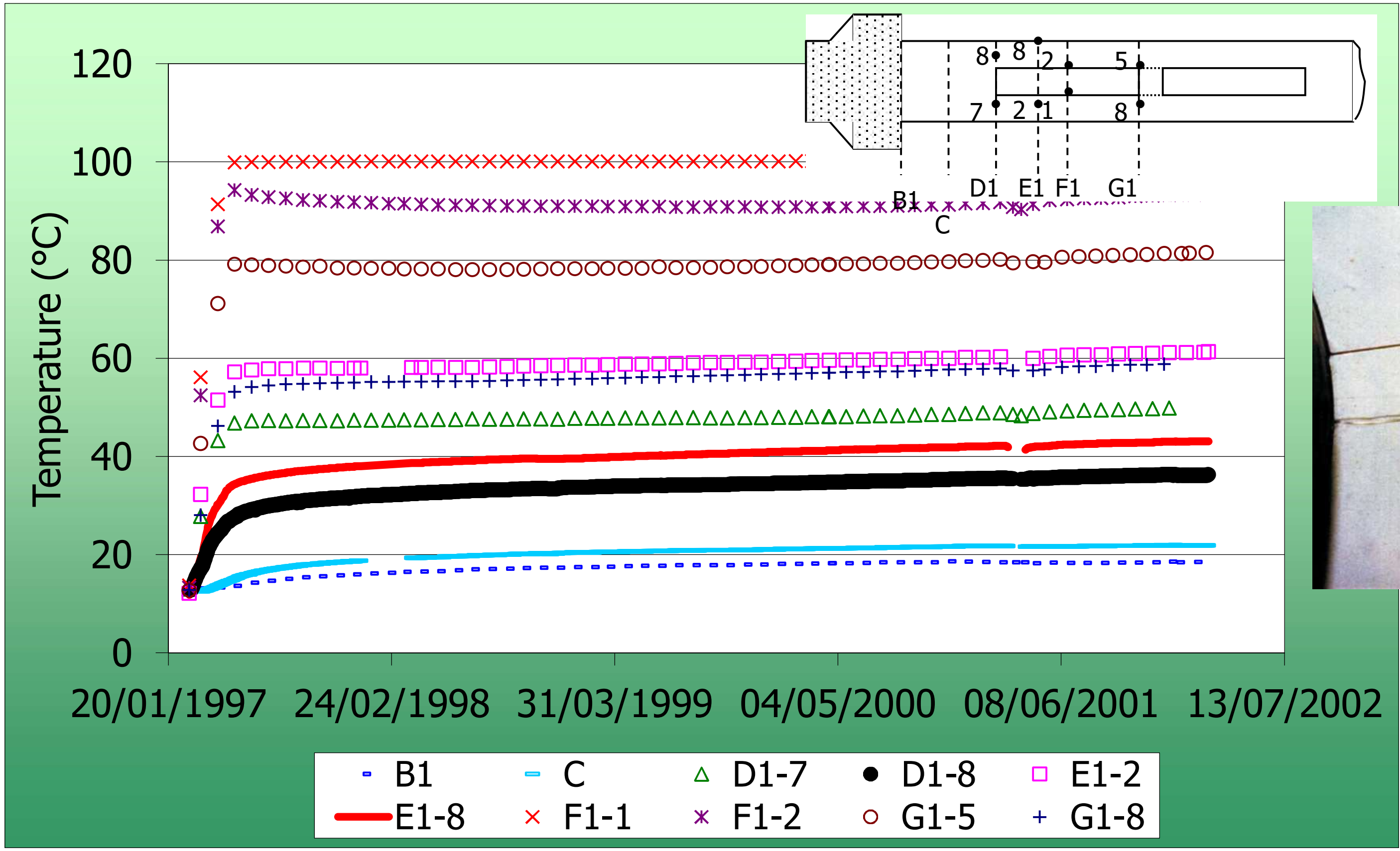


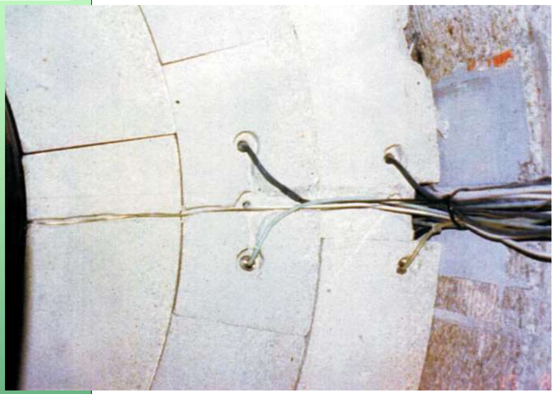
FEBEX IN SITU TEST: PREPARATION AND ASSEMBLY (1996-1997)



https://www.grimsel.com/images/stories/videos/febex.mp4

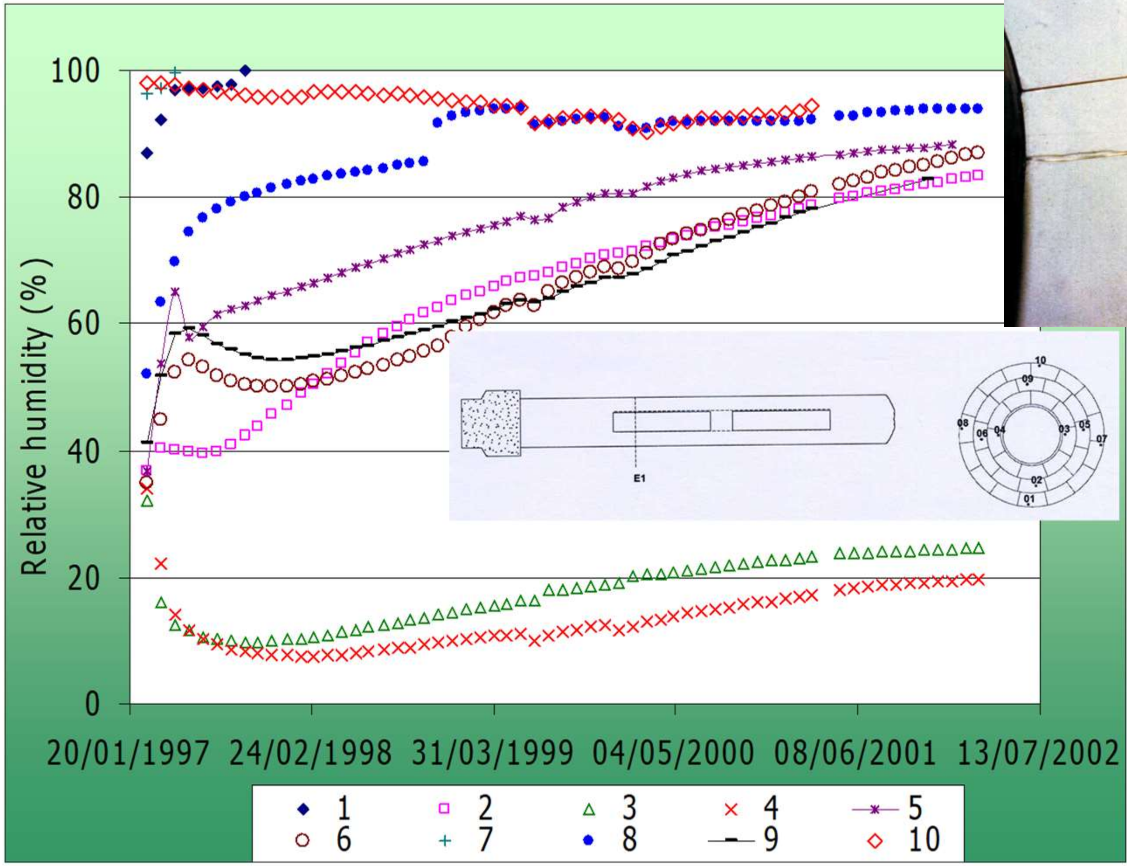
FEBEX IN SITU TEST: INITIAL EVOLUTION (5 YEARS)

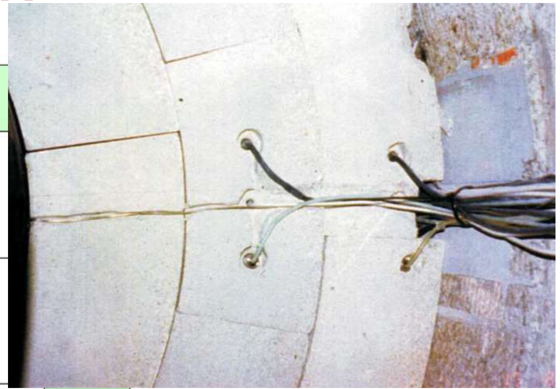




Bentonite section around heater 1

FEBEX IN SITU TEST: INITIAL EVOLUTION



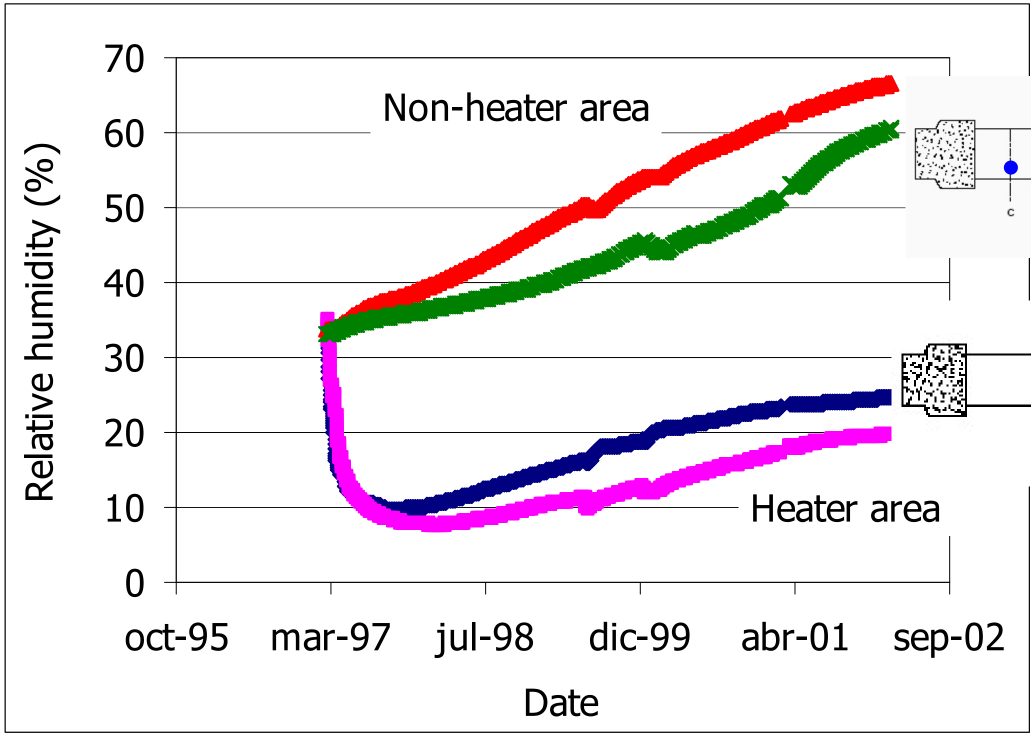


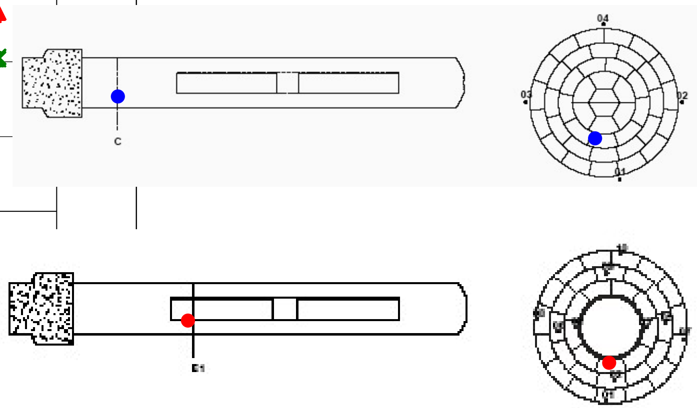
$$s = -10^{-6}\,\frac{R \times T}{V_w}\ln\left(\frac{\mathrm{HR}}{100}\right)$$

Bentonite section around heater 1

TH coupling

How does temperature affect saturation?





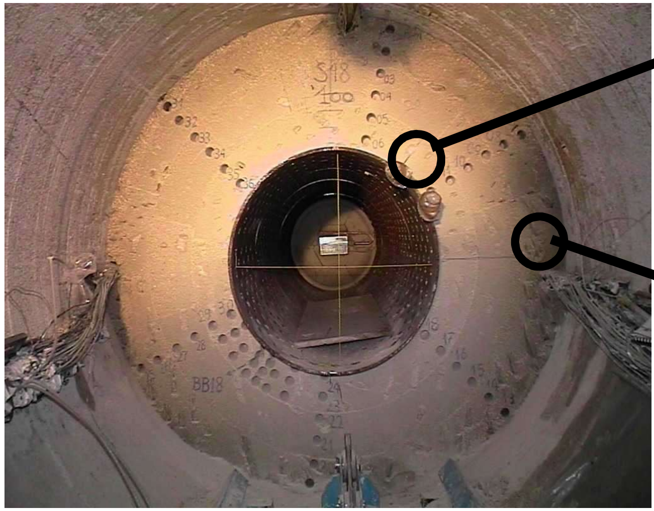
AITEMIN data base

Five years operation

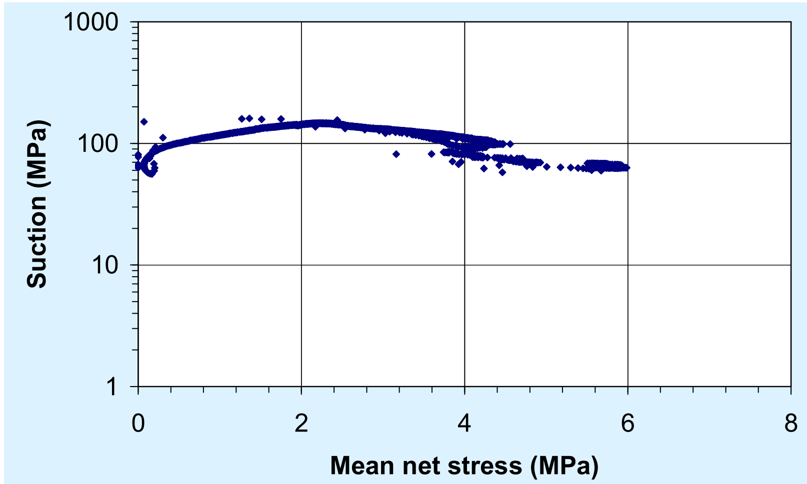
FEBEX

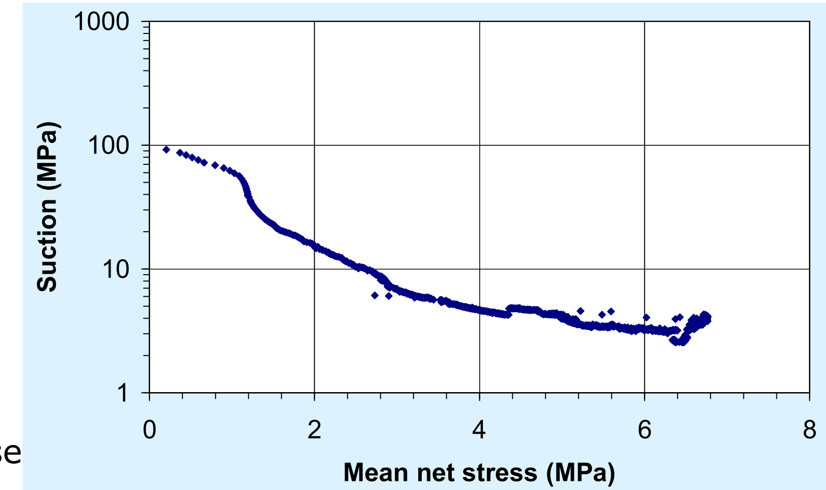
THM coupling

Stress paths in FEBEX *in situ* test



$$s = -10^{-6}\,\frac{R \times T}{V_w}\ln\left(\frac{\mathrm{HR}}{100}\right)$$

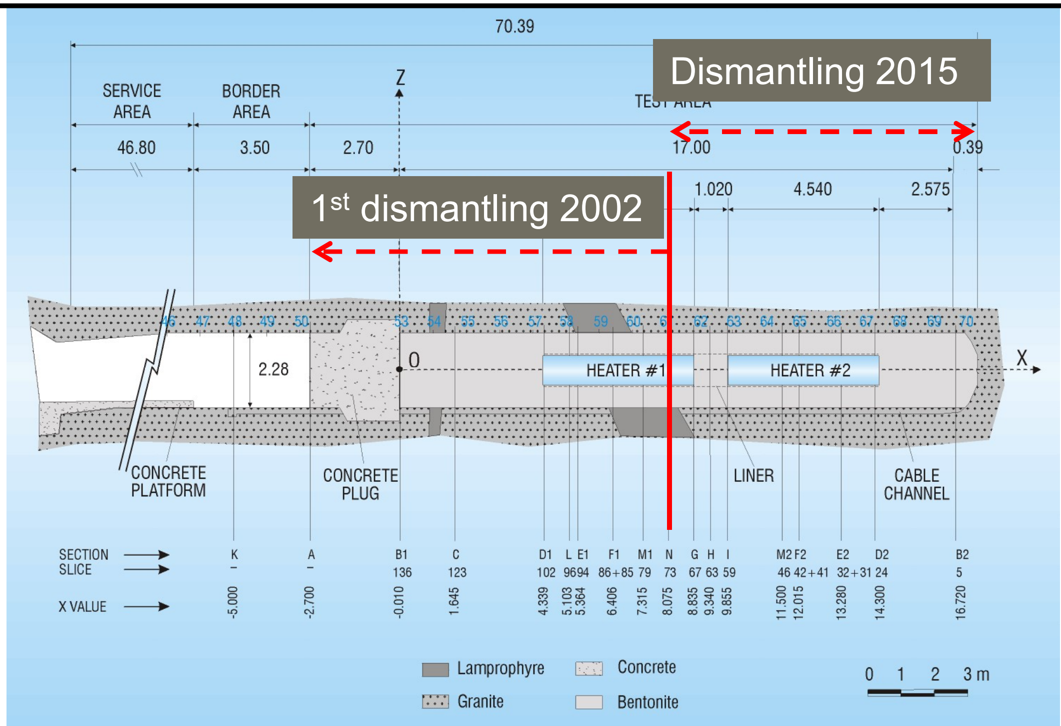




AITEMIN data base

FEBEX

FEBEX IN SITU TEST: PARTIAL DISMANTLING (2002)



- After 5 years operation (heating + natural hydration) half of the experiment was dismantled
- Samples of bentonite and other materials were taken
- The void left by the back of heater 1 was replaced by a steel dummy
- The gallery was closed again with a concrete plug

AIMS OF PARTIAL DISMANTLING

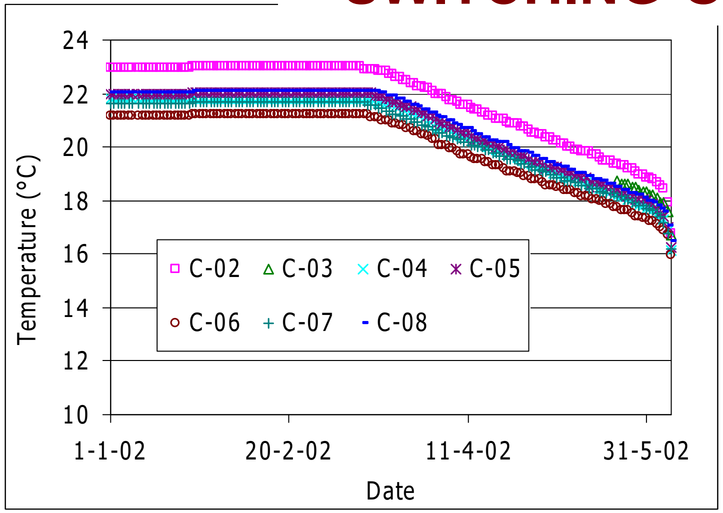
Characterise the state of the barrier → Validate the sensors performance and the THM and THG models

Determine changes in bentonite properties → Check the performance and durability of the barrier

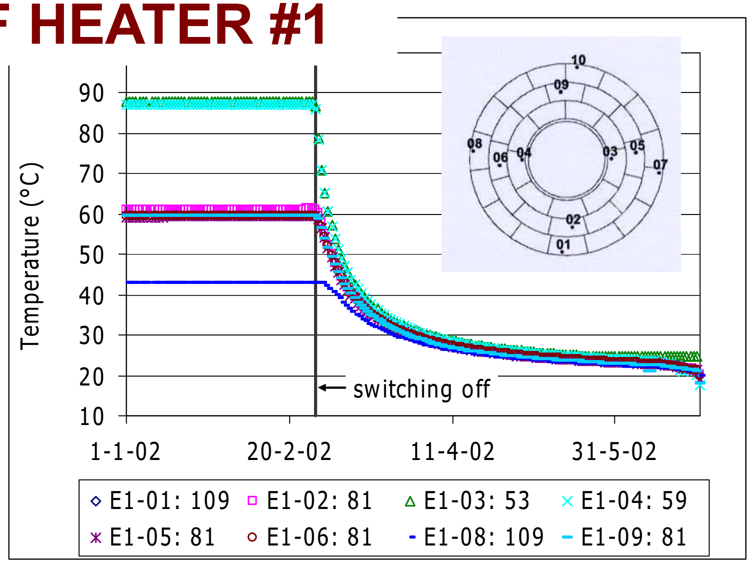
FEBEX IN SITU TEST: PARTIAL DISMANTLING (2002)

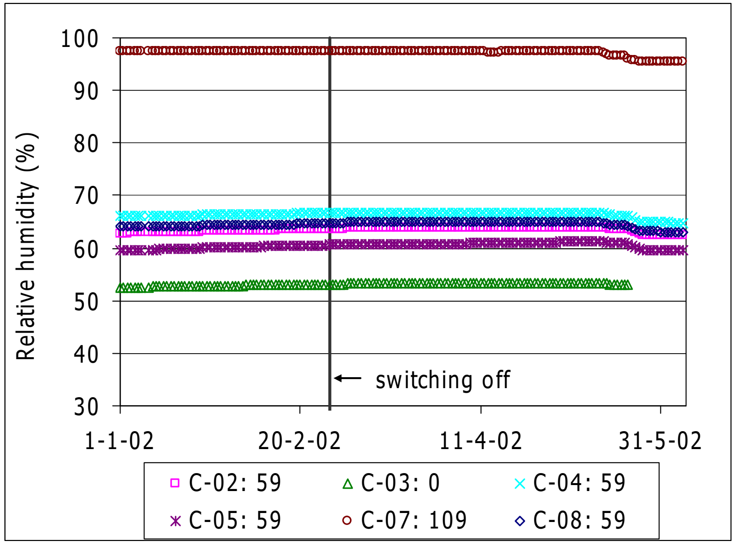
SWITCHING-OFF OF HEATER #1

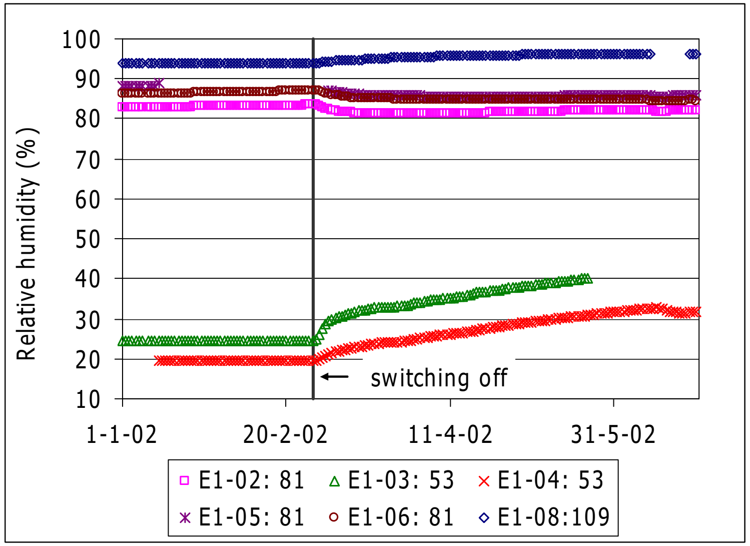
COLD SECTION



HOT SECTION







FEBEX IN SITU TEST: PARTIAL DISMANTLING (2002)

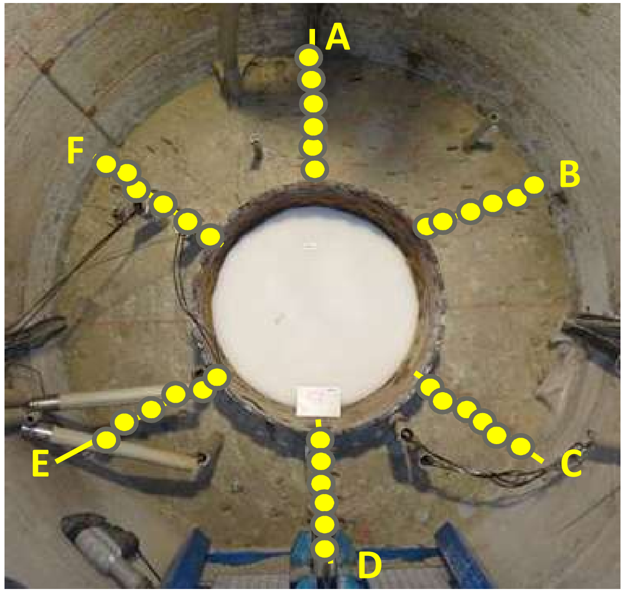
CONCRETE PLUG DEMOLITION

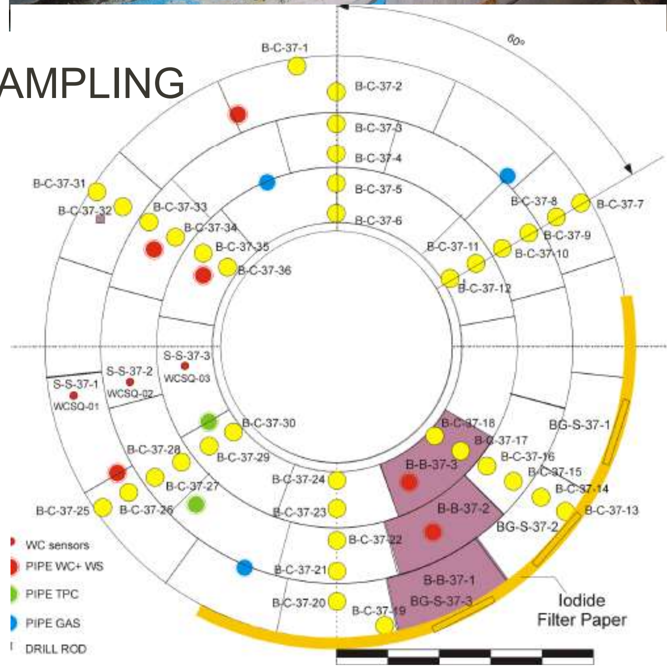
FIRST BENTONITE SLICES ARE REACHED

FEBEX IN SITU TEST: PARTIAL DISMANTLING (2002)

HEATER #1 EXTRACTION

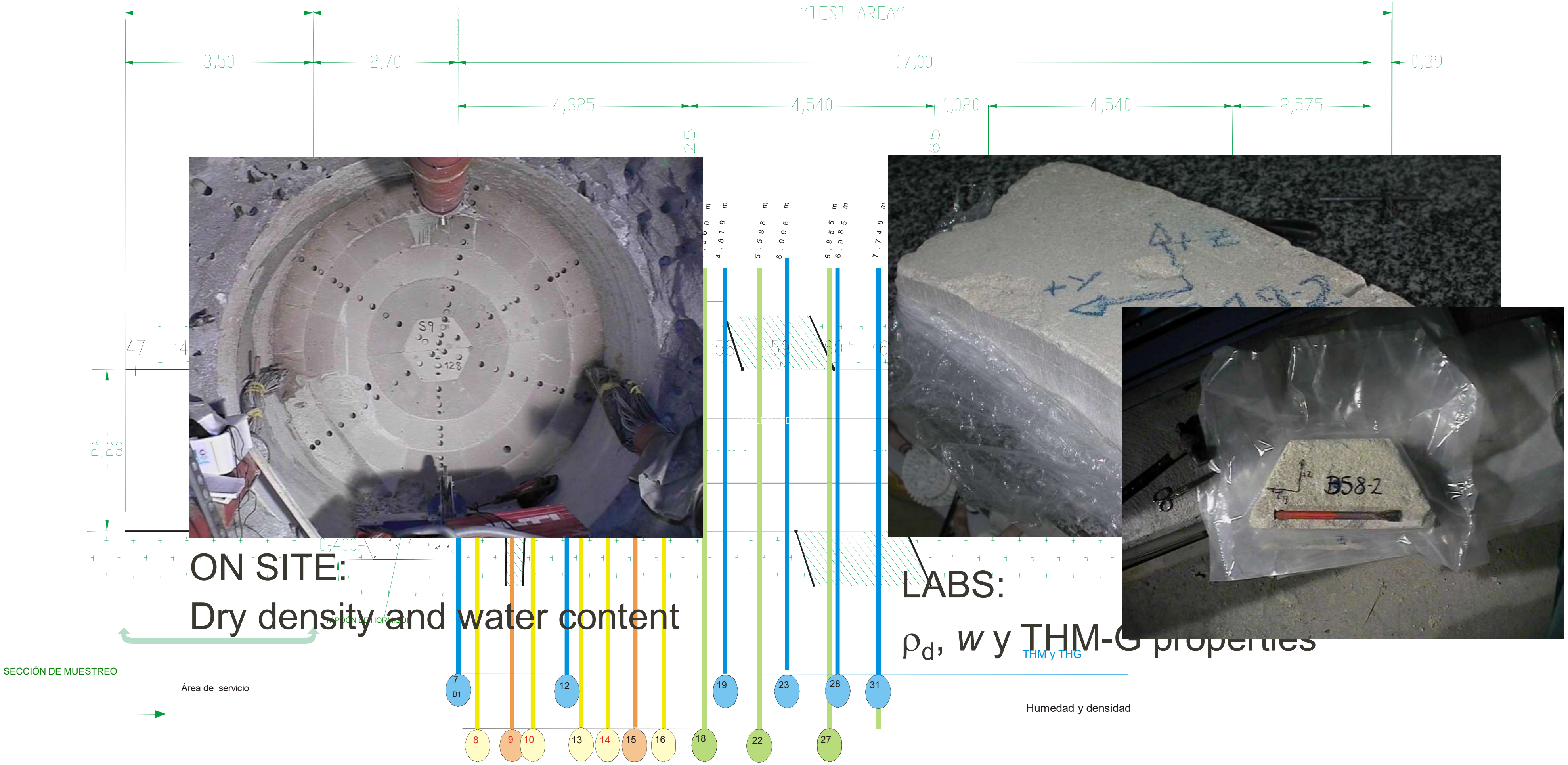
BENTONITE (AND OTHER MATERIALS) SAMPLING





FEBEX IN SITU TEST: PARTIAL DISMANTLING (2002)

SAMPLING



ON SITE:

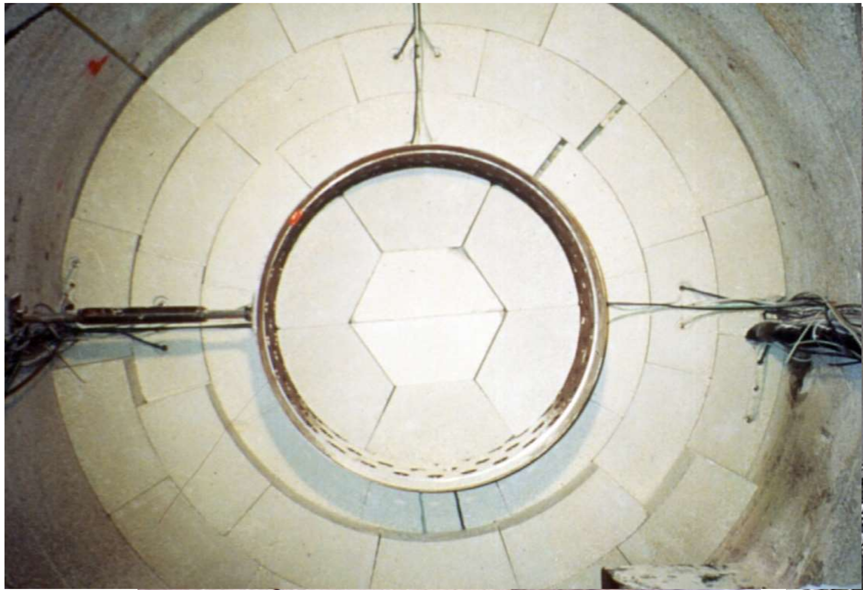
Dry density and water content

LABS:

ρ_d, *w* y THM-G properties

PARTIAL DISMANTLING: GAP SEALING

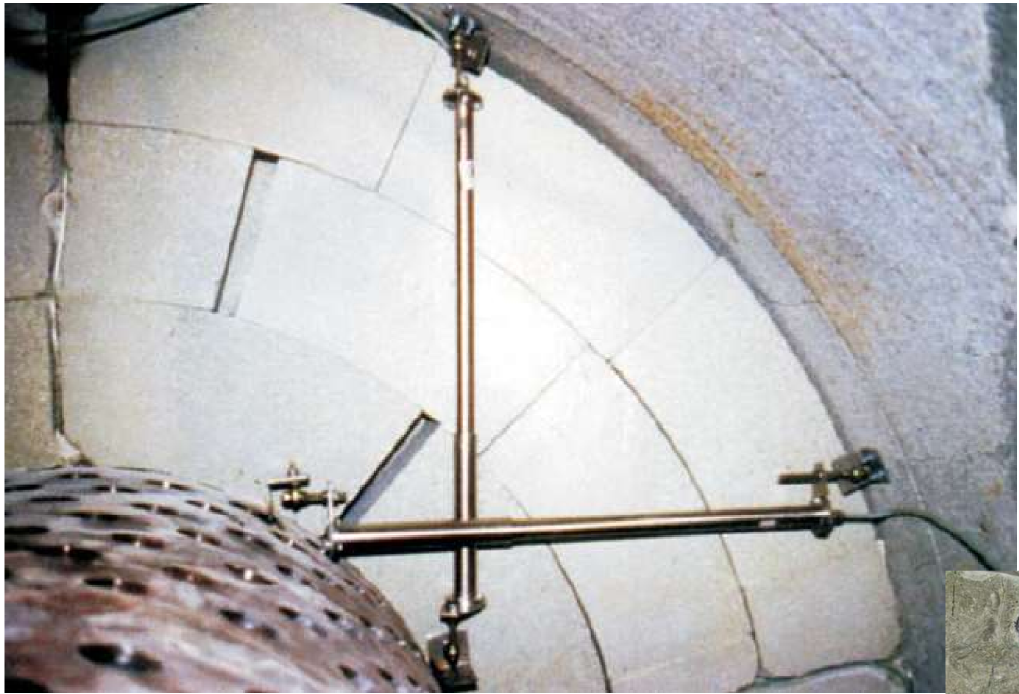
1997



2002

PARTIAL DISMANTLING: GAP SEALING

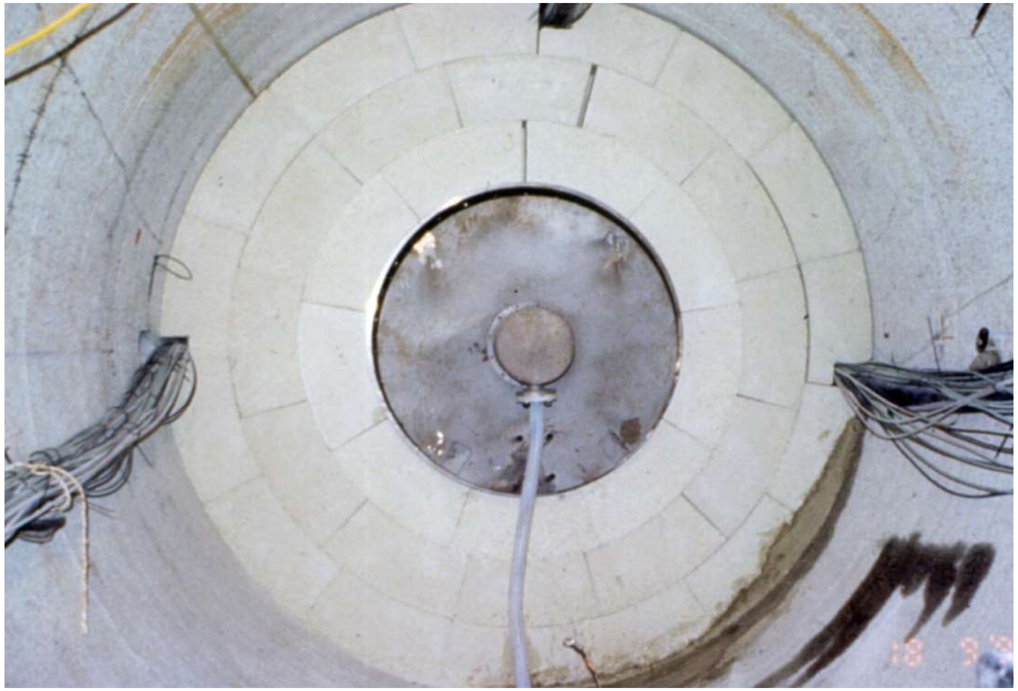
1997



2002

HM coupling: changes in density

Filling of gaps: decrease of the density of bentonite

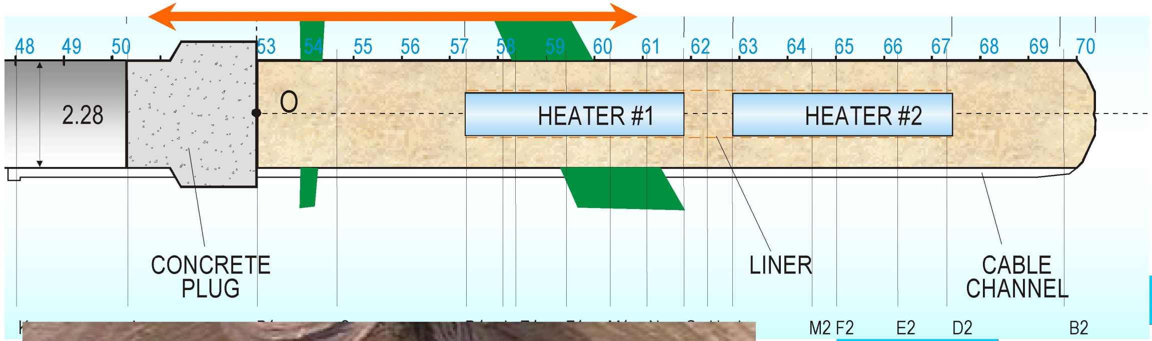


Initial block dry density: 1.70 g/cm^3

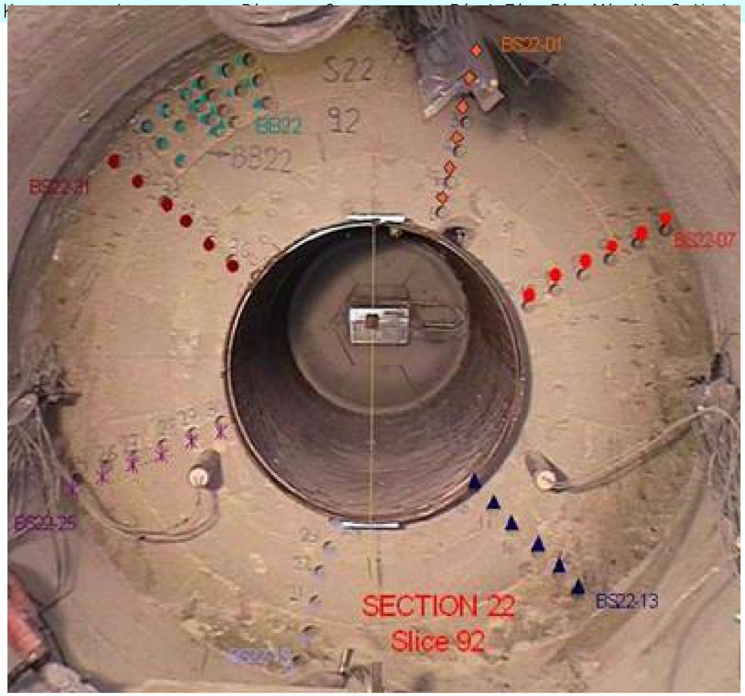
After 5 years: ρ_d=1.60 g/cm^3

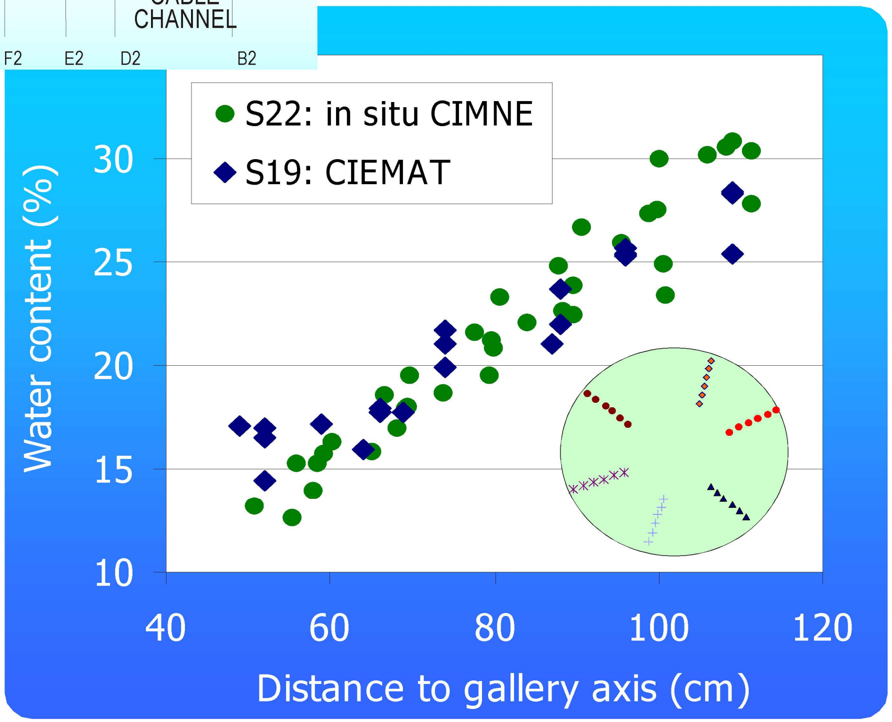
FEBEX

Hydration: changes in water content



Partial dismantling after 5 years operation

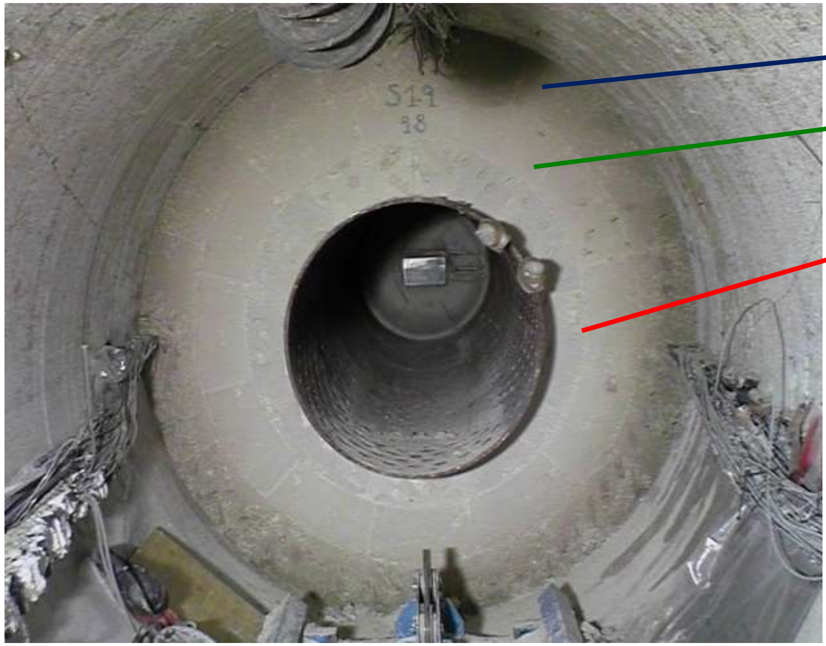




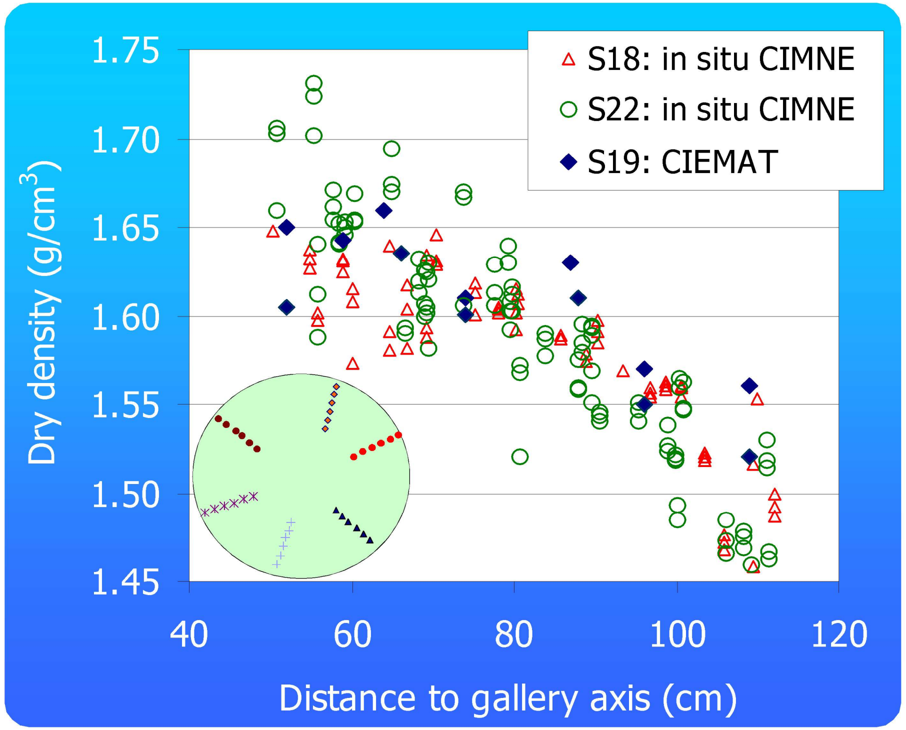
Villar *et al*. 2004

FEBEX

Hydration: changes in density

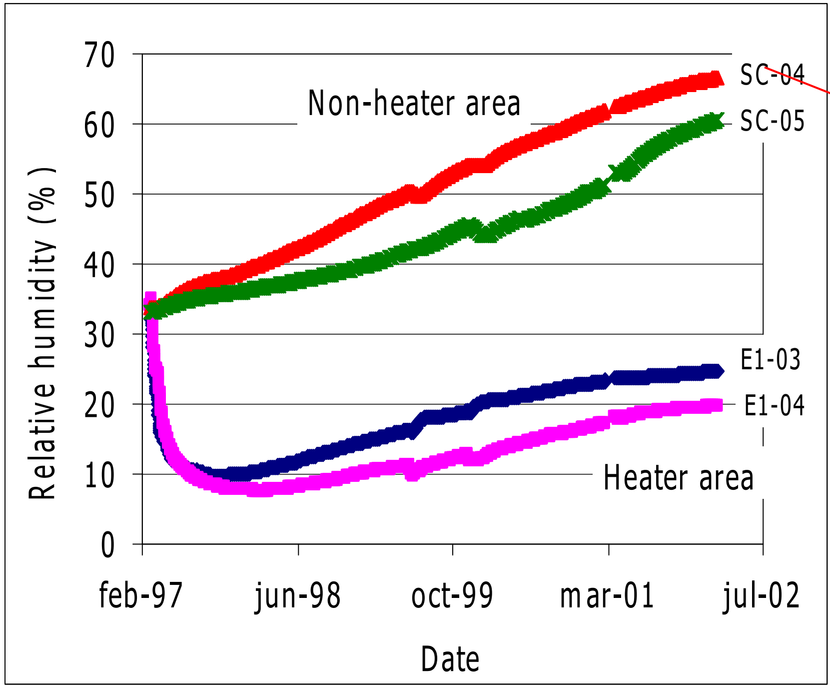


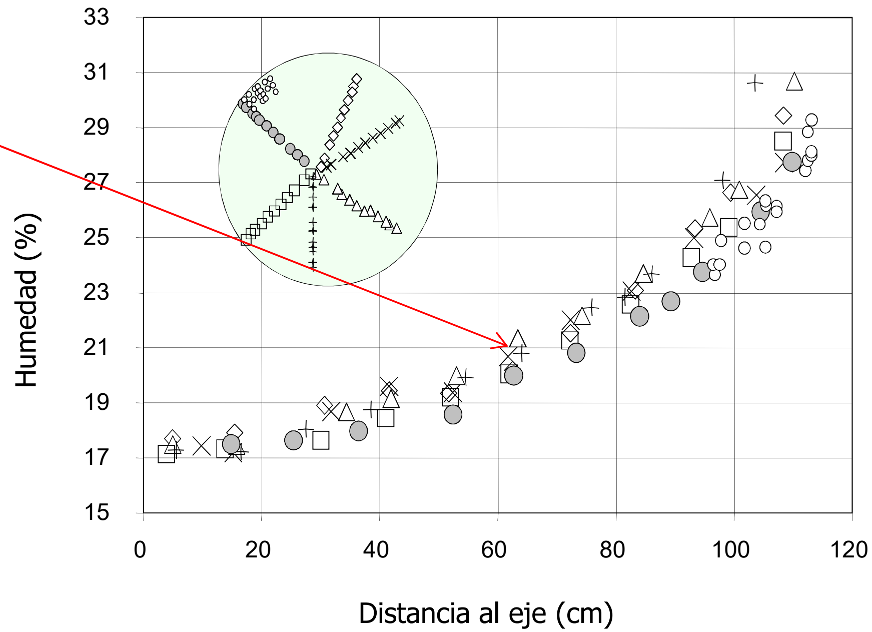
	ρ_d (g/cm^3)	w (%)	S_r (%)
External ring	1.51	27.6	95
Middle ring	1.59	21.8	85
Inner ring	1.65	16.1	67



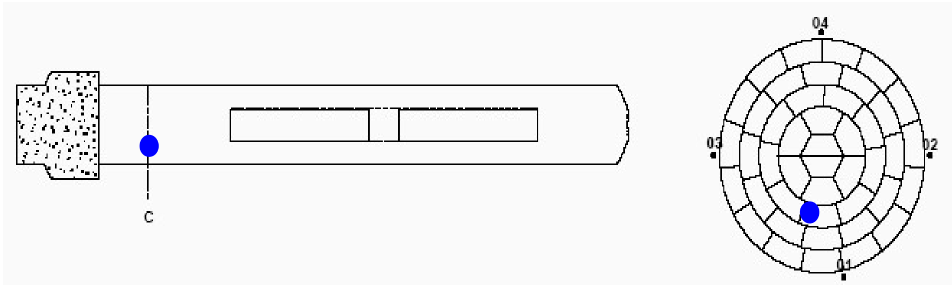
FEBEX

DENSITY AND WATER CONTENT AFTER 5 YEARS OPERATION AND 4 MONTHS COOLING



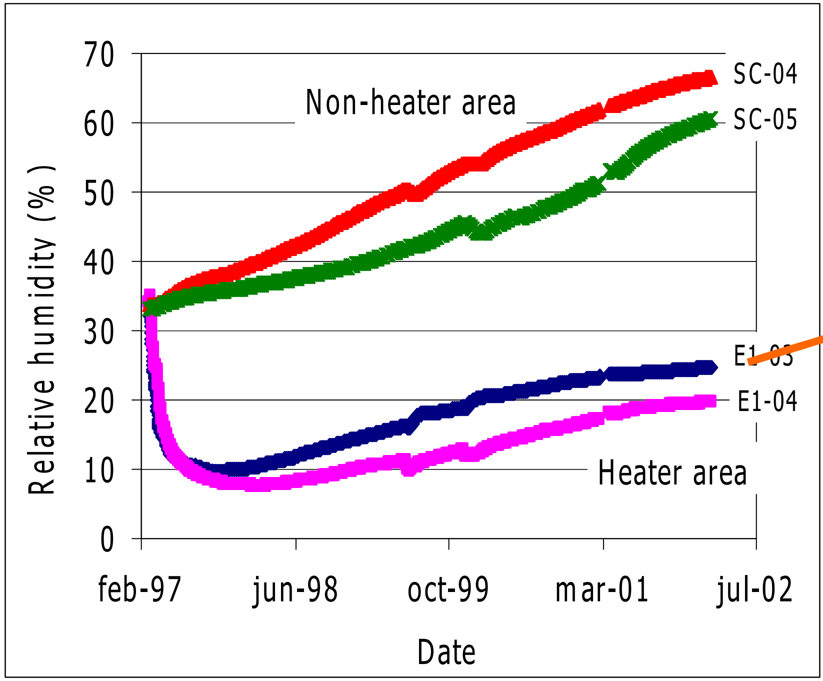


SENSORS PLACED AT 54 cm FROM GRANITE

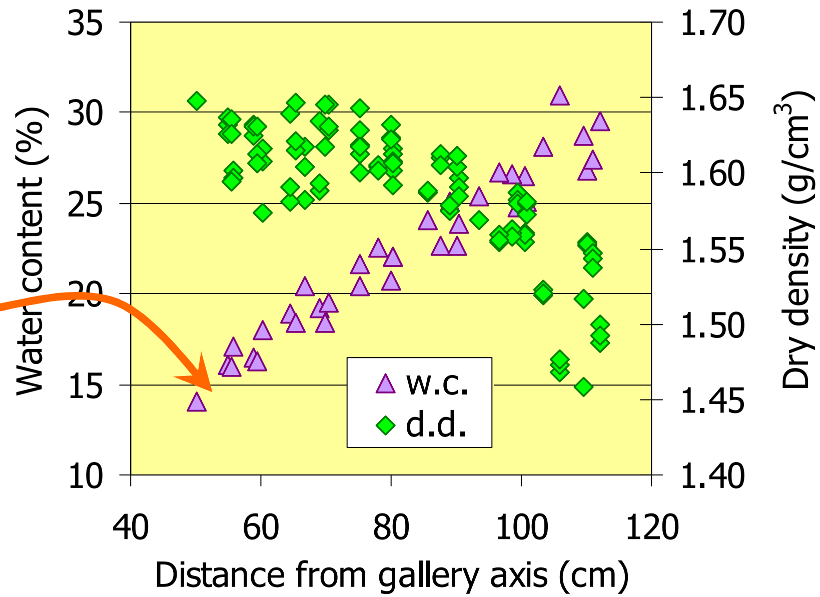


$$s = -10^{-6}\frac{R \times T}{V_w}\ln\left(\frac{HR}{100}\right)$$

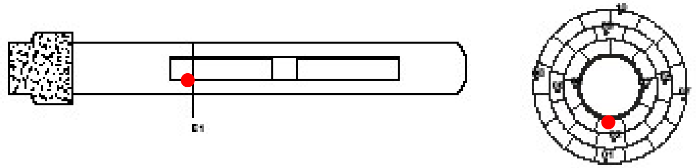
FEBEX IN SITU TEST: PARTIAL DISMANTLING



SENSORS PLACED AT 54 cm FROM GRANITE



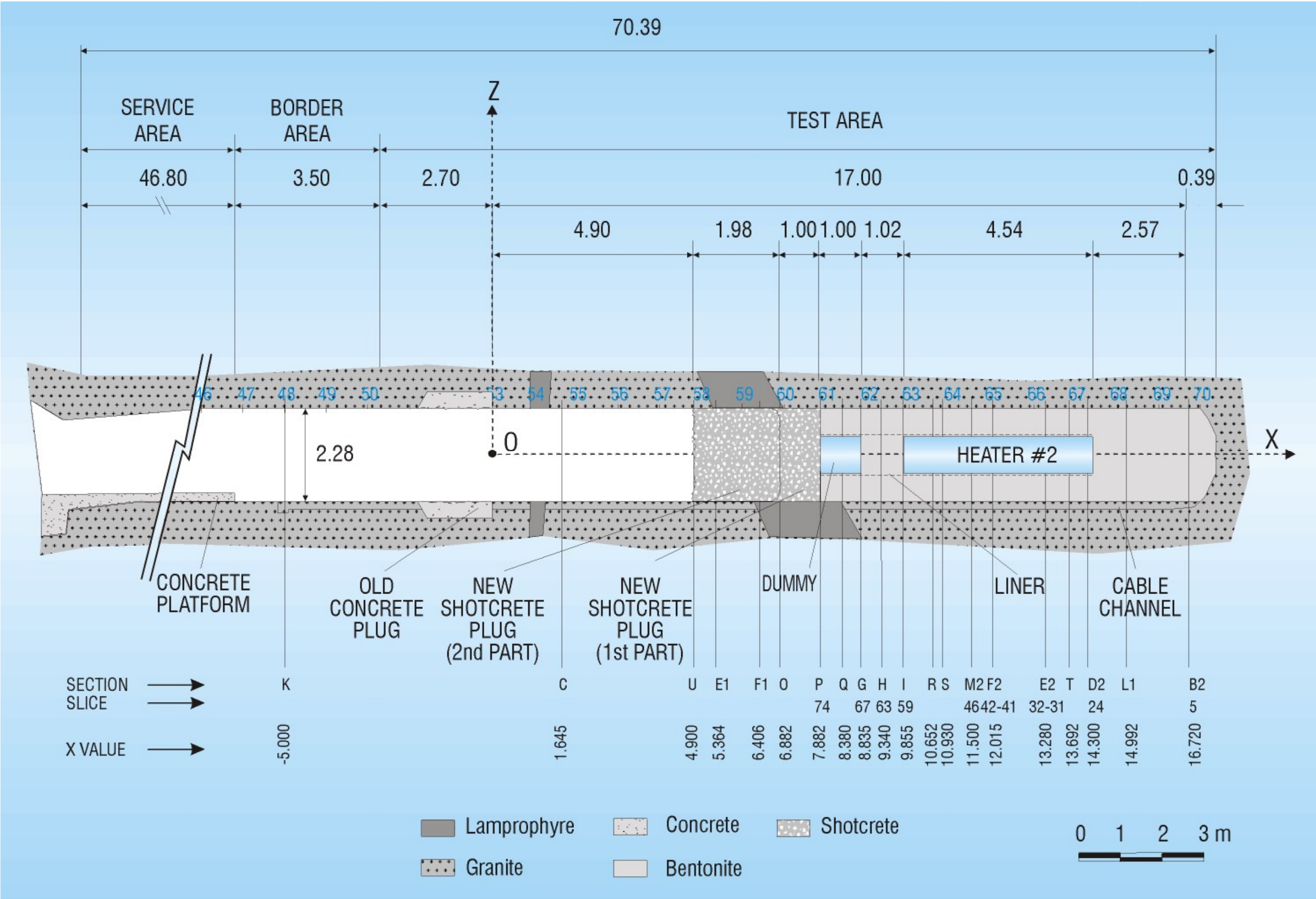
SECTION AROUND THE HEATER



The relative humidity measured by the sensors can be converted into suction by Kelvin's law and related to water content via the water retention curves determined in the untreated bentonite at different dry densities

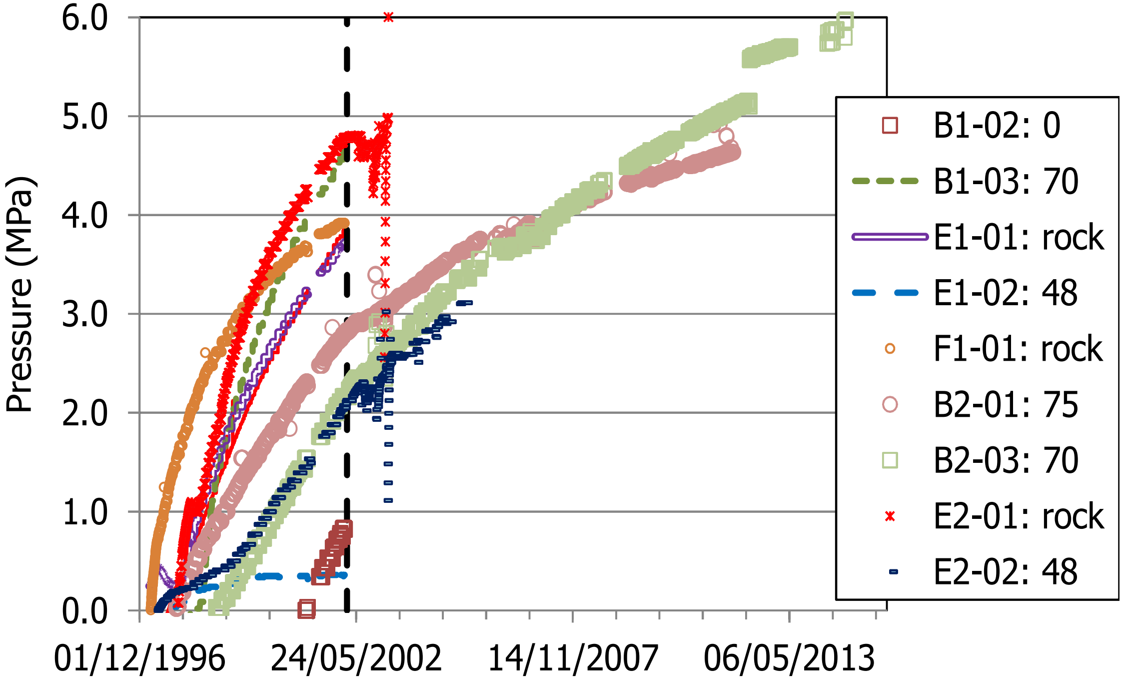
$$s = -10^{-6} \frac{R \times T}{V_w} \ln\left(\frac{HR}{100}\right)$$

FEBEX IN SITU TEST: OPERATION FROM 2002 TO 2015

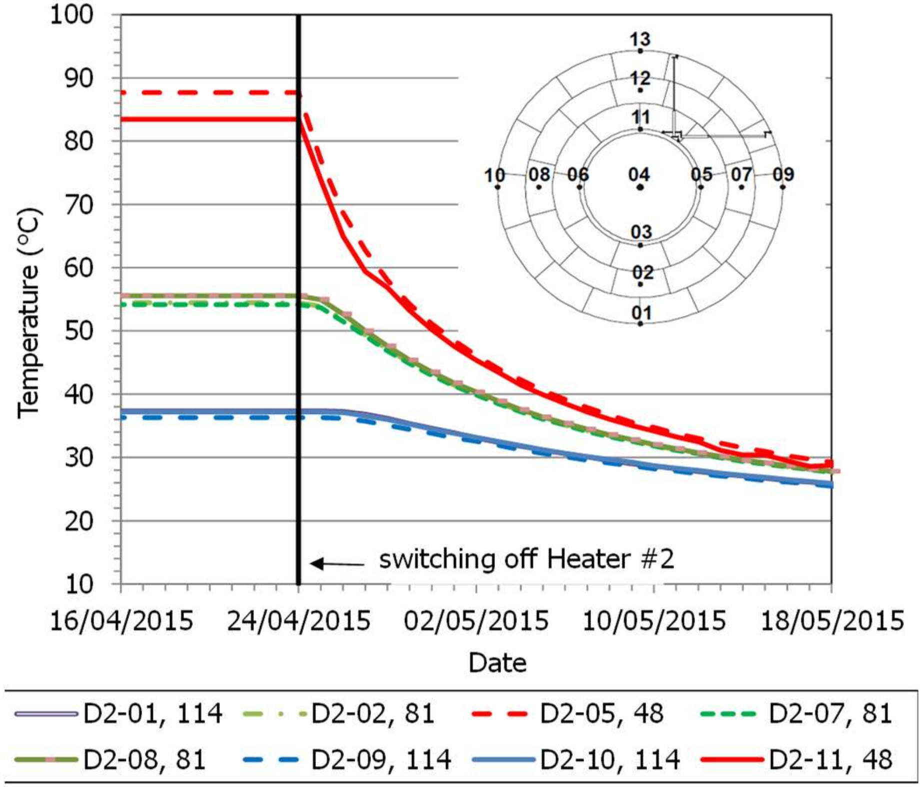


- The void left by the back of heater 1 was replaced by a steel dummy
- The gallery was closed again with a concrete plug and the experiment run for other 13 years
- Most sensors failed in this period

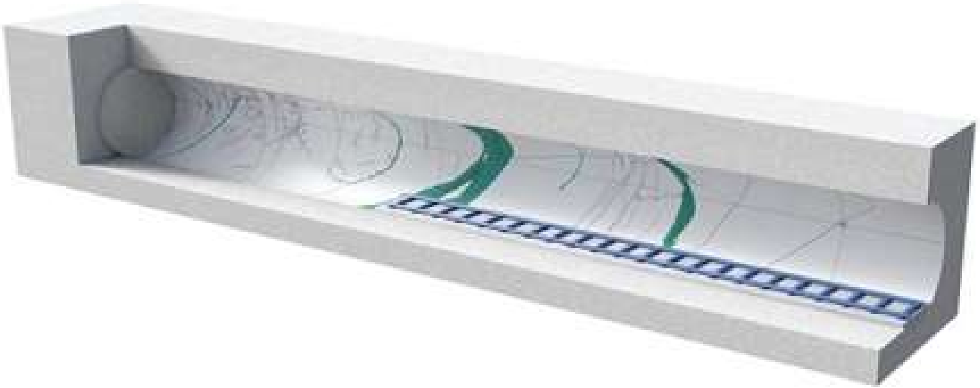
FEBEX IN SITU TEST: OPERATION FROM 2002 TO 2015 AND HEATER #2 SWITCHING OFF

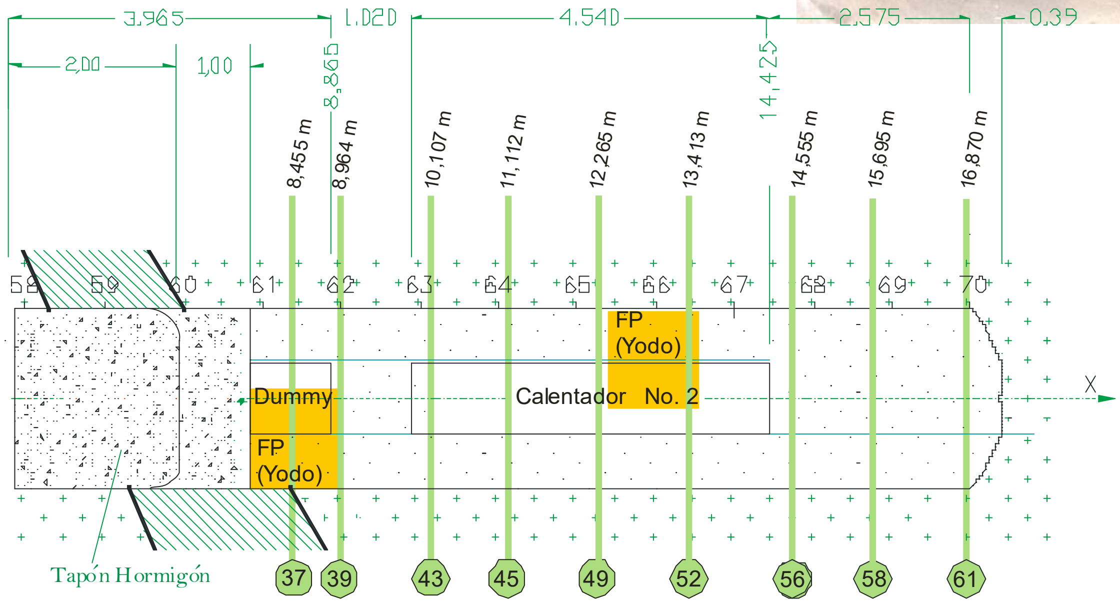


Total pressure evolution measured inside the bentonite from the beginning of operation. The distance of the sensor from the gallery axis is indicated in cm (rock: granite/bentonite contact), the dotted vertical line indicates the start of partial dismantling (Villar et al. 2020)



IN SITU FEBEX TEST: FINAL DISMANTLING (2015)





STATE OF THE BARRIER AFTER 18 YEARS OPERATION: VISUAL INSPECTION

The joints between blocks had dissapeared, as it was already observed in 2002

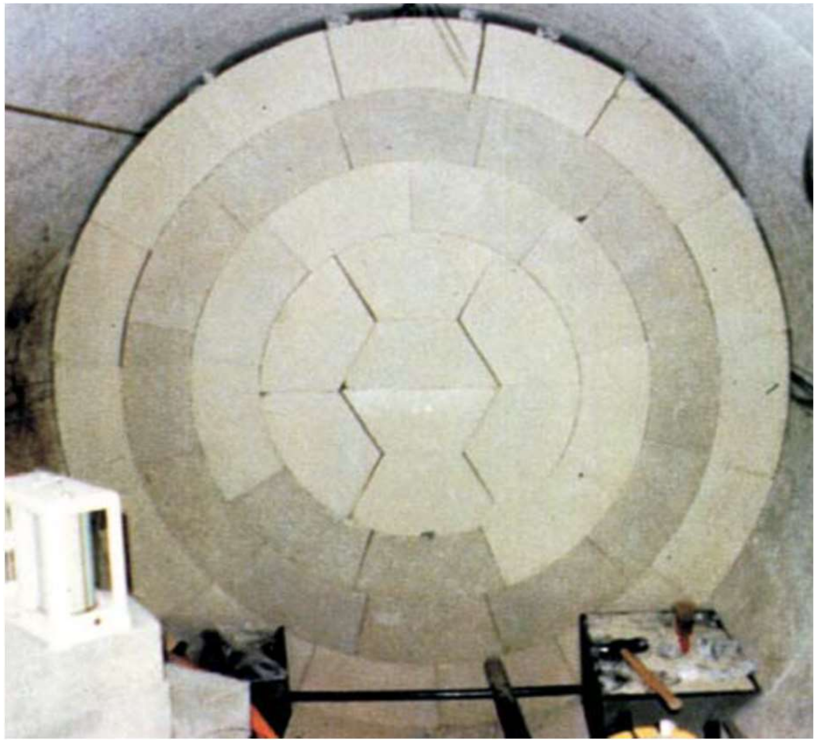
1997

2015

FINAL DISMANTLING: GAP SEALING

There were no gaps in the barrier, as it was already observed in 2002

1997



2015

STATE OF THE BARRIER AFTER 18 YEARS OPERATION: VISUAL INSPECTION

The contact between adjacent vertical sections and between granite and bentonite was tight

The bentonite intruded through the liner holes

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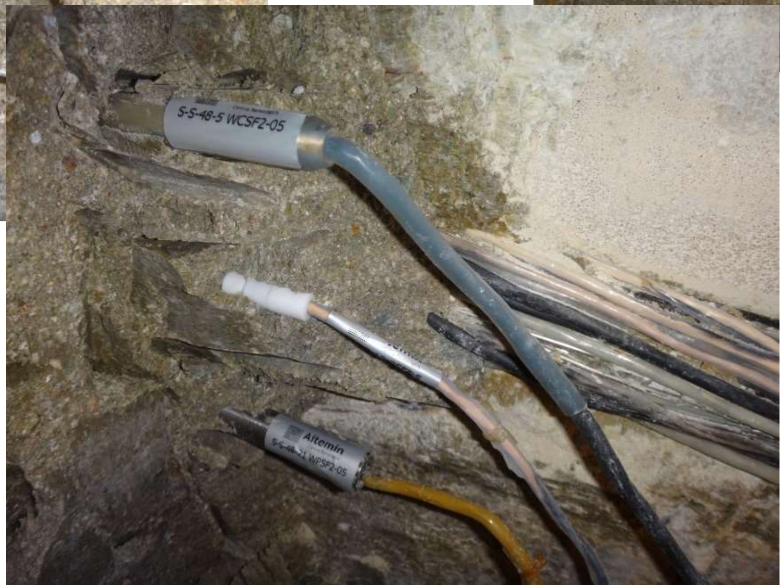
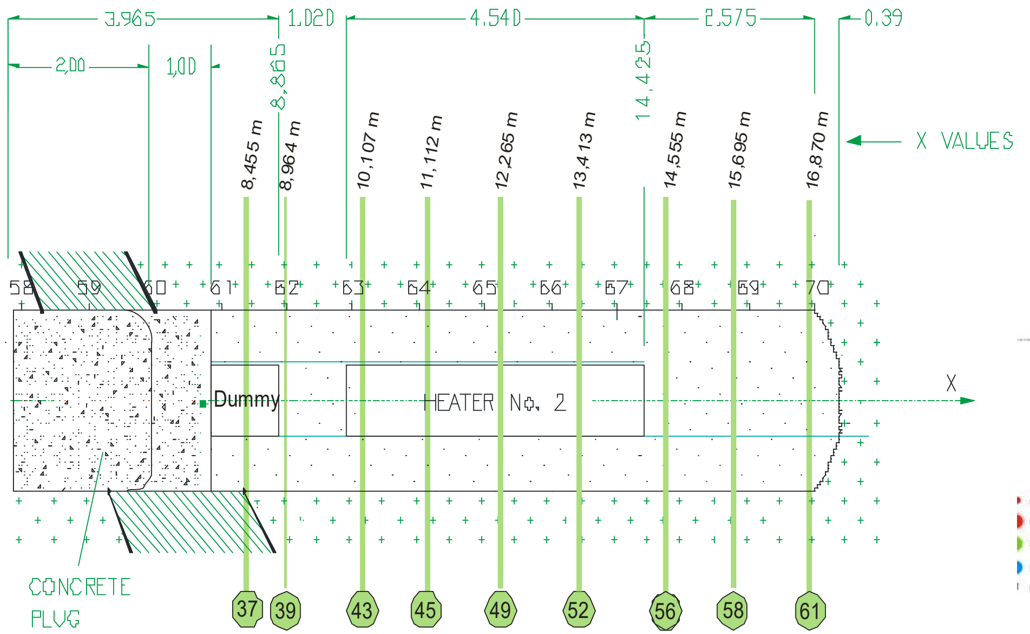
STATE OF THE BARRIER AFTER 18 YEARS OPERATION: VISUAL INSPECTION

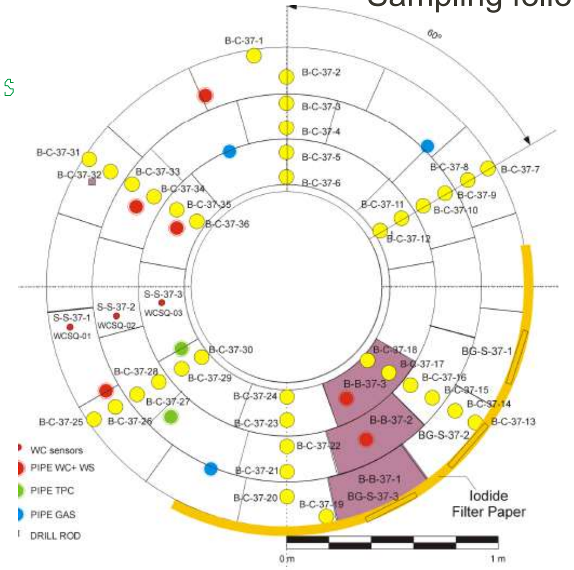
Sensor and other metallic elements: corrosion, stains



METHODOLOGY OF ONSITE ANALYSES



Sampling following a radial pattern



Drilling following a template

4-5 cm long core preserved before determination

Splitting the core in two, removing external parts, smoothing surfaces

Immersion of the samples in mercury to determine its volume befor drying in the oven

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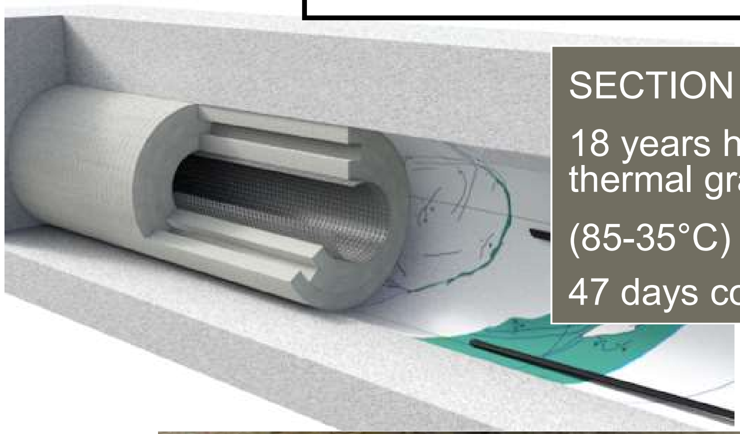
ONSITE MEASUREMENTS DURING DISMANTLING

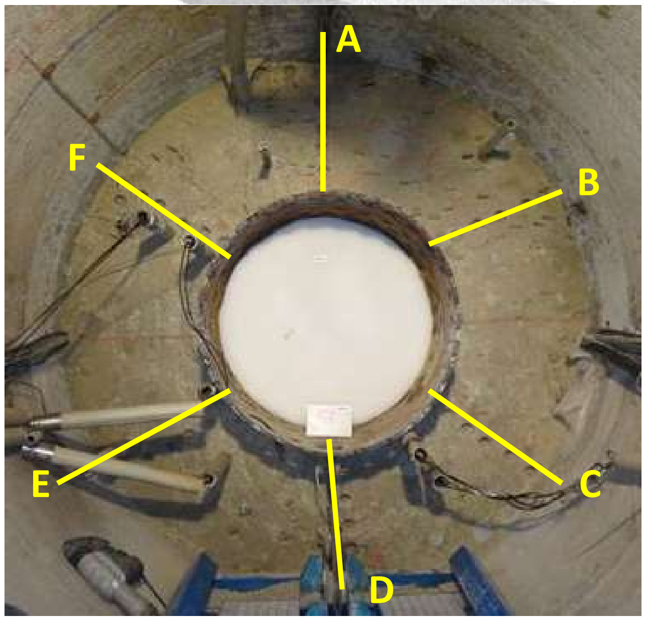


SECTION 43

18 years hydration under thermal gradient

(85-35°C)

47 days cooling

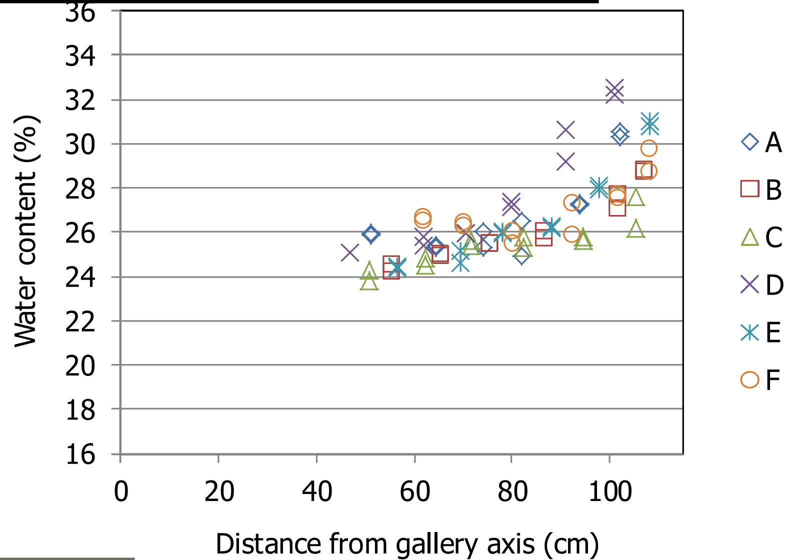


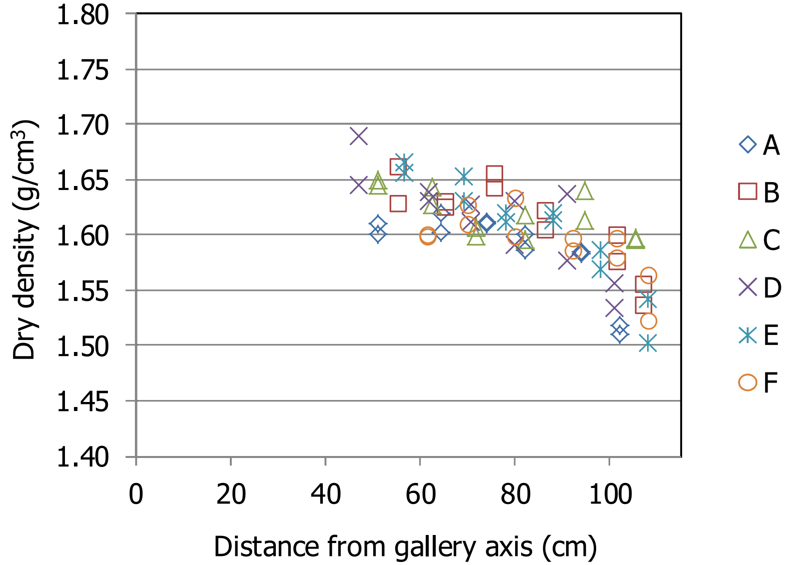
Average

w: 27.2%

ρ_d: 1.59 g/cm^3

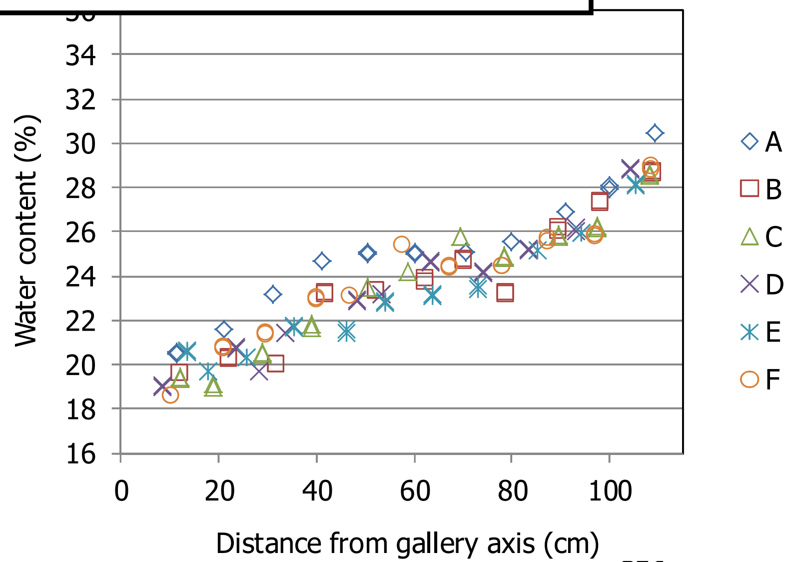
S_r: 105%

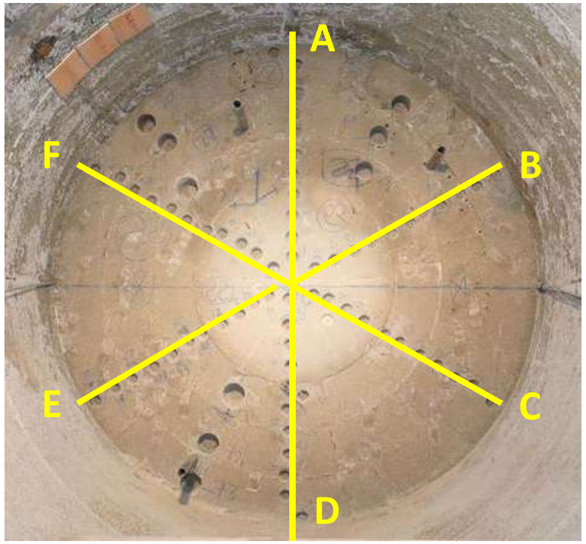




ONSITE MEASUREMENTS DURING DISMANTLING

SECTION 56
18 years hydration at T <36-88°C



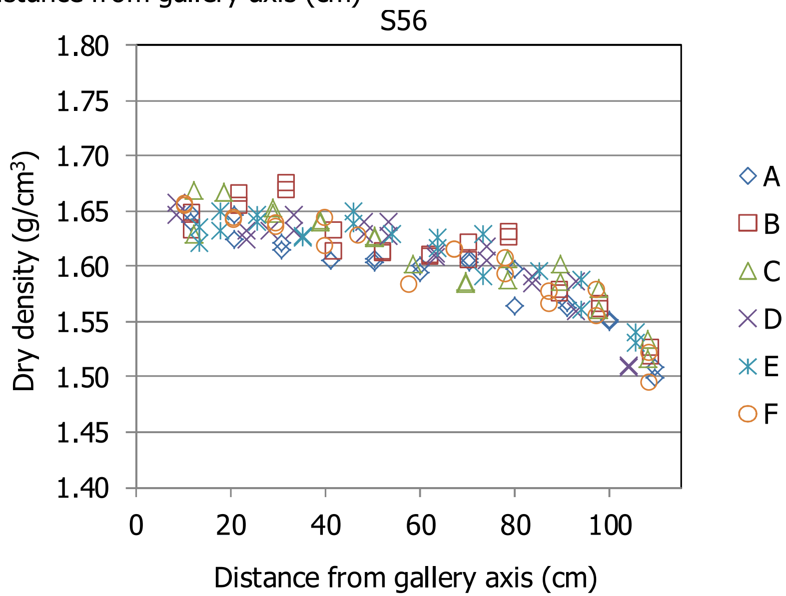


Average:

w: 26.0%

ρ_d: 1.57g/cm^3

S_r: 97%



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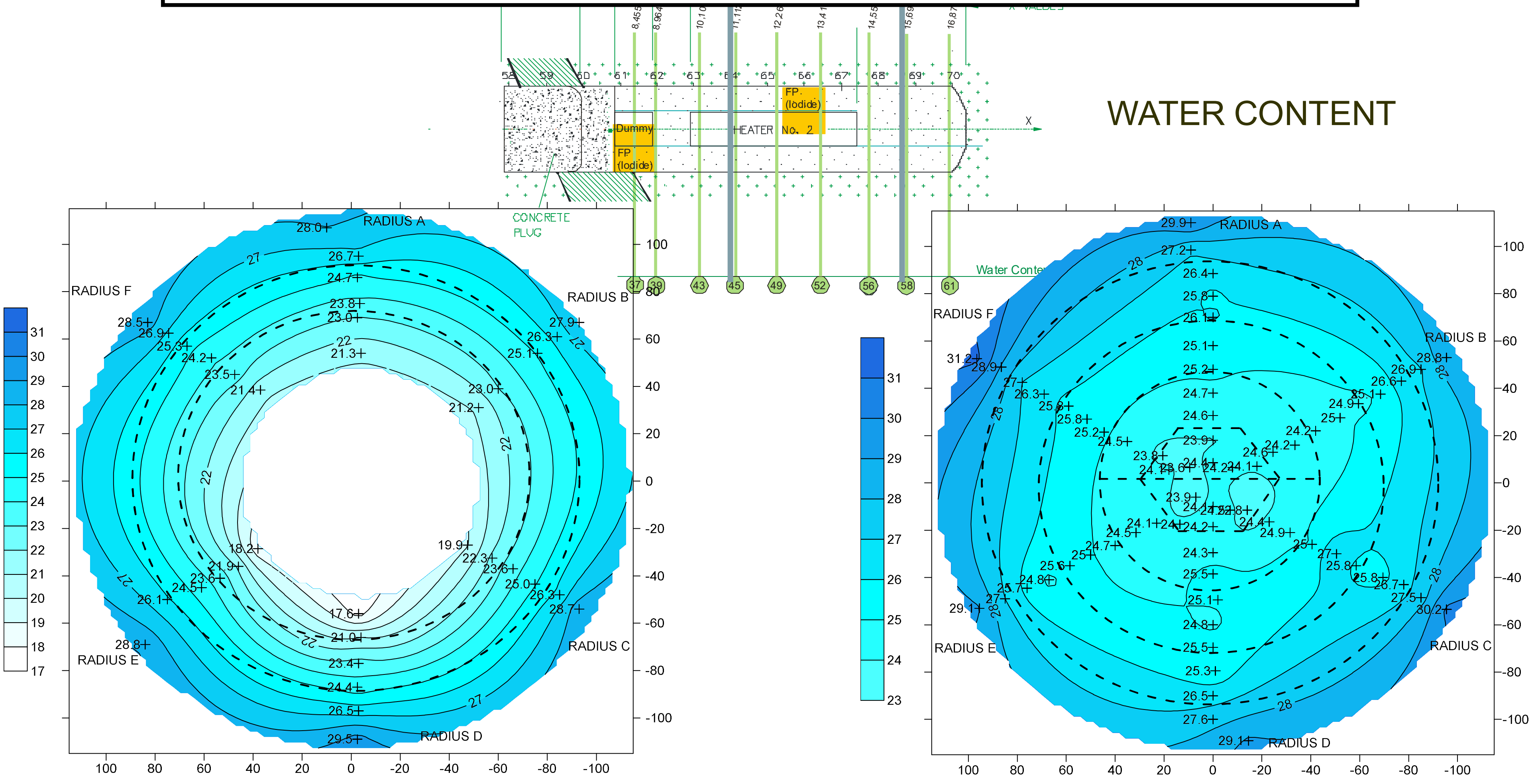
AXIAL SYMMETRY: COMPARISON “COOL/HOT” SECTIONS

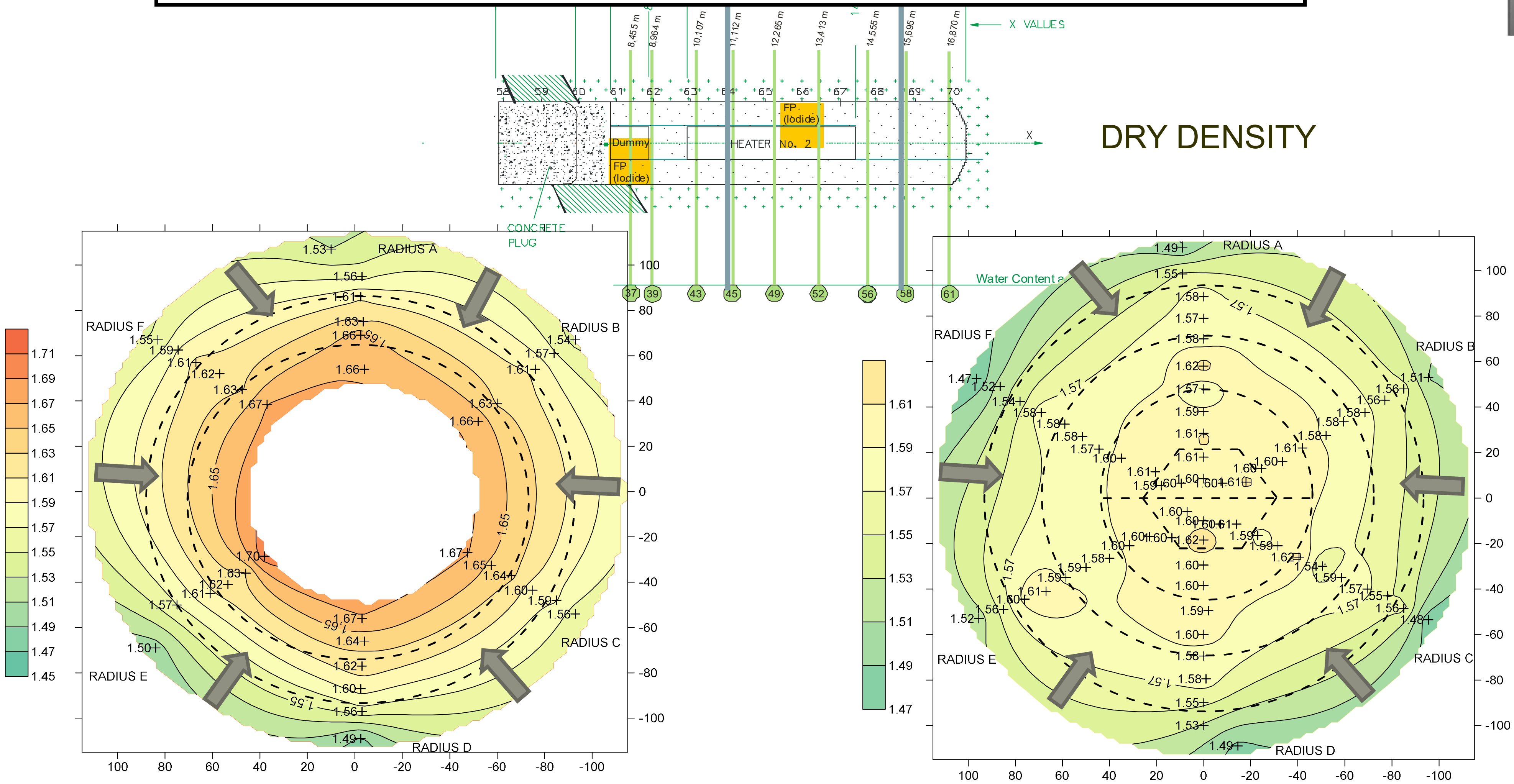
WATER CONTENT



HOT SECTION (S45)

COOL SECTION (S58)

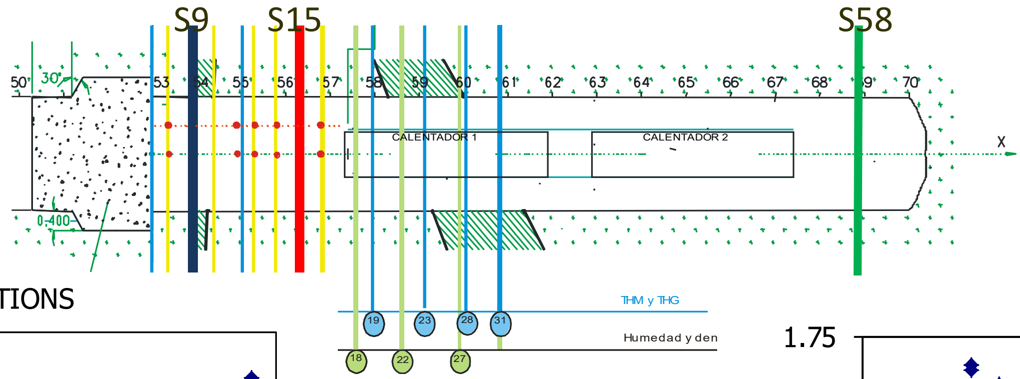
AXIAL SYMMETRY: COMPARISON "COOL/HOT" SECTIONS

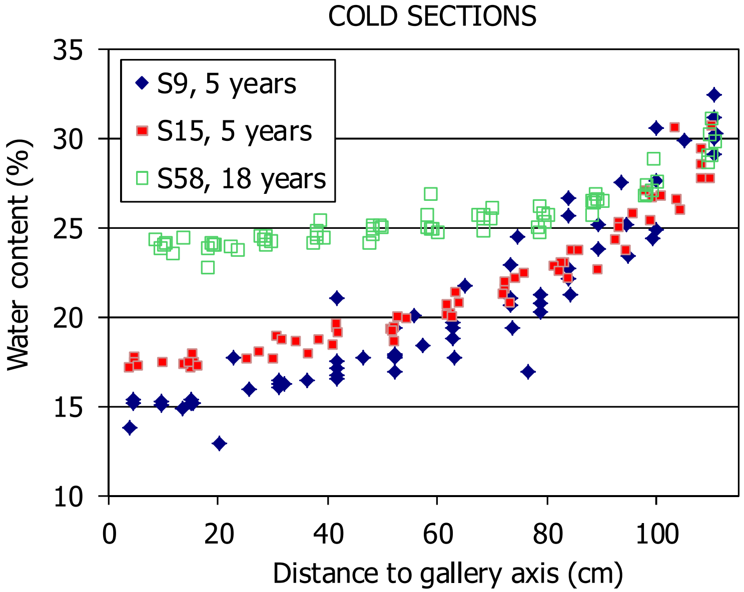


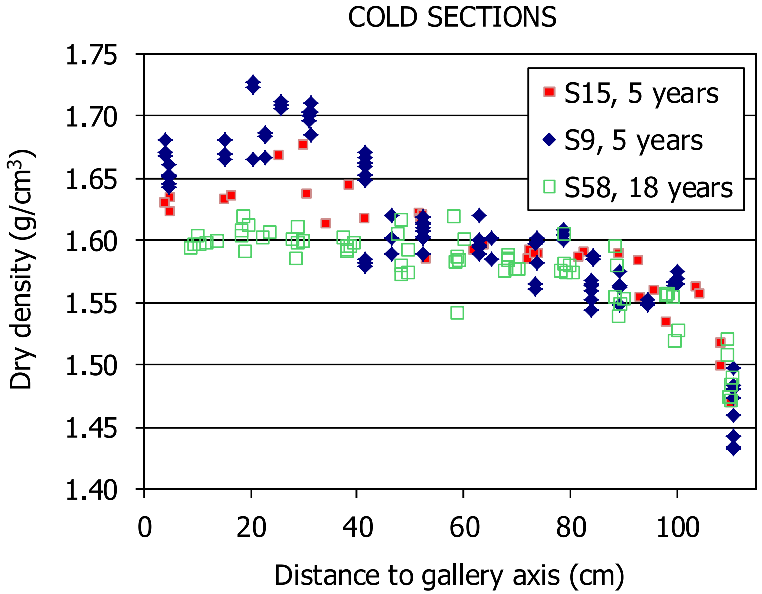
HOT SECTION (S45)

COOL SECTION (S58)

COMPARISON 5 – 18 YEARS OPERATION





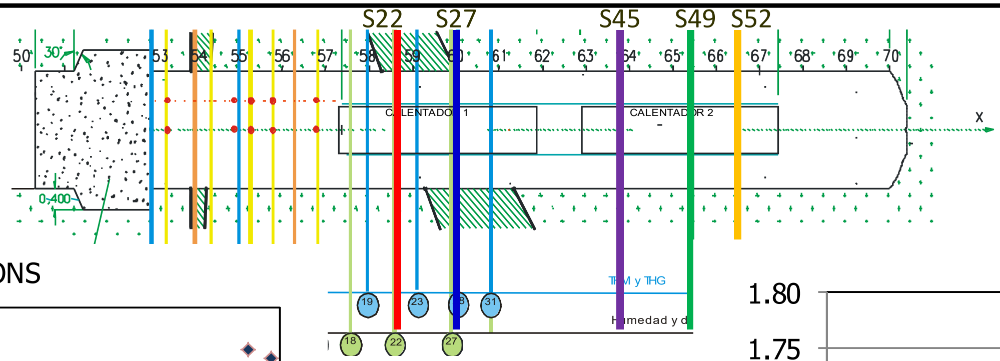


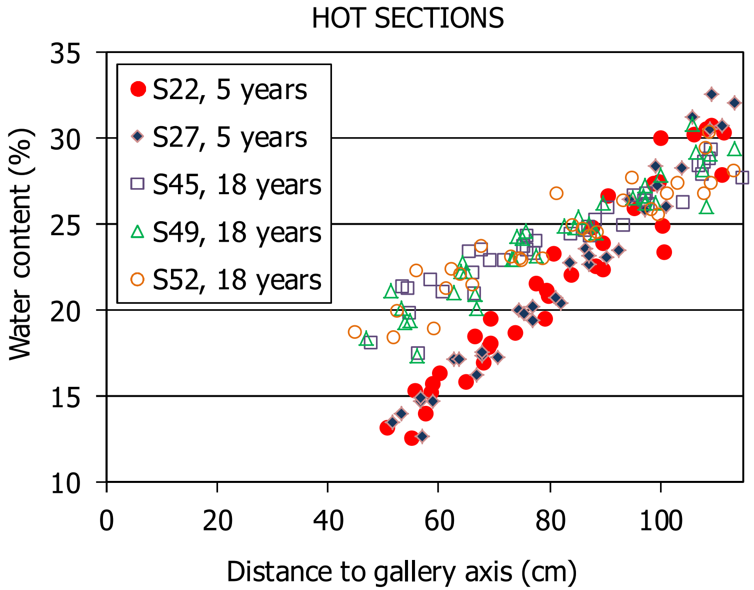
***w*, %**
S9: 22.9%
S15: 22.8%
S58: 27.1%

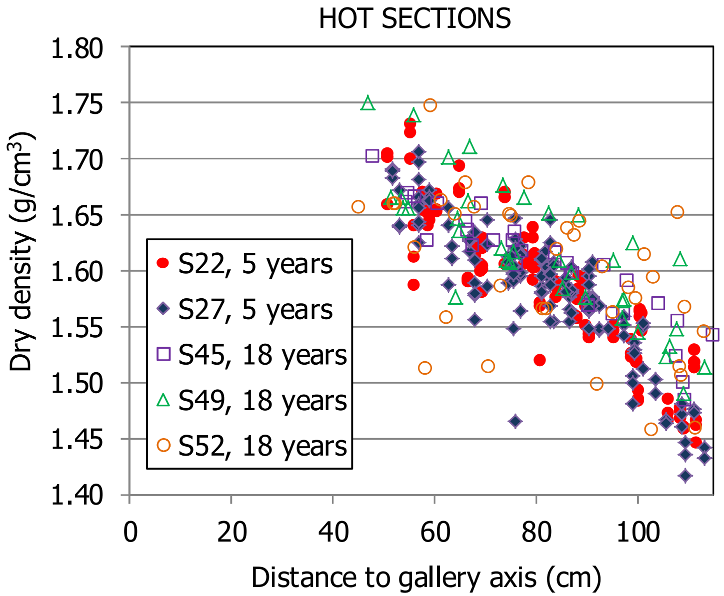
S_r, %
S9: 85%
S15: 86%
S58: 98%

ρ_d, g/cm^3
S9: 1.58 g/cm^3
S15: 1.58 g/cm^3
S58: 1.55 g/cm^3

COMPARISON 5 – 18 YEARS OPERATION







S22: 22.6% S45: 25.7%

S27: 22.6% S49: 25.9%

S52: 25.6%

S22: 85% S45: 98%

S27: 84% S49: 99%

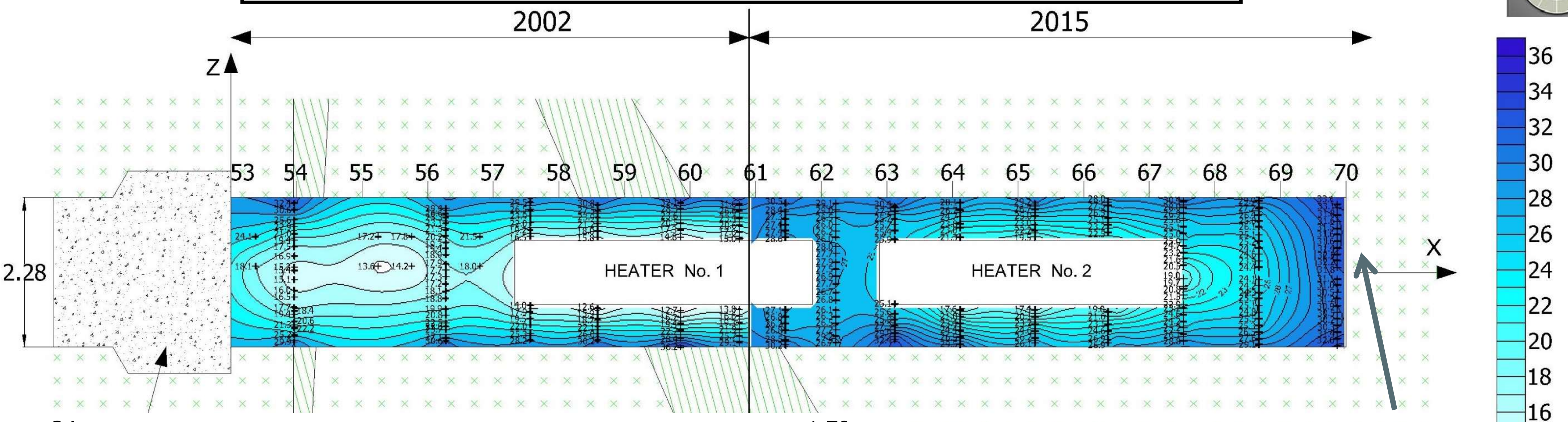
S52: 98%

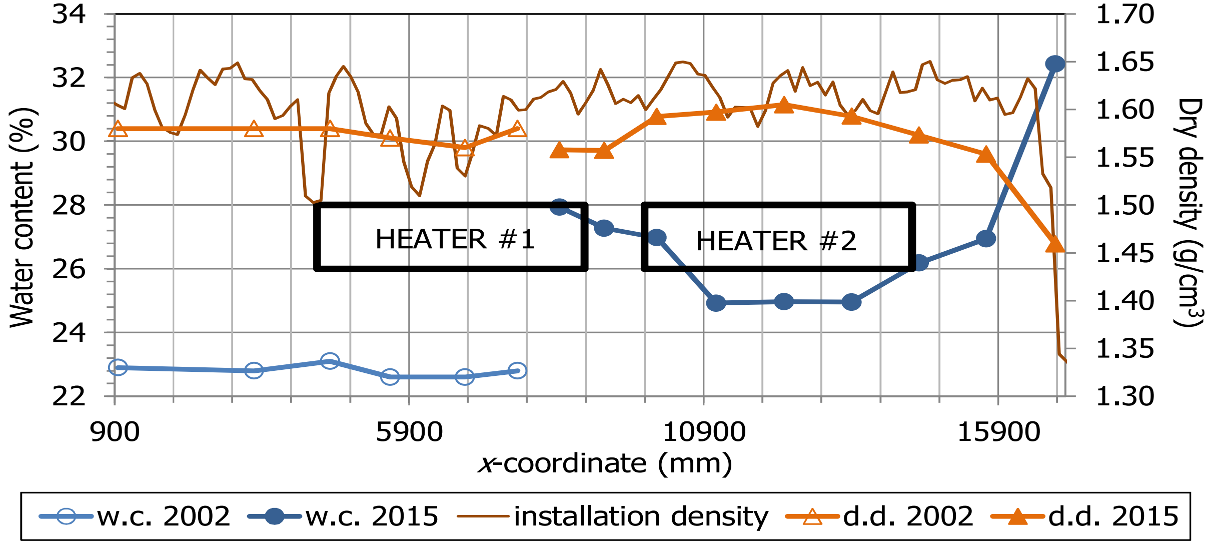
S22: 1.57 g/cm^3 S45: 1.59 g/cm^3

S27: 1.56 g/cm^3 S49: 1.59 g/cm^3

S52: 1.59 g/cm^3

LONGITUDINAL DISTRIBUTION OF WATER CONTENT





Dismantling date	*w* (%)	Installation ρ_d (g/cm^3)	ρ_d (g/cm^3)	S_r (%)
2002	22.9	1.59	1.58	87
2015	26.7	1.61	1.57	100

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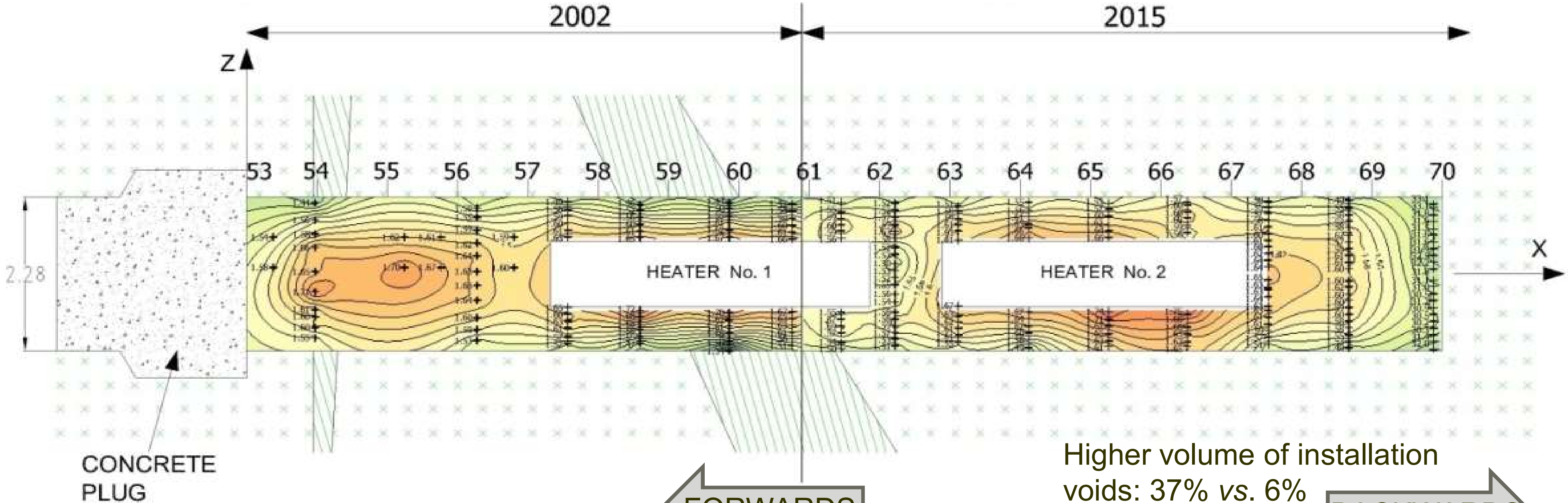
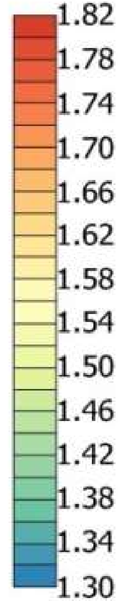
LONGITUDINAL DISTRIBUTION OF DRY DENSITY

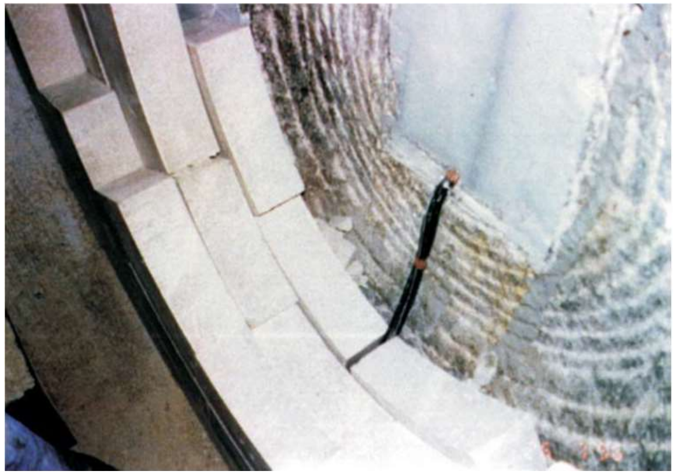




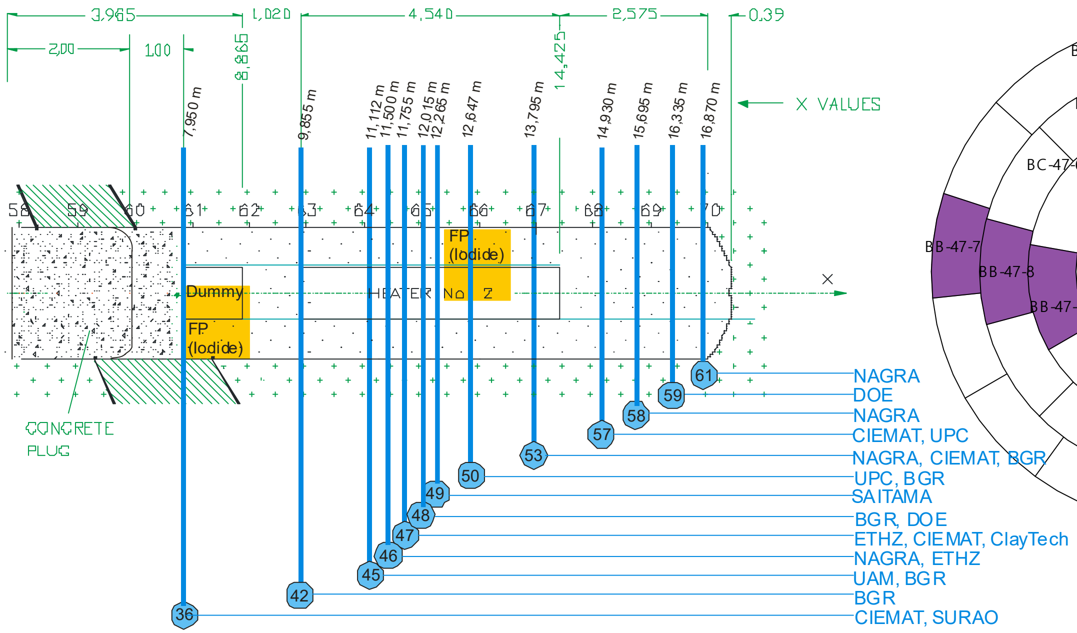
FORWARDS

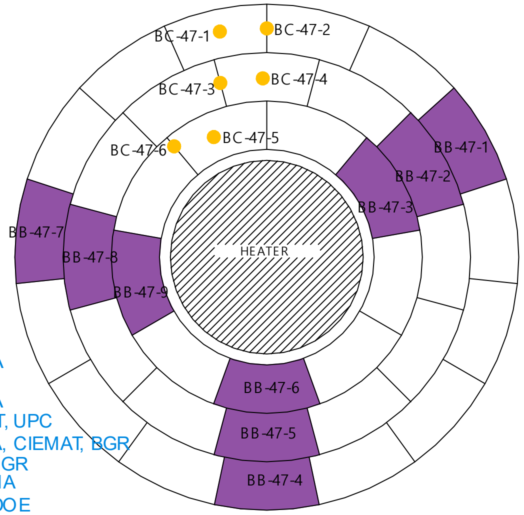
Higher volume of installation voids: 37% *vs*. 6%

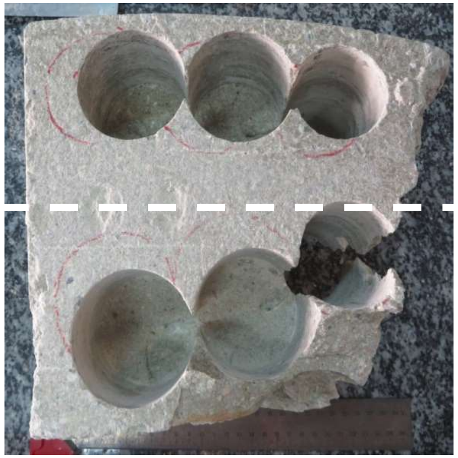
BACKWARDS



SAMPLING OF BLOCKS AND CORES FOR THM-G DETERMINATIONS IN LABS

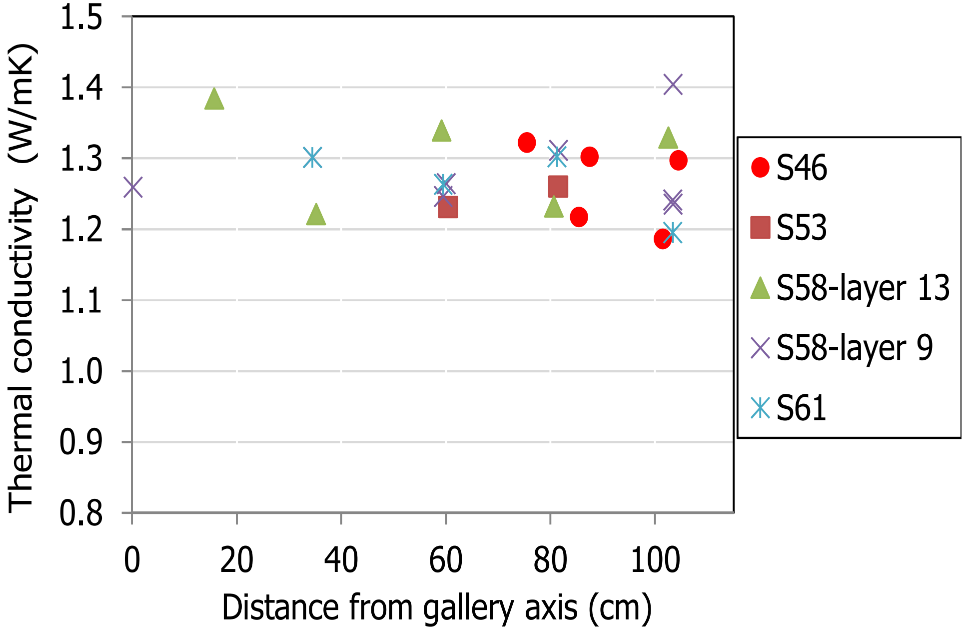




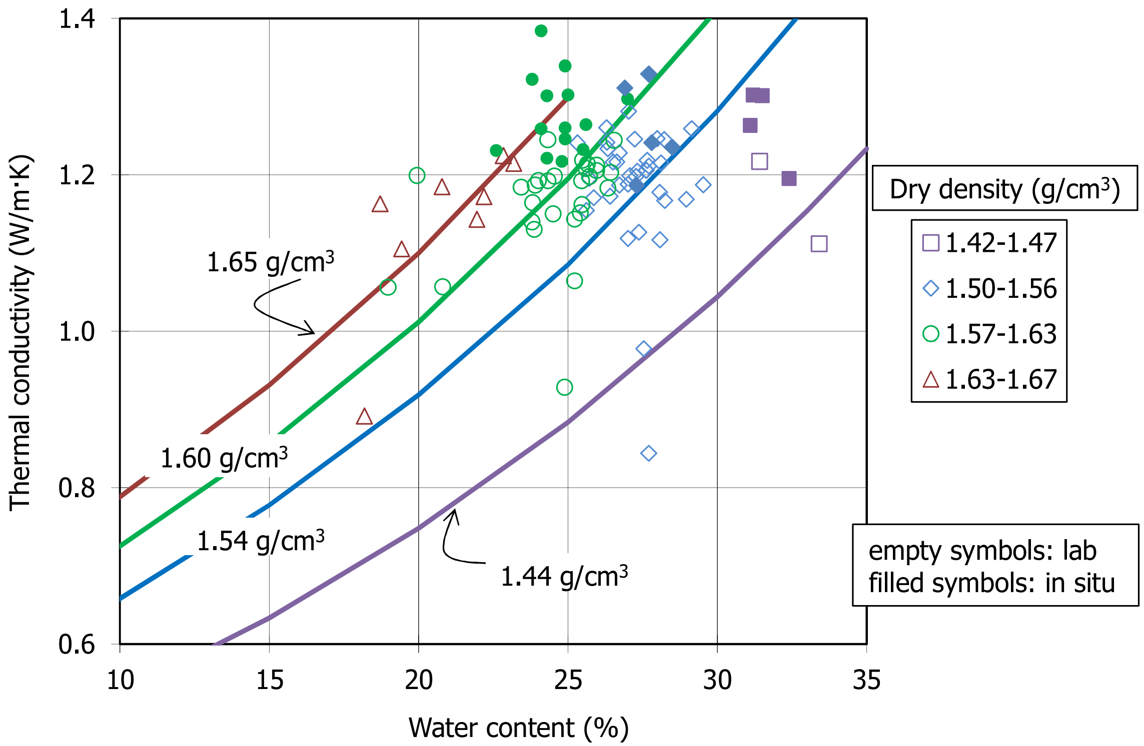


The hydro-mechanical properties of the FEBEX bentonite have been studied for many years. They depend mainly on the bentonite water content and dry density. Empirical correlations between permeability, swelling pressure, thermal conductivity, etc. and dry density and water content have been obtained over the years. In the labs these properties were determined in samples from the in situ test and compared with those of the untreated bentonites

THM PROPERTIES OF BARRIER SAMPLES AFTER OPERATION FOR 18 YEARS: THERMAL CONDUCTIVITY

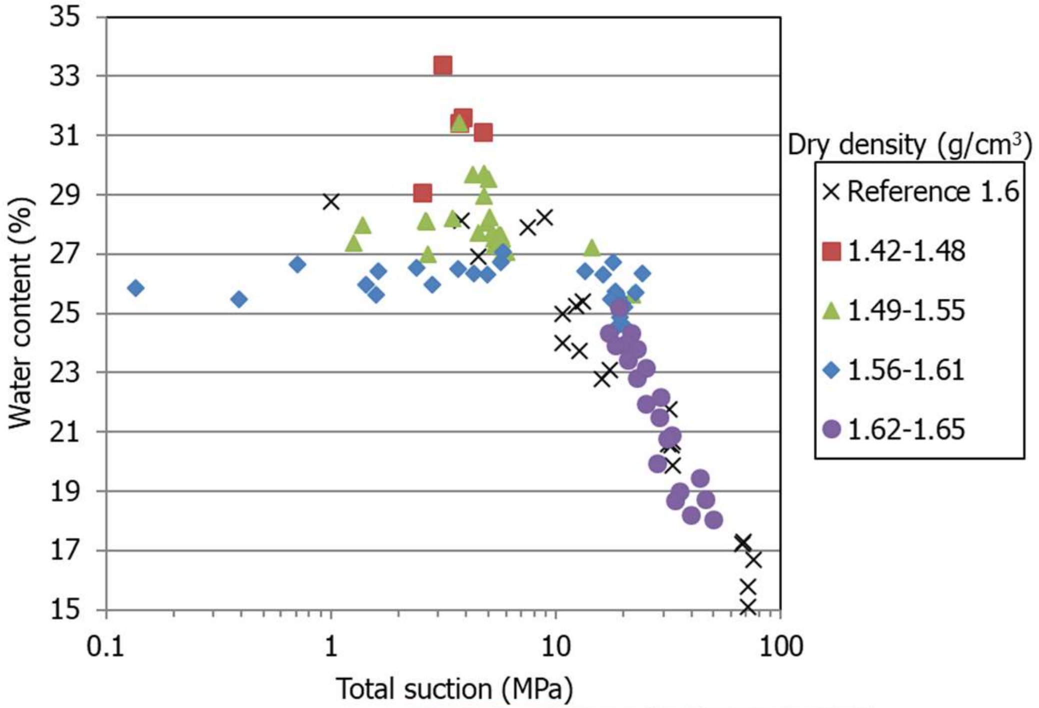


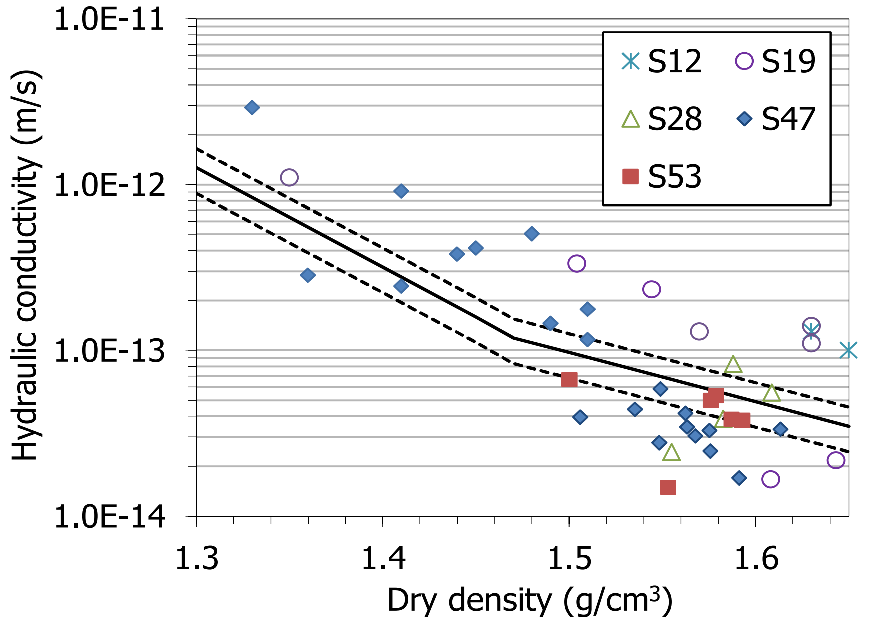
Thermal conductivity measured on site in different sampling sections



Comparison of values measured on site with empirical correlations obtained in untreated bentonite

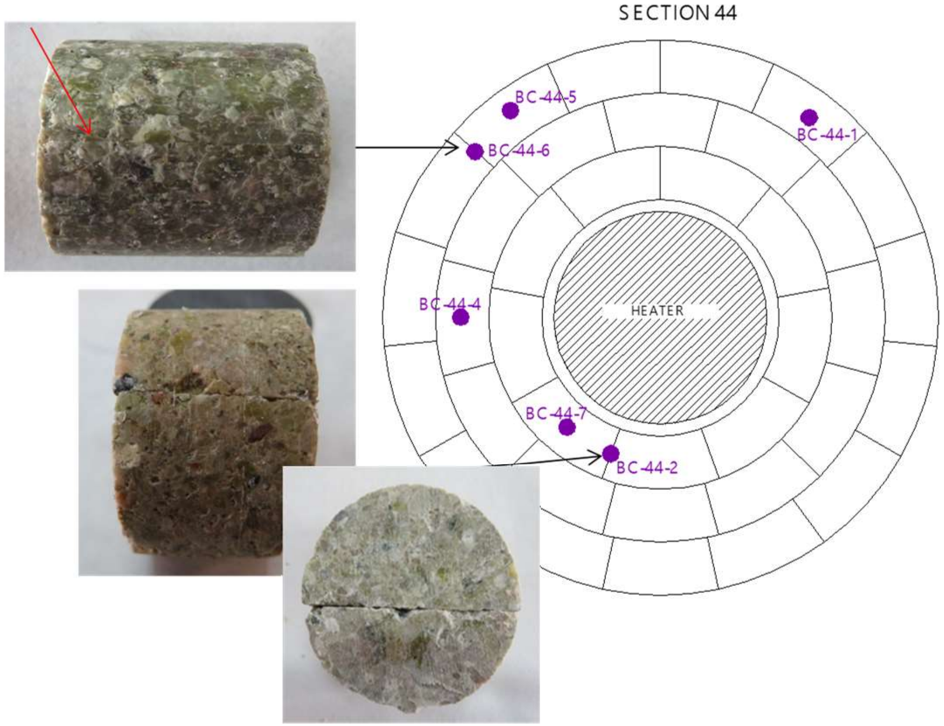
THM PROPERTIES OF BARRIER SAMPLES AFTER OPERATION FOR 18 YEARS: WATER RETENTION AND HYDRAULIC CONDUCTIVITY

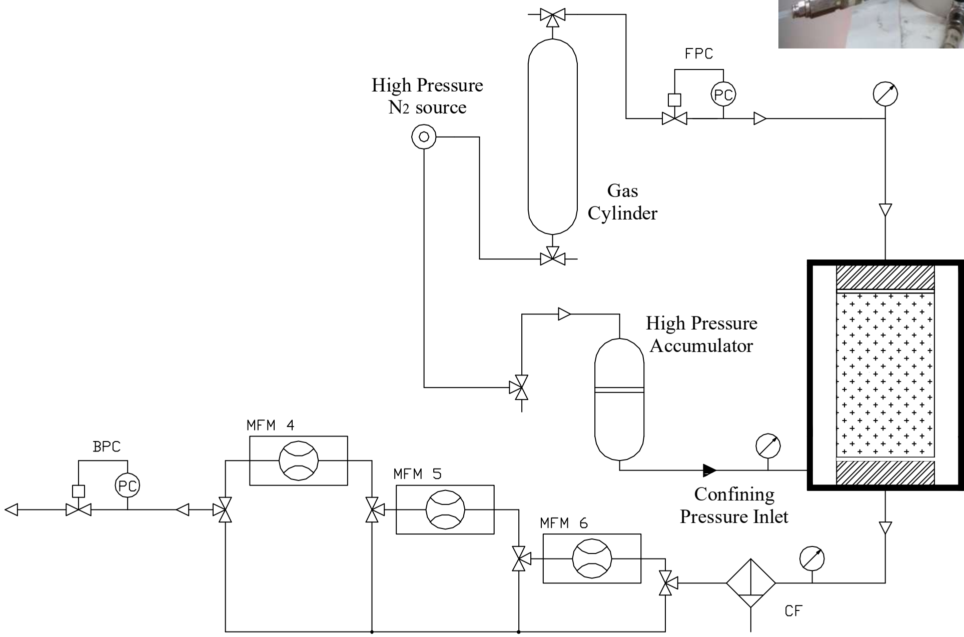




Measurement of suction in the lab with psychrometers

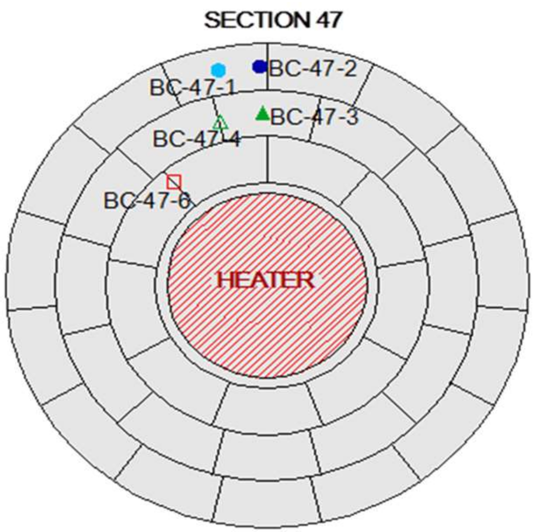
THM PROPERTIES OF BARRIER SAMPLES AFTER OPERATION FOR 18 YEARS: GAS PERMEABILITY: EFFECT OF JOINTS

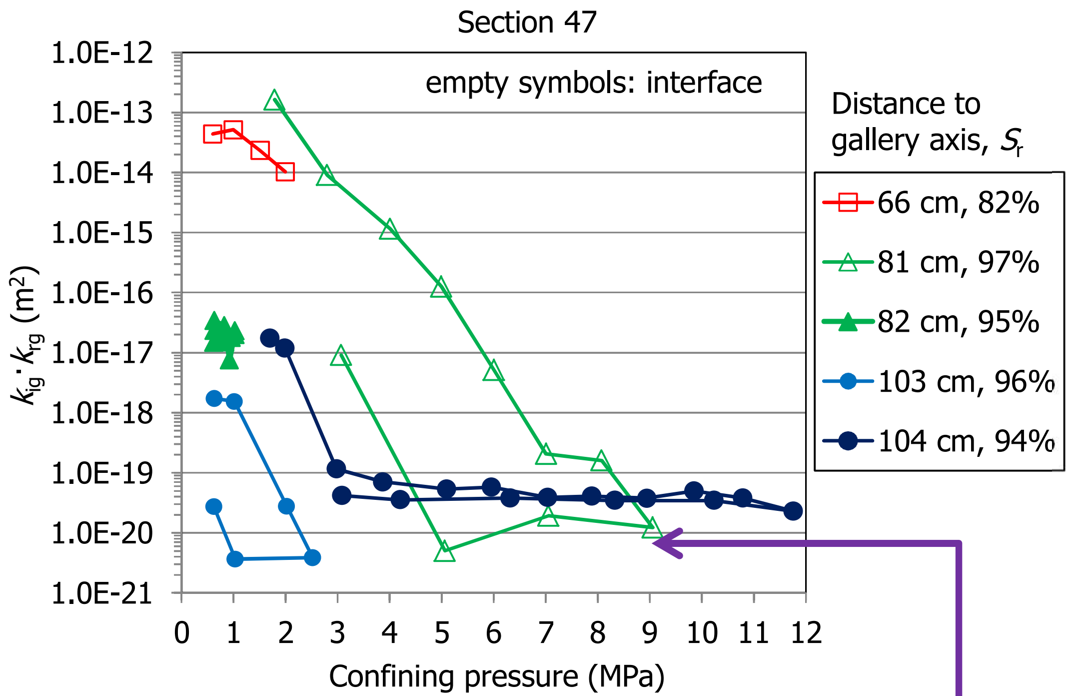


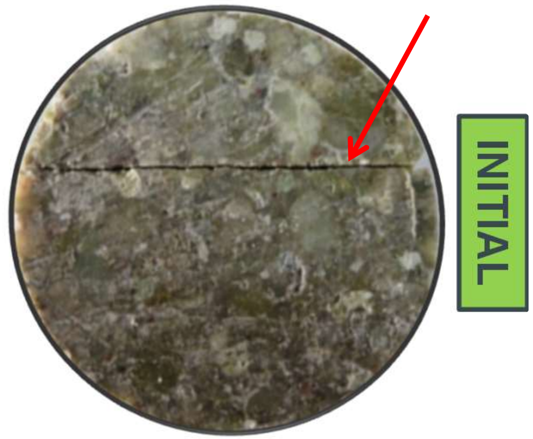


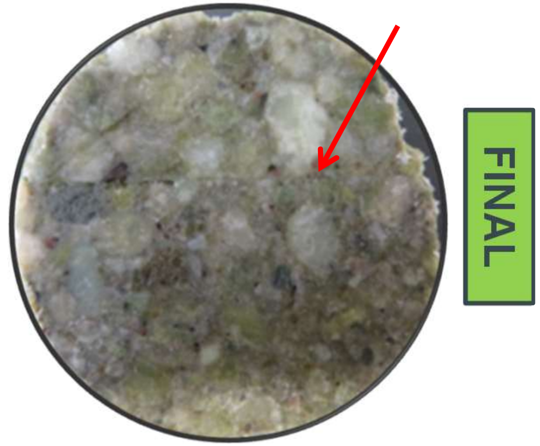
TRIMMING OF SAMPLES DRILLED FROM THE BLOCKS ON SITE (SOME IN THE MIDDLE OF BLOCKS AND OTHERS BETWEEN TWO BLOCKS) AND MEASUREMENT OF GAS PERMEABILITY

THM PROPERTIES OF BARRIER SAMPLES AFTER OPERATION FOR 18 YEARS: GAS PERMEABILITY: EFFECT OF JOINTS





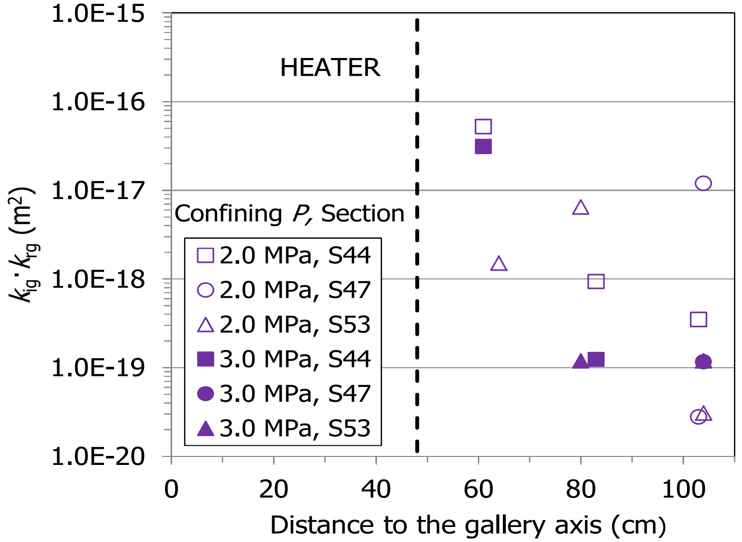


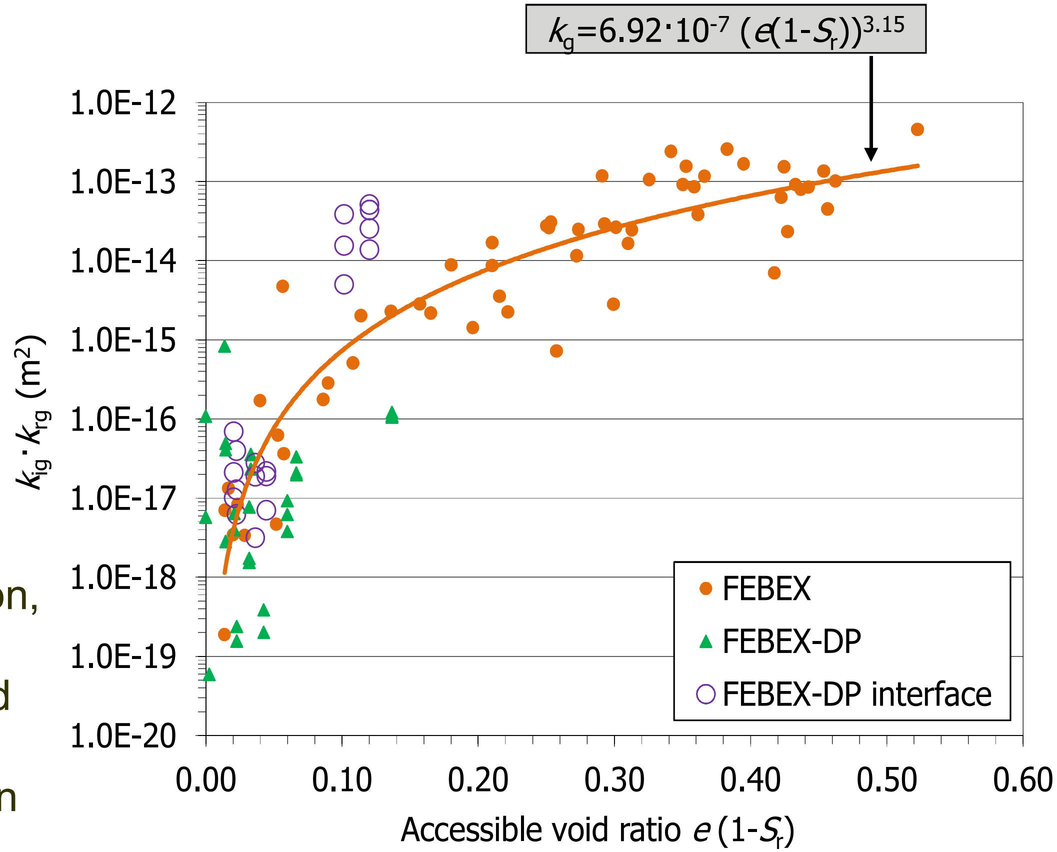


Irreversible closure of pathways during the test

- ✓ Gas permeability decreases with confining pressure, particularly for P_{conf}<4 MPa (the dry density of the samples increased during the tests)
- ✓ Samples closer to the gallery axis (drier, lower S_r) have higher k_g
- ✓ The gas permeability of samples with interface is higher
- ✓ Samples with interface of the external ring (more saturated) behave as samples without interface

THM PROPERTIES OF BARRIER SAMPLES AFTER OPERATION FOR 18 YEARS: GAS PERMEABILITY: EFFECT OF JOINTS





- ✓ Gas permeability decreases with the degree of saturation, and consequently is lower near the granite
- ✓ Effect of interfaces less noticeable in the more saturated samples
- ✓ Gas permeability of the FEBEX-DP samples depends on the accessible void ratio in the same way as was to be expected for the FEBEX reference bentonite

FEBEX/FEBEX-DP – Summary safety relevant aspects

- Low hydraulic conductivity	→	Properties not altered, diffusion dominated
- Chemical retention of RN	→	Sorption properties unlikely altered
- Sufficient density	→	Density gradients, mean 1.59 g/cm^3
- Sufficient swelling pressure	→	~6 MPa (for 1.6 g/cm^3); lab-scale confirmed in 1:1 exp.
- Mechanical support	→	Sufficient support
- Sufficient gas transport capacity	→	Not relevant
- Minimise microbial corrosion	→	No indication of MIC on canister, instruments
- Resistance to mineral transformation	→	No significant transformations detected
- Sufficient heat conduction	→	Confirmed

Kober et al. Davos Clay Conference 2017

CONCLUSIONS 1/2

- ✓In granite host rock with enough water availability, the bentonite expansive capacity is enough to fill all the voids , the initial dry density of the blocks (1.70 g/cm^3) decreasing to an average barrier density of 1.60 g/cm^3
- ✓After 18 years hydration the distribution of water content and dry density in vertical sections still showed axial symmetry, with higher water content and lower dry density in the external part of the barrier
- ✓The average water content and the humidity gradient was higher in hot sections, i.e. around the heater: heating delays hydration
- ✓Hence, the average water content and density values in vertical sections changed along the barrier

CONCLUSIONS 2/2

✓The state observed in some parts of the barrier seems to have been originated at the beginning of operation and has not been modified subsequently: some of the deformations occurred could be irreversible

✓The measurements taken upon dismantling do not reflect exactly those during operation, because 1) there was a cooling period and 2) the barrier experienced expansion when the concrete plug was demolished

✓**The importance of the water content and density changes in the barrier comes from the fact that the thermo-hydro-mechanical properties of bentonite (thermal conductivity, permeability, swelling capacity, water retention capacity) depend basically on these parameters**

Final remarks

- No irreversible modifications of THM properties of the buffer have been observed
- The influence of radiation on THM properties has not been tested
- Modelling is required to extrapolate to long-term behaviour

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The FEBEX project was financed by ENRESA and the EC Contracts FI4W-CT95-006 and FIKWCT-2000-00016

The FEBEX-DP Consortium (NAGRA, SKB, POSIVA, CIEMAT, KAERI) financed the dismantling operation and onsite determinations in 2015

European Joint Programme on Radioactive Waste Management