Arbeitsbericht NAB 16-21

FEBEX-DP:

Bentonite TDR probe inspection and data verification report

May 2017

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1 Introduction

1.1 The FEBEX project

FEBEX (Full-scale Engineered Barrier Experiment in Crystalline Host Rock) is a research and demonstration project that was initiated by Enresa (Spain).

The aim of the project is to study the behaviour of near-field components in a repository for high-level radioactive waste in granite formations according to the Spanish concept. The main objectives of the project can be divided into two areas:

a) As a feasibility demonstration of constructing the engineered barrier system in a horizontal configuration for deep geological storage, and the analysis of the technical problems encountered for this disposal method

b) A better understanding of the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) processes in the near field, and development and validation of the modelling tools required for interpretation and prediction of the evolution of such processes

The project consists of two large-scale tests (see Fig. 1-1) – "in situ" and "mock-up" (the latter is managed by CIEMAT in Spain) –, a series of laboratory tests, and THM and THG modelling tasks.

The full-scale heating test (in-situ test), to which this document refers, was performed at the Grimsel underground laboratory in Switzerland, also known as Grimsel Test Site (GTS) or Felslabor Grimsel (FLG in German). A complete description of the FEBEX project objectives and test program can be found in the Fuentes-Cantillana et al. (1998a).

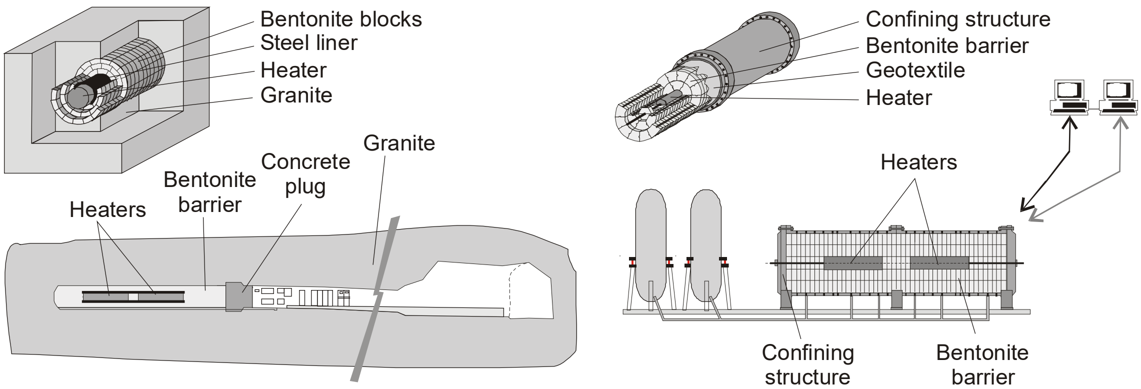


Fig. 1-1: Overall layout of FEBEX in-situ test (left) and mock-up test (right).

The project started in 1994, and has been supported by the European Commission through consecutive contracts, identified as FEBEX I (contract No. FI4W-CT-95-0006) for the period January 1996 to June 1999, and FEBEX II (contract No. FIKW-CT-2000-00016), from September 2000 to December 2004. From January 2005 to December 2007NF-PRO took over. And finally, in January 2008 the in-situ test was transferred from Enresa to a consortium composed by SKB (Sweden), POSIVA (Finland), CIEMAT (Spain), Nagra (Switzerland) and more recently KAERI (South Korea), the FEBEXe Consortium, which supports it currently.

The final in-situ experiment excavation was carried out in 2015 and new partners, interested in taking part in the planned sampling and analyses, have been incorporated into the Consortium (now called FEBEX-DP) for that purpose, namely US DOE (USA), Obayashi (Japan), RWM (UK), Andra (France), BGR (Germany) and SURAO (Check Republic).

1.2 Test configuration during FEBEX I

The installation of the in-situ test was carried out at the GTS. A horizontal drift with a diameter of 2.28 m was excavated in the Grimsel granodiorite specifically for this experiment using a TBM (a tunnel boring machine). Two electrical heaters, of the same size and of a similar weight as the reference canisters, were placed in the axis of the drift. The gaps between the heaters and the rock were backfilled with compacted bentonite blocks, up to a length of 17.40 m, this requiring a total 115'716 kg of bentonite. The backfilled section was sealed with a plain concrete plug placed into a recess excavated in the rock and having a length of 2.70 m and a volume of 17.8 m^3. Fig. 1-2 shows the dimensions and layout of the test components schematically.

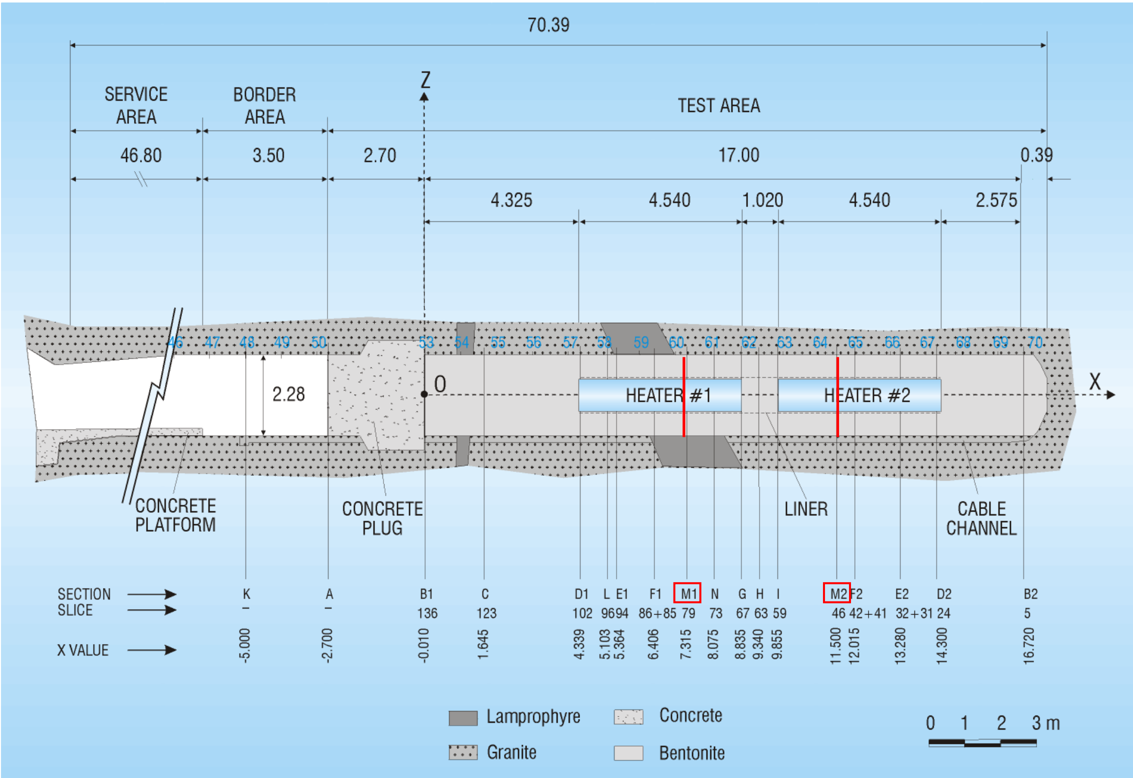


Fig. 1-2: General layout of the FEBEX "in situ" test (FEBEX I configuration).

Red lines: position of TDR measurements at Sections M1 and M2.

A total of 632 instruments were placed in the system along a number of instrumented sections, both in the bentonite buffer and in the host rock, to monitor relevant parameters such as temperature, humidity, total and pore pressure, displacements, etc. The characteristics and positions of these instruments are fully described in Fuentes-Cantillana & García-Siñeriz (1998b).

A Data Acquisition and Control System (DACS) located in the service area of the FEBEX drift collected the data provided by the instruments. This system recorded and stored information from the sensors and also controlled the power applied to the electrical heaters, in order to maintain a constant temperature at the heaters/bentonite interface. The DACS allowed the experiment to be run in an automated mode, with remote supervision from Madrid. Data stored at the local DACS were periodically downloaded in Madrid and used to build the experimental Master Data Base.

The construction of the concrete plug was completed in October 1996, and the heating operation started on 28 February 1997. After a warm-up period of 53 days, a constant temperature of 100 °C was maintained at the heaters/bentonite interface, while at the same time the bentonite buffer was slowly hydrated with water naturally flowing from the rock. A complete report that includes both the installation of the test and the results gathered after two years of operation is given in Fuentes-Cantillana et al. (2000).

1.3 Dismantling of Heater #1 and test configuration afterwards (FEBEX II)

A partial dismantling of the FEBEX in-situ test was carried out during the summer of 2002, after 5 years of continuous heating. The operation included the demolition of the concrete plug, the removal of the section of the test corresponding to the first heater, and the sealing of the remaining section of the test with a new shotcrete plug. A large number of samples from all types of materials were taken for analysis. A number of instruments were subsequently dismantled, as well as a few new ones installed. Accordingly, system design was adapted, and the physical layout was changed in order to ease the partial dismantling operation.

The buffer and all components were removed up to a distance of 2 meters from Heater #2 to minimize disturbance of the non-dismantled area. A dummy steel cylinder with a length of 1 m was inserted in the void left by Heater #1 in the center of the buffer. Some new sensors were installed in that one additional meter of bentonite buffer.

Additional sensors were introduced in boreholes drilled in the buffer parallel to the drift. To simplify this operation, the new concrete plug was constructed in two phases: an initial temporary plug measuring just 1 m in length, which was built immediately after dismantling, and a second section to complete the plug length to the 3 m planned in the design of the experiment. Unlike FEBEX I, the new plug was a parallel one, without a recess excavated in the rock, constructed by shotcreting.

The description of the partial dismantling operation is given in the report "Dismantling of the Heater #1 at the FEBEX "in situ" test. Description of operations" (Bárcena et al. 2003). The configuration of the test, after completing the partial dismantling operation and construction of the full plug length, is shown in Fig. 1-3.

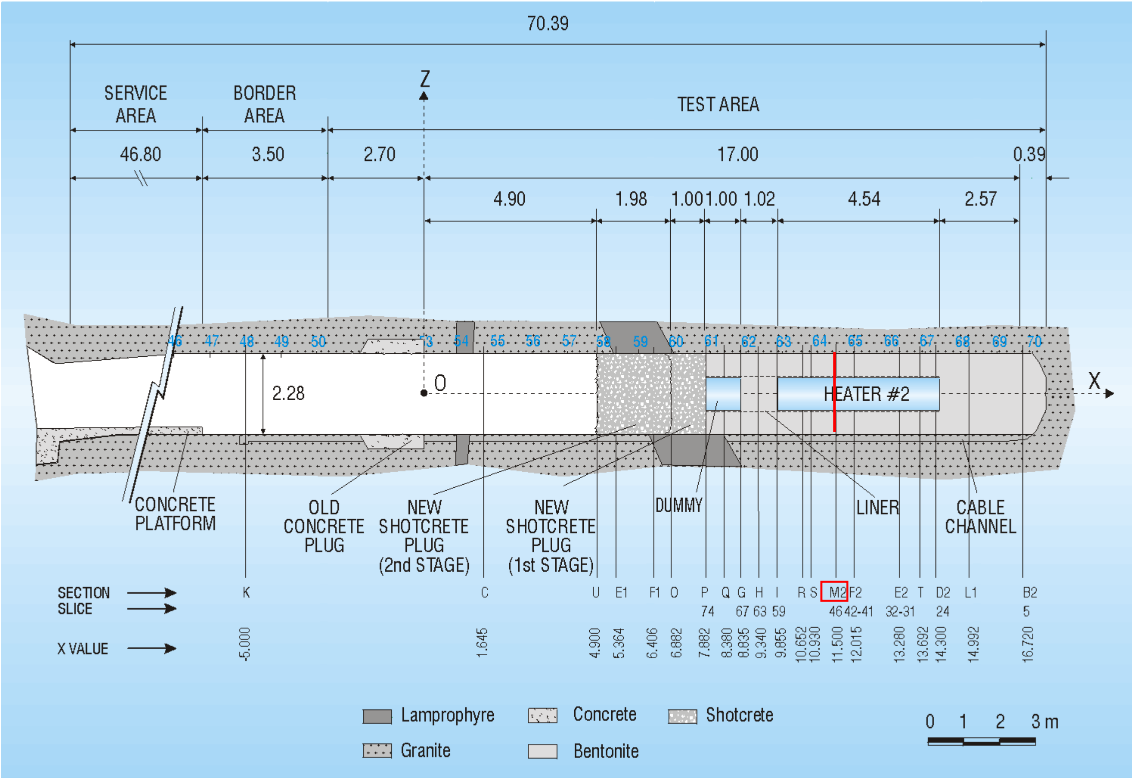


Fig. 1-3: Status of the FEBEX "In situ" test after the partial dismantling (FEBEX II configuration).

Red line: position of TDR measurements at Section M2.

A more complete report that describes the test from the conception up to two years of operation after the partial dismantling is the document in Huertas et al. (2006).

1.4 Concept of the dismantling of Heater #2 (FEBEX-DP)

The objective of the second dismantling operation, carried out throughout 2015, was to dismantle all the remaining parts of the in-situ test, including Heater #2. This operation includes carrying out a complete sampling of the bentonite, rock, relevant interfaces, sensors, metallic components and tracers to allow the analysis of the barriers' condition after 18 years of heating and natural hydration.

Analytical results will be compared with data obtained from the partial dismantling (Huertas et al. 2006); the monitoring data (AITEMIN 2014) as well as with the results derived from modelling efforts (Lanyon & Gaus 2013). The results are expected to increase the current knowledge and confidence for the FEBEX-DP partners in bentonite performance with a focus on thermo-hydro-mechanical (THM) and thermo-hydro-chemical (THC) processes as well as on corrosion and microbial activity. The reporting of the laboratory analysis and dismantling results is expected to be complete by mid of 2017 with a final integrated report issued late in 2017.

All details about the planned dismantling operation and sampling program are given in the reference documents: "FEBEX-DP (GTS) Full Dismantling Test Plan" (Bárcena & García-Siñeriz 2015a), "FEBEX-DP (GTS) Full Dismantling Sampling Plan" (Bárcena & García-Siñeriz 2015b) and its update (Rey et al. 2016).

A detailed description of the dismantling operation and sampling documentation can be found in Sineriz et al. (2016).

1.5 Objectives and contents

This report documents activities carried out and the main results gathered during the final dismantling of the FEBEX in-situ test. More specifically, this report focusses on the time domain reflectometry (TDR) probes installed in Section M2 of the bentonite buffer for monitoring water content and on the water content data provided by the TDR probes that survived the entire 18 years of the experiment.

A general description of the TDR probes and their retrieval is described in Chapter 2 and 3, respectively. Chapter 4 presents the measured volumetric water content and temperature before and during the probe retrieval. The laboratory results for the samples taken in the vicinity of the TDR probes are summarised in Chapter 5. In Chapter 6, the volumetric water content values were "re-scaled" to accommodate the possible drift of temperature correction over the extremely long experimental duration. Finally, Chapter 7 provides the main conclusions.

2 Description of TDR probes

The FEBEX bentonite TDR probes (sensor codes WT-M2-03~12, the focus of this report) were placed in the barrier made of highly compressed bentonite blocks around Heater #2. They have generated volumetric water content (VWC) data in Section M2 (dismantling Sections 46 and 47 according the sampling plan, Bárcena & García-Siñeriz 2015b and its update, Rey et al. 2015) since 1997. Selected information on the installation and specifications of the TDR probes, which are identical to those installed in M1, is summarised in this section.

2.1 Specifications

Due to a relatively large distance, up to 24 m, between the probes and the TDR reflectometer unit (Tektronix 1502C), a low-loss coaxial cable (RG213) was used. The characteristic impedance of this type of cable is 50 ± 2Ω, the signal delay is about 5.0 ns/m and the attenuation is 0.28 dB/m at 1 GHz (Marschall et al. 1997).

The length of the bentonite probes was 500 mm and the diameter is 20 mm (Fig. 2-1 and 2-2). The probe consists of a cylindrical Teflon rod, on the surface of which two copper foils (length 470 mm, width 10 mm, thickness 0.6 mm) were fixed. The two copper foils were cut short at the back end of the rod and connected to the coax cable at the upper end. Finally, the entire probe was coated with Polyolefine shrinkable tubing. Both ends of the coated probe were sealed with an epoxy resin.

A temperature correction was necessary to interpret the TDR measurements properly, thus, temperature was also monitored with a temperature sensor positioned in the immediate vicinity of the connection between each TDR probe and the coaxial cable. Semi-conductor temperature sensors (PTC) of type Siemens KTY 10-62 were used. The operating temperature range is 0 °C ... + 150 °C with an accuracy of 0.5 %. The temperature sensors were wired to the multiplexer with an RG59 (75 Ω) twisted-pair cable.

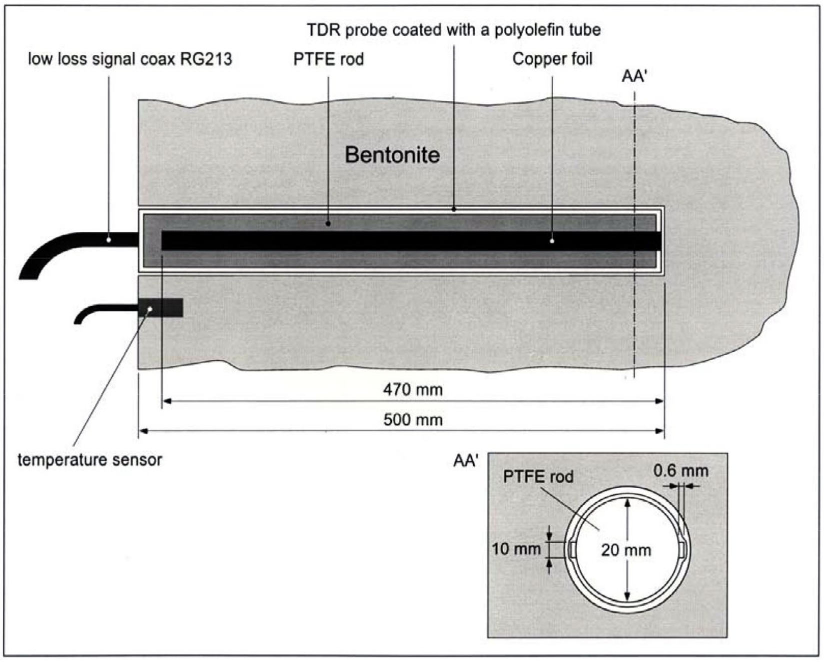


Fig. 2-1: Dimensions of the bentonite TDR probe.

Fig. 2-2: Bentonite TDR probes before installation and without coating (left) and with coating (right).

2.2 Position and installation

The TDR probes were installed in the bentonite barrier at the positions shown in Fig. 2-3 and 2-4 and Tab. 2-1 (also defined as instrumented Section M2). They were installed parallel to the tunnel axis across slices/layers of the bentonite blocks 46, 45, 44 and 43 (Fig. 2-5), and each slice had a thickness of 12.5 cm, approximately at TM 64.5-65.0 m). For the installation of the probes (parallel to the tunnel axis), 52 cm long boreholes were drilled with a diameter of 22.5 + 0.5 mm. Small grooves were made on the surface of the bentonite blocks for routing the cables towards the cable channels located in the buffer periphery .

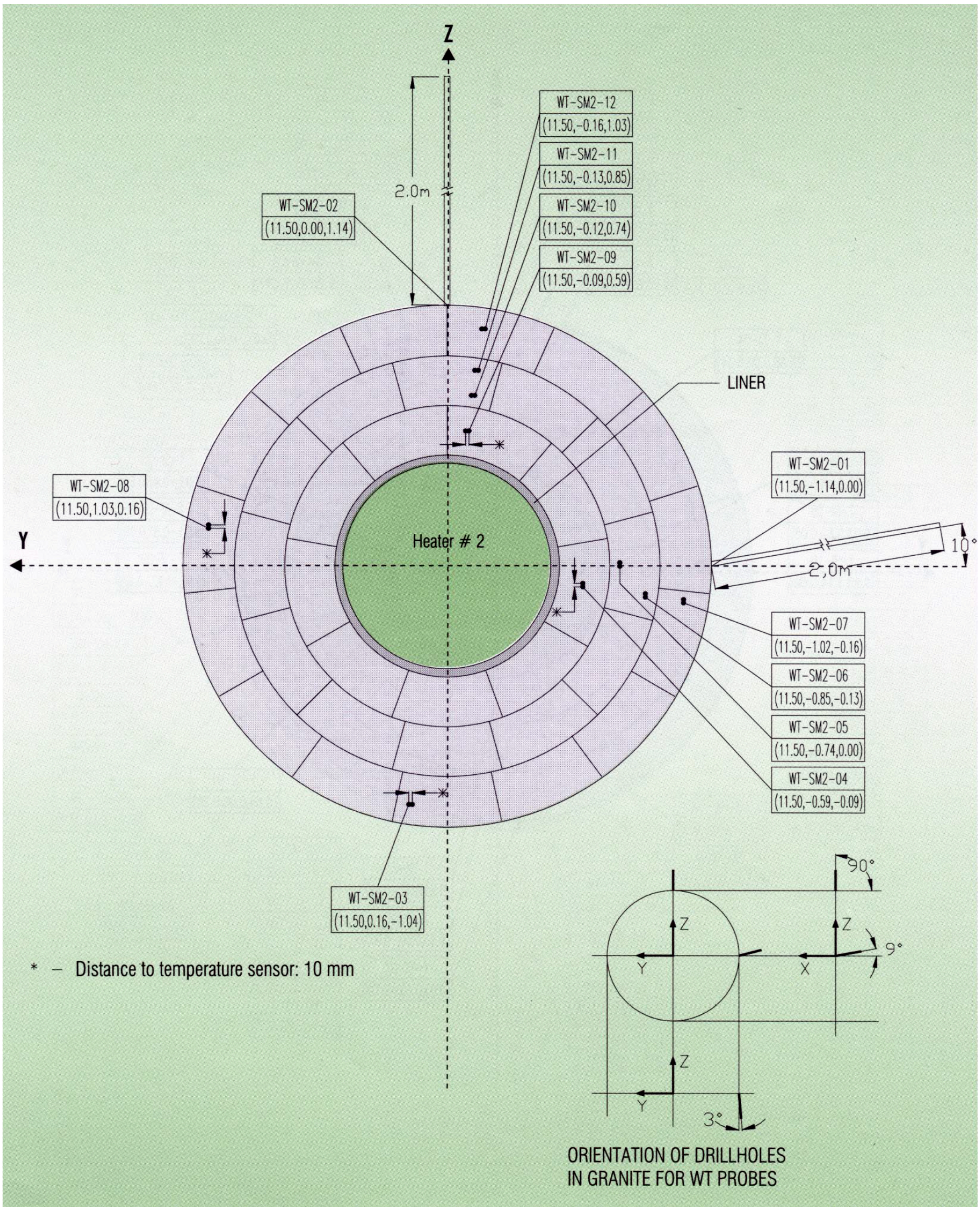


Fig. 2-3: Position of the probes.

Note that the "S" before the M2 was not used in the codes throughout this report.

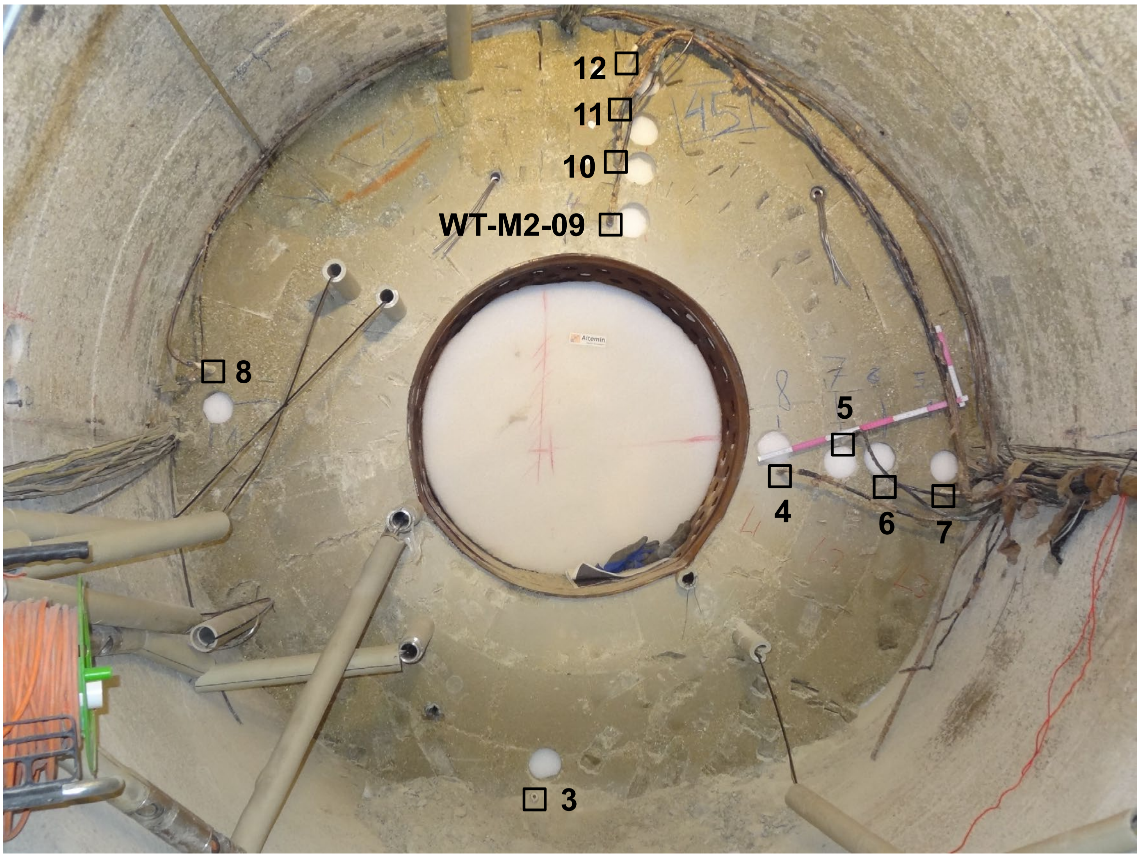


Fig. 2-4: Position of the probes on the face of Slice No. 45.
Photograph also shows the sampling positions (white circles).

Tab. 2-1: Position of the TDR probes.

Probe No.	Horizontal (cm)*	Vertical (cm)	From center (cm)	From liner (cm)
WT-M2-03	16	-104	105	57
WT-M2-03	-59	-9	60	11
WT-M2-03	-74	0	74	26
WT-M2-03	-85	-13	86	37
WT-M2-03	-102	-16	103	55
WT-M2-03	103	16	104	56
WT-M2-03	-9	59	60	11
WT-M2-03	-12	74	75	26
WT-M2-03	-13	85	86	37
WT-M2-03	-16	103	104	56

* Left side

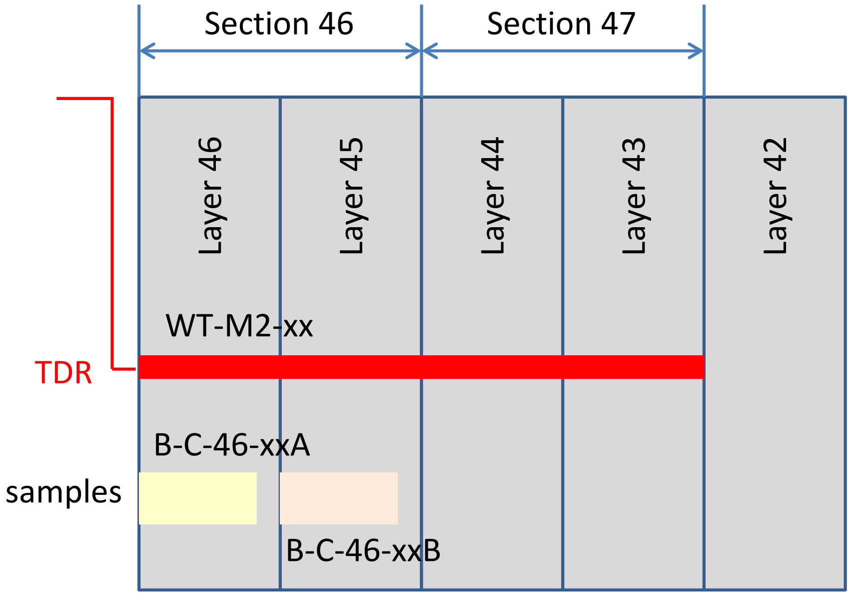


Fig. 2-5: Axial position of the bentonite TDR probe relative to bentonite block slices/layers. Sampling positions are also shown.

The bentonite blocks were made of Serrata Clay produced in Spain with a montmorillonite content of 92 ± 3 % with the specific weight of 2.70 Mg/m^3. The blocks were made to have the initial water content of 13.1 to 14.9 % with the mean value of 14.4 % and a dry density of 1.69 – 1.70 Mg/m^3 (Enresa 1998). Tab. 2-2 summarises the key parameters of the bentonite slices instrumented with TDR probes. The table also shows that the gaps between the blocks and tunnel wall led to a lower mean dry density.

Tab. 2-2: Key parameters of bentonite slices instrumented with TDR probes.
With a probe length of 50 mm, four bentonite slices shown were intersected.

Dismantling section No.	**Bentonite slice/layer No.**	**Dry density*** (Mg/m^3)	**Void ratio*** (%)	**Tunnel meter**** (start)	**Tunnel meter**** (end)
46	46	1.64	2.88	11.625	11.500
	45	1.58	6.44	11.755	11.615
47	44	1.58	6.38	11.870	11.755
	43	1.58	6.31	12.015	11.870

* Dry density ist he mean value including the gaps indicated by the void ratio.
** Values consistent with the sampling plan.

2.3 Cable routing

From the outer surface of instrumented Section M2 (bentonite block Slice No. 46), bundles of TDR and temperature sensor cables were routed to the tunnel wall and from there they were loosely attached to the roof and/or the side of the tunnel wall up to the data acquisition devices. As an additional protection, the cable bundles were coated with a Teflon band up to tunnel meter 60.9 (Fig. 2-6).

Fig. 2-6: Installed bentonite TDR probes and temperature sensors in Section M2, bentonite Slice No. 46.

The probes extend over TM 64.5 – 65.0 m. Starting from tunnel meter 60.9, the cables are protected with a shrinkable sleeve.

3 Retrieval of TDR probes

In 2002, the first half of the FEBEX experiment was dismantled within the framework of FEBEX II and heater No. 1 was retrieved after five years of continuous heating. A total of ten bentonite TDR probes (sensor codes WT-M1-03~12) installed in Section M1, shown in Fig. 1-2, were retrieved in the first dismantling campaign. Only three out of ten TDR probes WT-M1-06, 09 and 11 in Section M1 were functional at the time of the retrieval (note: temperature sensor at No. 11 had failed). Fig. 3-1a schematically illustrates the functionality of the TDR probes and temperature sensors in Section M1 at the time of dismantling in 2002. For the temperature sensors, only one had failed during the early phase. More details are provided in Albert et al. (2003).

After 18 years of monitoring and continuous heating, the dismantling of the other half (FEBEX-DP project) was carried out between February and August 2015. The other set of bentonite TDR probes (WT-M2-03~12) installed in Section M2 were retrieved over a period of June 24 – 30, 2015.

Fig. 3-1b illustrates the functionality of the TDR probes and temperature sensors in Section M2. At the time of dismantling, 40 % of the temperature sensors, and 70 % of the TDR probes had survived (with one TDR probe giving erroneous readings). Despite the significantly long test duration, more TDR probes survived in Section M2 compared to those retrieved in Section M1 in 2002. In the following sections, the retrieval of the TDR probes in Section M2 and the probe inspection results are summarised.

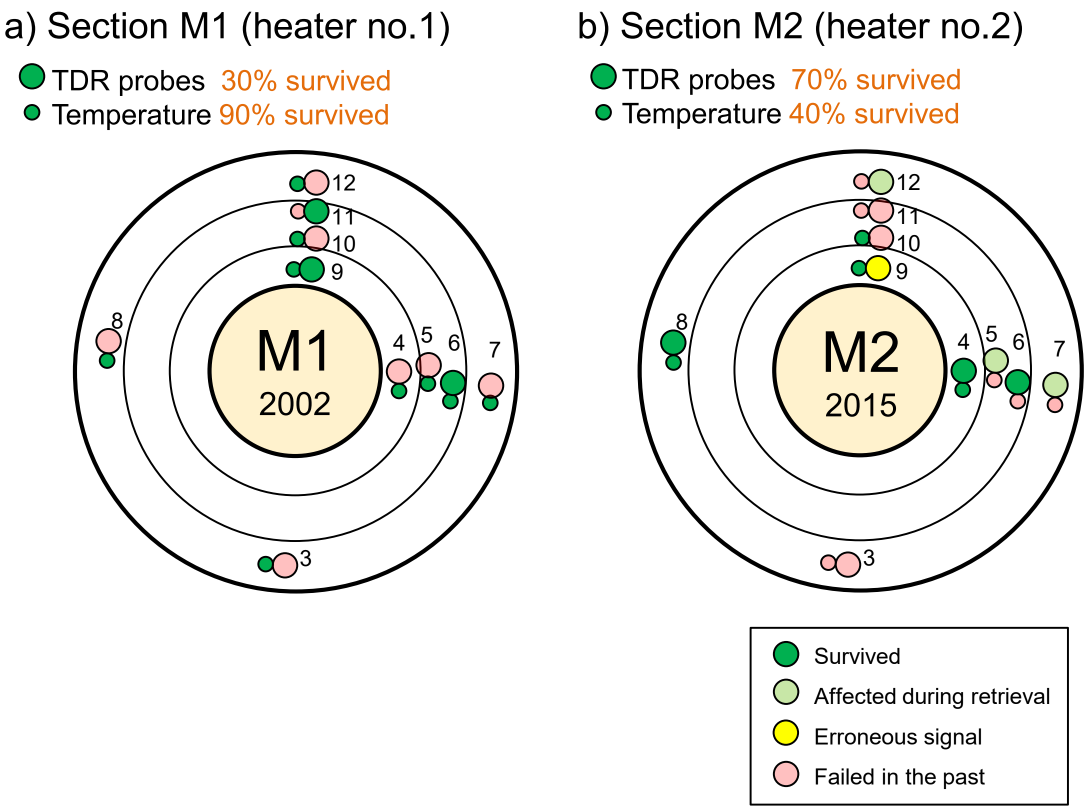


Fig. 3-1: Status of the TDR probes and temperature sensors.

a) Section M1 in 2002. b) Section M2 in 2015.

3.1 Sequence of operations

Regarding the retrieval of the bentonite TDR probes in Section M2, the dates of the most important actions are summarised in Tab. 3-1. After the probes were retrieved from the bentonite blocks, they were kept in the tunnel until their visual inspection on July 7, 2015; next they were hung in the air for some more days to obtain monitoring values in air until the cables were finally cut mid-July.

Tab. 3-1: Selected key dates during FEBEX dismantling.

Events highly related to bentonite TDR retrieval are shown in Italic.

Excavation (plug demolition started)	April 8, 2015
Heater switched off	April 24, 2015
Excavation (first bentonite layer)	May 8, 2015
Excavation (reached TDR probe head)	June 24, 2015 (*last day* of data analysed)
All TDR probes free in air	June 30, 2015
On-site inspection	July 7, 2015
Disconnected from Tektronix 1502C	Mid July, 2015

3.2 Excavation and TDR retrieval

As shown in Tab. 3-1, the retrieval of the 10 bentonite TDR probes took place from June 24 to June 30, 2015. The bentonite block layers were removed in steps using power chisels. Although performed carefully, the chisel damaged the coating film of most of the probes. Fig. 3-1 shows selected photos taken during the removal of bentonite blocks around the TDR probes. The damages on the probes are visible on some photos (for instance a, b, d, f and i). It has to be noted that, as described in the next section, Probe No. 9 seems to have been affected by the heat and moisture. This led to major cracking of the coating film.

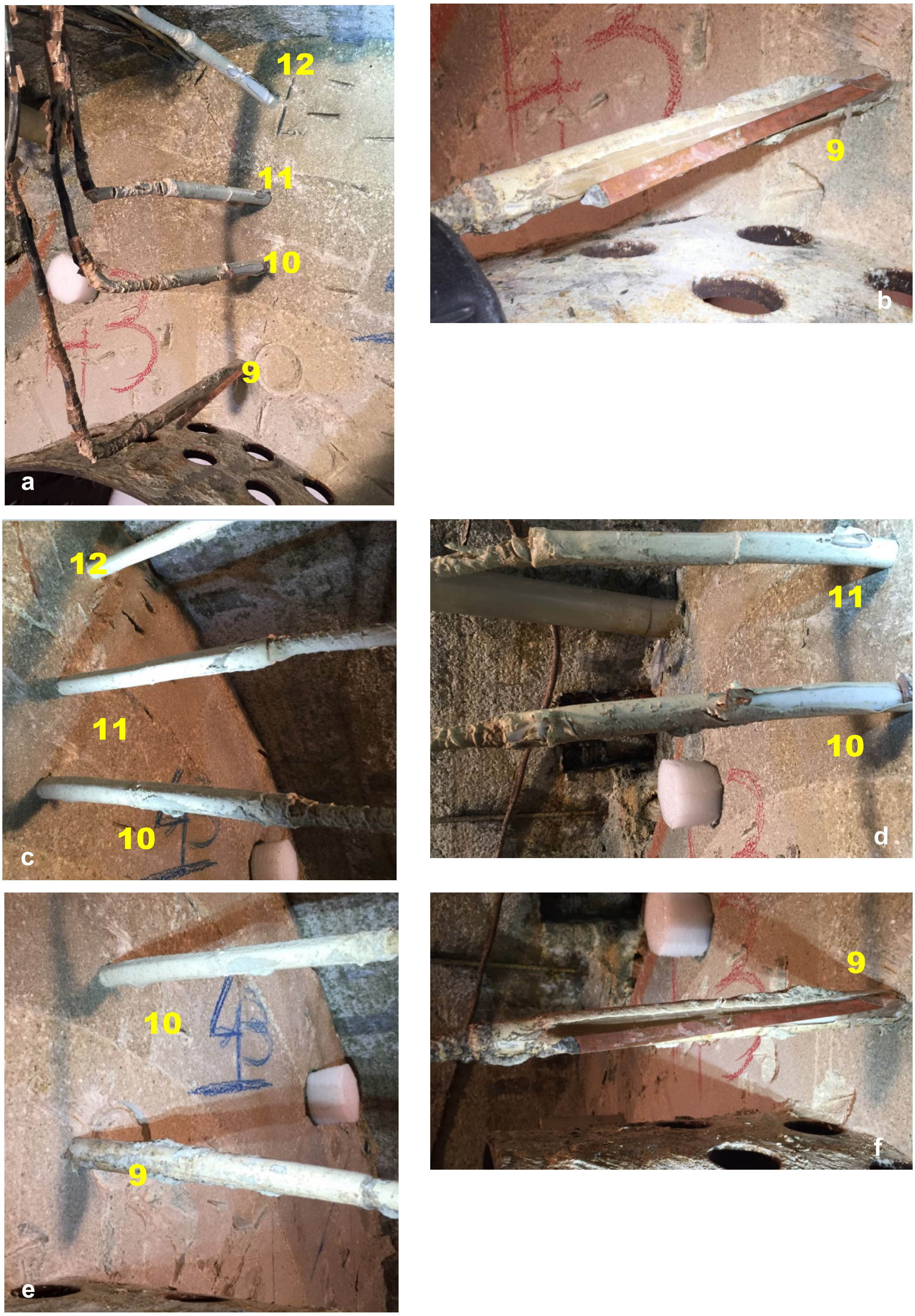


Fig. 3-2: Conditions of the TDR probes during dismantling (photos taken by Aitemin).

Fig. 3-2: Cont.

3.2 On-site Inspection after retrieval

After their retrieval was completed on June 30, 2015, the TDR probes were left in the air while still connected to the TDR unit.

On July 7, 2015, an on-site visual inspection was made on the retrieved TDR probes. This section summarises the state and conditions of the TDR probes after their retrieval.

Despite high functionality during the 18 year-long monitoring phase, all the TDR probes exhibited various types of damage at the time of the on-site inspection. The observed damage can be divided primarily into two types:

1. Damage due to dismantling
2. Damage due to long-term use under high temperature and moisture conditions

The first type is mainly characterized by cracking or tearing of the coating film and some of the more severe damage included partial scraping of the coating film, electrode and Teflon rod by the power chisel. The second type included; cracking of the surface coating film, shearing at the bentonite block joints and cracking of the cable protection. The observations are summarised in Tab. 3-2 and detailed photos are shown in Appendix A. Note that because of the damage, the probes were not re-calibrated. After finishing the TDR probe inspection, the co-axial cables were cut, the probes were taken out of the FEBEX tunnel, and the measurements were stopped mid-July.

Tab. 3-2: Summary of the state and conditions of the bentonite TDR probes.

Sensor No. (WT-M2-xx)	**Distance from heater** (m)	**Co-ax cable**	**Cable-head connection**	**Head**	**Shar deformation at block joints** (mm)	**Electrodes**	**Water calibration possible?**	**Remarks**
3	0.60	Cut	Missing	Missing	Small, small, small	Both ends cut/out	No	
4	0.15	Cracked (old)	Small cracks	Ok	2.0, 0.5, 1.5	Locally slightly visibled	No	Closest to heater, cable seemed cracked for a while, surface looked brown
5	0.29	Cut	Cracked	Ok	0.5, 0.5, 0.5	Ok	Yes, with head in air	
6	0.41	Cracked, cut?	Ok	Ok	Small but whole probe bent	Small cracks on coating	No	
7	0.58	Ok	Ok	Ok	Small but slightly bent	Pealed, 3 and 7 cm long	No	
8	0.59	Ok	Ok	Ok	0.5, 1.5, 0	Pealed 0.5 cm, deep crack 6 cm	No	
9	0.15	Ok	Cracked	Coating cracked	Small, small, 3.0	One fully out 38 cm	No	closest to heater, malfunctioning during measurement, long crack on coating, overheating and/or large shearing might have led to water intrusion inside coating, surface looked brown
10	0.30	Ok	Ok	Coating pealed	1.0, small, 3.0	One electrode cut 2ith 12 cm pealed	No	Large shearing
11	0.41	Almost disconnect ed/cut?	Two cuts	Ok	2.0, small, 3.0	Pealed 2 and 4 cm	No	Large shearing
12	0.59	Ok	Ok	Ok	1.0, small, 0.5	Pealed 15 cm	No	

"Cut", "Pealed" refer to damages during retrieval.
"Cracked" refer to possible natural damage before dismantle.
Shear deformation values were for three joints between Slices 46 and 45 and 44 and 44 and 43.

3.4 Summary of TDR probe retrieval and inspection

The key findings obtained during the retrieval and inspection of the TDR probes in Section M2 are summarised below.

- Although to a different extent, two of the probes (WT-M2-04 and 09) that were close to the heater (~ 15 cm) seemed affected by the harsh environment (including the effect of the overheating incident in 2009). The surface of the coating film of these probes was more discoloured (brown) than the coating of the other probes.
- WT-M2-04 had a minor old crack on the surface coating. Water may have entered here leading to disturbances on the TDR trace.
- WT-M2-09 had old major cracks on the surface coating. The copper electrodes showed corrosion-like stains. It was presumed that water had intruded inside the coating film and affected the TDR trace.
- Some of the probes (WT-M2-04, 05, 06, 09 and 11) had cracks on the cable protection. The cracks looked somewhat old. The conductors were not disconnected. Probe No. 11 showed the most severe damage on the co-axial cable; this probe had failed in 2004 whereas the others survived until June 2015. Little is known about the effect of damage or water intrusion into the outer shield of the co-axial cable to the TDR signal.
- Most of the probes showed shear deformation at the bentonite block interfaces (every 12.5 cm along the probe length). The deformation ranged from very slight to as much as ~ 3 mm. The surface coating seemed to have had a sufficient resistance against the shearing. The effect on the TDR signals was considered insignificant.
- Besides the shear deformations, the majority of severe damage to the probes seems to have been caused by the power chisel during the removal of bentonite blocks under difficult conditions. The damage was so severe that re-calibration could not be performed.

A comparison with the TDR probes (WT-M1-03 through 12) retrieved in the previous dismantling of Heater 1 performed in 2002 (Albert et al. 2003) reveals the following.

- The cable damage (cracks, disconnections) seems less this time for the M2 probes despite the longer monitoring period than the damage observed for the M1 probes. Only Probe No. WT-M2-11 had its cable nearly disconnected whereas, in the previous dismantling, three M1 cables were almost disconnected. The cables in M1 and M2 sections were installed and routed by different teams. The M2 cables were rather loosely installed which could have contributed to a less severe damage.
- Seven out of 10 TDR probes from Section M2 were functional; Probe No. M2-09 did, however, give erroneous readings. The survival rate for the M2 TDR probes for 18 years was 70 % and higher than that of the M1 TDR probes (30 %) for 5 years which might have partially resulted from the different cable installation methods described above.
- Fig. 2-13 in NIB 03-003 (Albert et al. 2003) indicates that physical damage to the probes caused during the previous dismantling seems to have been less than the damage observed this time.

4 In-situ water content and temperature data

4.1 Data during the entire 18-year experiment duration

Selected major events that took place during the entire course of the FEBEX experiment are summarised in Tab. 4-1. There were several heater failure events as well as an overheating incident in late 2009 where the heater surface temperature rose from 100 °C to 120 °C for about two days.

Tab. 4-1: Selected major events during the course of the experiment.

When	Event	Remarks
February 27 March 1997	Both heaters switched on	
February 28, 2002	Heater 1 switched off	Partial dismantling
July 11, 2002	Section M1 dismantled	
February 6 – 13, 2003	Heater 2 power loss	Malfunctioning of the UPS
June 24, 2003	New plug constructed	
November 19 – 21, 2003	Heater 2 power drop	
November 7, 2009	Heater 2 overheating	62 hours, max. temperature increase was16 °C at heater surface
May 4, 2012	Heater 2 power loss	20 hours stop due to electrical maintenance in GTS
November 24, 2013	Heater 2 sensor failure	
November 26, 2014	Heater 2 power loss	Power controller failure
April 24, 2015	Heater 2 switched off	Final dismantling

4.1.1 Temperature

Fig. 4-1 shows the 18-year evolution of the temperature in the bentonite blocks in Section M2. The temperature stabilised within the first 2 – 3 months with a distinct gradient in the radial direction. Power shut-off of heater No. 1 took place in 2002; at some distance away this was registered as a gradual decrease everywhere whereas unexpected power loss of Heater #2 in 2003 caused a significant and sudden temperature drop. As will be noted later in more detail, half of the temperature sensors failed by early 2004.

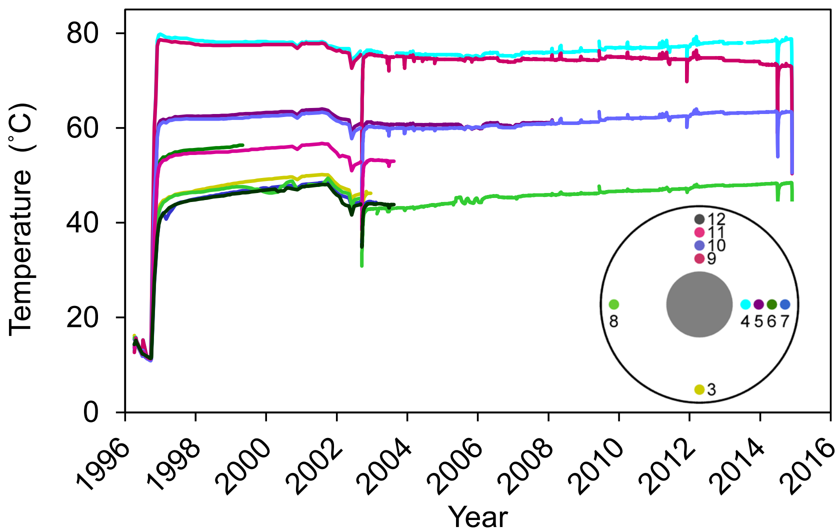


Fig. 4-1: Changes in temperature in the bentonite blocks around Heater #2 provided by temperature sensors associated to TDR probes (Schlaeger et al. 2016).

The temperature gradient around Heater #2 just before switching off in 2002 and 2015 is plotted in Fig. 4-2. The heater surface temperature is also plotted at the position of the liner surface. A strong radial gradient is seen with very little variation between 2002 and 2015. The data in 2002 are along two different transects showing the radial gradient has negligible spatial variation.

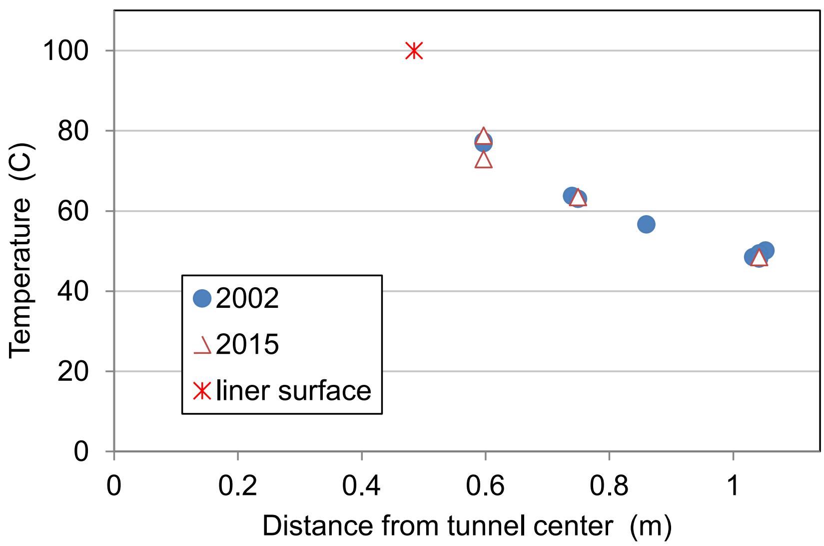


Fig. 4-2: Radial temperature profiles in the bentonite blocks around Heater #2 in 2002 and 2015.

4.1.2 Volumetric water content

The TDR signals reflect amount of water (i.e. volumetric fraction) within a certain sampling volume and, thus, are more suited to estimate VWC rather than gravimetric water content. Fig. 4-3 shows the 18-year evolution of VWC in the bentonite blocks in Section M2 estimated based on the revised calibration after the partial dismantling (Albert et al. 2003).

In general, VWC in the outer bentonite block reached saturation after 1 – 2 years, VWC in the middle blocks showed rapid increase during 2 – 4 years. The innermost blocks showed significantly slower saturation.

During the overheating incident in late 2009, two TDR probes close to the heater (WT-M2-04 and 09) showed a clear jump in VWC. After this incident, the increase in water content indicated that both of these probes were probably affected. The overheating led to the generation or enhancement of surface coating cracks on these probes which led to water/vapour intrusion inside the probes.

Based on the inspection of the probes described in the previous section, the coating film of these probes was damaged. With a trace of water observed inside the probe, it was suspected that the overheating had caused the damage on the coating film, allowed water to seep in, and led to an overestimation of VWC although to a different extent. Nonetheless, one of these two TDR probes (WT-M2-04) indicated that VWC reached its maximum finally after ~ 17 years just before the dismantling. The other one (WT-M2-09) which was found more heavily damaged, on the other hand, kept showing an unrealistic increase.

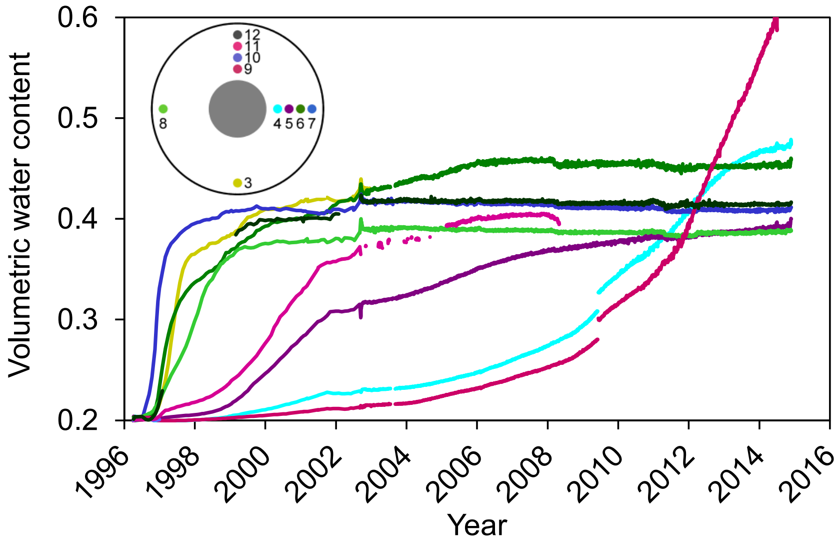


Fig. 4-3: Changes in water content provided by the TDR probes in the bentonite blocks around Heater #2 (Schlaeger et al. 2016).

Data only until the power shut off of Heater #2 are shown.

4.2 Data during the retrieval

The temperature data from mid-April 2015 (when the dismantling started) until the end of June 2015 (when excavation reached the TDR probes) are shown in Fig. 4-4. At the time of the dismantling, four out of ten temperature sensors were still functional. Sensor No. 08 exhibited unstable readings after the demolition of the concrete plug was completed. It was presumed that the sensor cable got damaged during the removal of the concrete plug. The remaining three sensors showed a temperature of about 16 – 17 °C when the excavation reached the bentonite slices where the TDRs and temperature sensors were installed. Note that temperature sensor 08 started showing about 16 °C afterwards. The temperature values before and after the heater shut-off are summarised in Tab. 4-2.

The air temperature recorded at tunnel meter (TM) 44 m (20 m away from the dismantling face) showed an average value of 16.1 °C during June 24 – 30, 2015. It is fair to assume that the temperature of the bentonite blocks was about 17 °C based on the survived temperature sensors, when the last TDR measurements were taken.

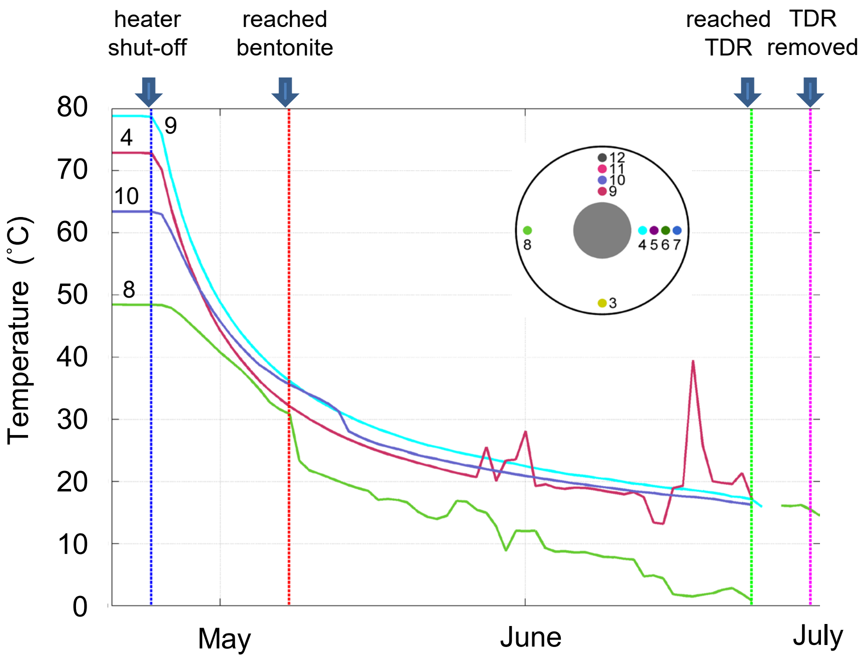


Fig. 4-4: Temperature recordings in Section M2 during the excavation period, April – June, 2015.

Tab. 4-2: Temperature sensors in the bentonite block Slice No. 46.

Position	**Failure date**	**(A) Temperature at heater shutoff on April 24, 2015** (°C)	**(B) Temperature on June 24, 2015** (°C)	**Difference (A) – (B)**
WT-M2-03	21.05.2003	-	-	-
WT-M2-04	Survived until 24.06.2015	78.7	17.1	61.6
WT-M2-05	19.07.2008	-	-	-
WT-M2-06	01.10.1999	-	-	-
WT-M2-07	16.07.2003	-	-	-
WT-M2-08	Survived until 24.06.2015	48.4	16.1	32.3
WT-M2-09	Survived until 24.06.2015	72.8	17.1	55.7
WT-M2-10	Survived until 24.06.2015	63.4	16.2	47.2
WT-M2-11	15.01.2004	-	-	-
WT-M2-12	15.01.2004	-	-	-

Fig. 4-5 shows the TDR travel time changes after the heater shut-off. Probes 4 and 9 (close to the heater) showed an abrupt decrease whereas the others showed a rather gradual decrease. Furthermore, likely due to some damage to the cables before reaching the probes, four probes (5, 7, 9 and 12) started yielding erroneous signals. For those probes, only the traces assumed correct were shown and analysed.

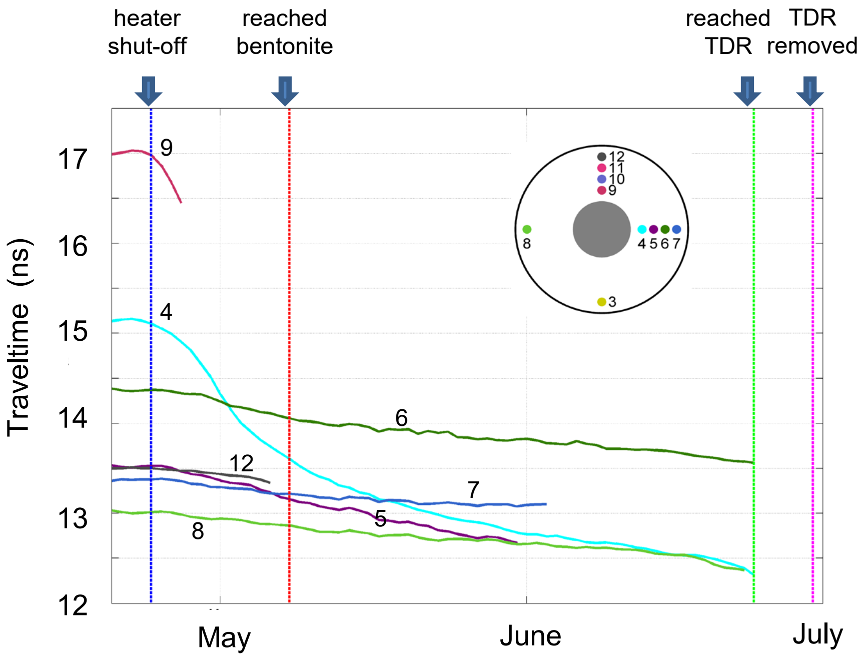


Fig. 4-5: Travel time data of TDR sensors in Section M2 during the excavation period April – June, 2015.

Fig. 4-6 shows the estimated volumetric water content from the travel time with a temperature correction. As noted in the inspection section, TDR No. 9 was severely damaged likely before the dismantling, the high water content value was considered erroneous.

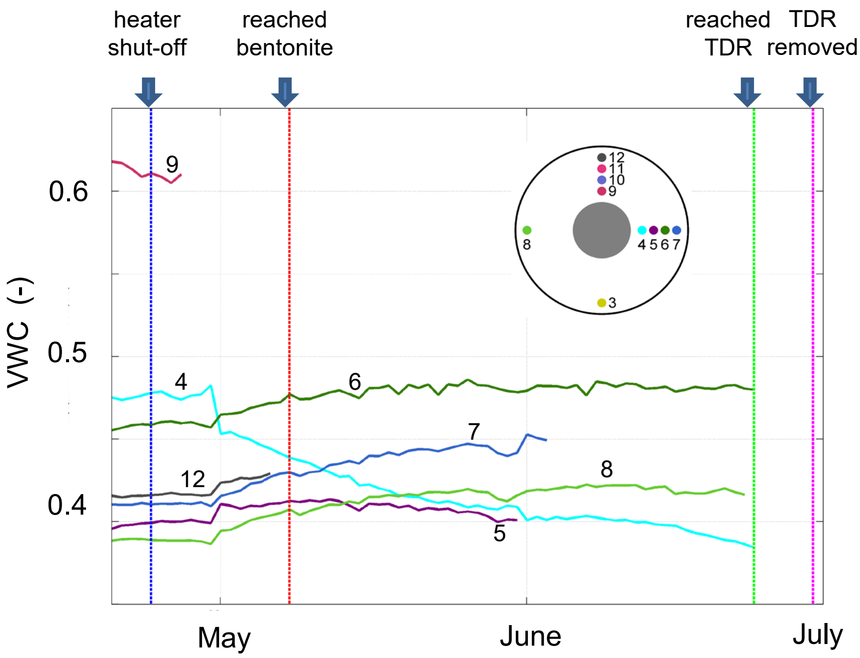


Fig. 4-6: Volumetric water content evolution after heater shut-off April – June, 2015 with temperature correction.

The VWC values at the time of heater shut-off and just before the TDR probe removal are summarised in Tab. 4-3. For Probe No. 4, the difference in the VWC before and after the heater shut-off is as large as 0.094. For Probe No. 9, the VWC on June 24 was not estimated due to insufficient information to do so. Both probes 4 and 9 had cracks on the coating film which had likely allowed water to intrude inside the probe. It was suspected that the temperature correction established based on the data using intact probes could not fully correct the VWC.

The actual VWC values on April 24 and June 24 were not expected to be different due to the low permeability of the bentonite blocks. Thus, the VWC differences shown in Tab. 4-3 result from the suspected changes in the temperature correction (due to the damage to the probes) as well as a drift during a long-term measurement under harsh conditions.

Tab. 4-3: Summary of volumetric water content (VWC) values before and after the heater shutoff.

Sensor	**Failure date**	**(A) VWC at heater shutoff on April 24, 2015**	**(B) VWC on June 24, 2015**	**Difference** (A) – (B)**
WT-M2-03	22.05.2003	-	-	-
WT-M2-04	Survived until 25.06.2015	0.478	0.384	+0.094
WT-M2-05	Data analysed until 01.06.2015	0.399	0.403*	-0.003
WT-M2-06	Survived until 25.06.2015	0.459	0.480	-0.021
WT-M2-07	Data analysed until 04.06.2015	0.411	0.450*	-0.039
WT-M2-08	Survived until 24.06.2015	0.389	0.417	-0.028
WT-M2-09	Data analysed until 28.04.2015	0.611	n/a	n/a
WT-M2-10	31.05.1997	-	-	-
WT-M2-11	01.10.2008	-	-	-
WT-M2-12	Data analysed until 07.05.2015	0.416	0.446	-0.030

* Assumed as final value on June 24, 2015.

** Positive value means VWC before the heater shut-off was likely "overestimated".

5 Laboratory sample analysis

In this section, the VWC values estimated with TDR are compared with the results of the laboratory sample determination of water content performed at ETH (Plötze 2016).

Samples near the TDR probes

During June 24 – 29, 2015, a total of 20 bentonite samples (B-C-46-1 through 10, two samples in the tunnel axis direction) were drilled in the vicinity of the ten TDR probes for lab analysis. Their positions (from Section 46, Slices 46 and 45) are as shown in Fig. 5-1. The average temperature recorded in the tunnel at approximately 20 m away from the dismantle face during this period was 16.1 °C. The samples were vacuum-packed immediately after the collection and sent to ETH Zürich where the volumetric water content was determined in the laboratory (Plötze 2016). The results are summarised in Tab. 5-1.

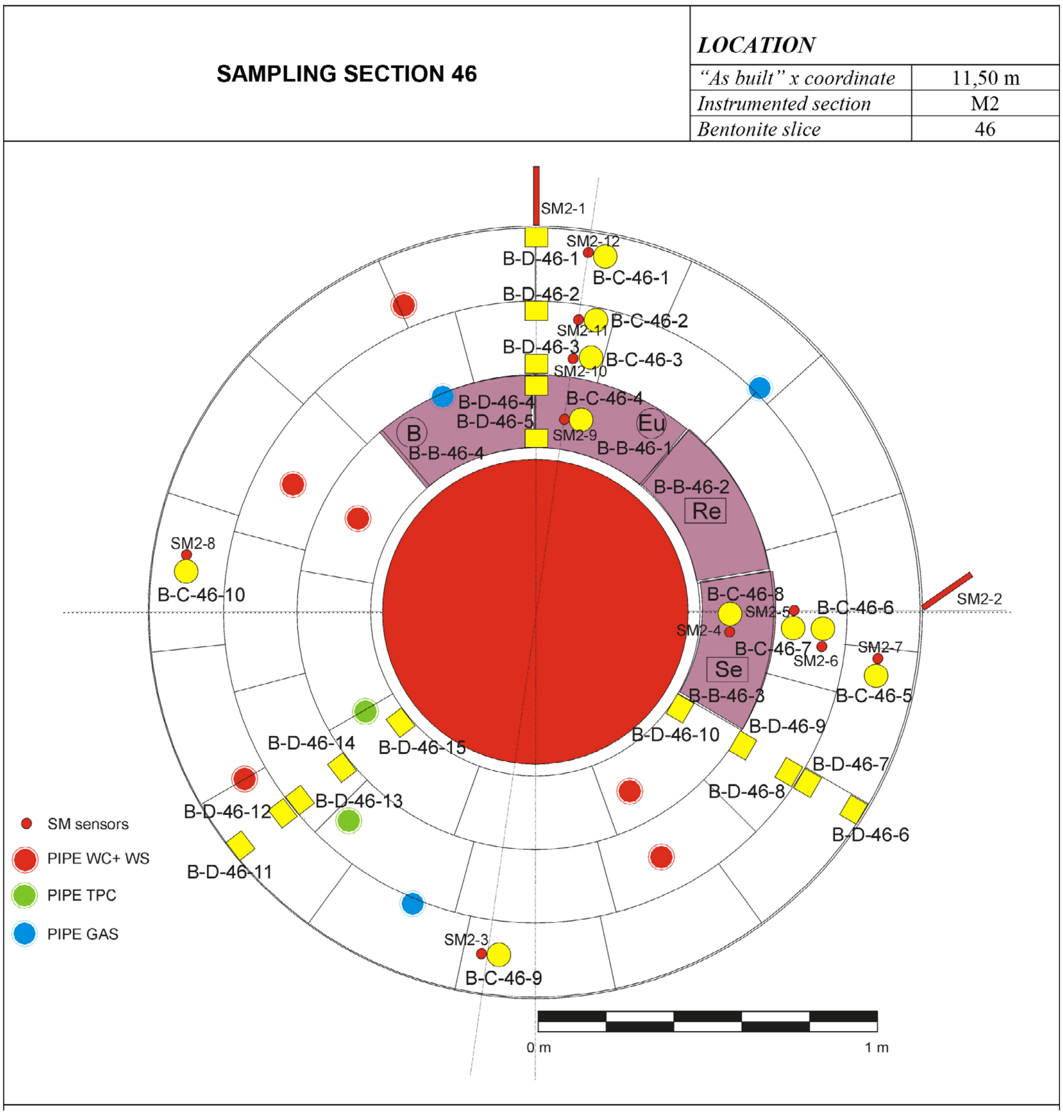


Fig. 5-1: Bentonite samples collected near the TDR probes (B-C-46-1 through 10 indicated with yellow circles).

Tab. 5-1: Sample analysis results and TDR/temp readings at corresponding locations.

TDR Probe No. (WT-M2-xx)	**TDR vol. water content***	**Temp** (°C)*	**Sample No. (B-C-46-xx)****	**Sample bulk density** (Mg/m^3)**	**Sample dry density** (Mg/m^3)**	**Sample vol. water content** ***	**Position**
3	-	-	9	1.982	1.732	0.433	6:00, out
4	0.384	17.1	8	1.917	1.723	0.335	3:00, in
5	0.403	-	7	1.953	1.715	0.408	3:00
6	0.480	-	6	1.956	1.706	0.426	3:00
7	0.455	-	5	1.904	1.602	0.483	3:00, out
8	0.417	16.1	10	1.966	1.708	0.440	9:00, out
9	0.611****	17.1	4	1.952	1.746	0.361	12:00, in
10	-	16.2	3	1.960	1.728	0.401	12:00
11	-	-	2	1.933	1.685	0.417	12:00
12	0.446	17.1	1	1.923	1.659	0.439	12:00, out

* Data on 24 June, 2015 just before the samples were collected. For those the data on June 24 are unavailable, last readings are given.
** Average values of two samples over two layers of bentonite blocks (Plötze 2016).
*** Volumetric water content was estimated assuming bentonite grain density of 2.7 Mg/m^3.
**** Likely overestimated due to damage to the TDR probe and signal loss after the heater shutdown.

Fig. 5-2 shows the bulk density of the samples as a function of distance from the heater surface. The bulk density ranged from 1.90 to 1.98 Mg/m^3 with no distinct trend.

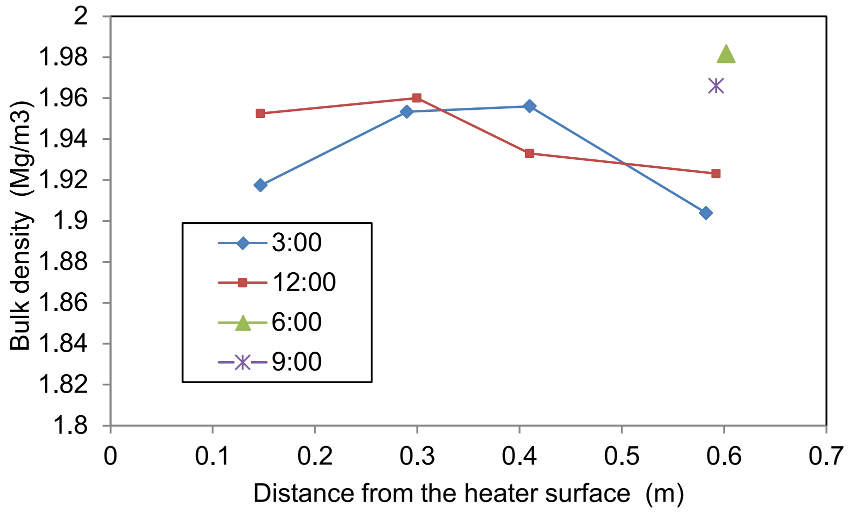


Fig. 5-2: Laboratory sample analysis results (Plötze 2016). Bulk density as a function of distance from the heater. The legend indicates the transect position.

Gravimetric water content in Fig. 5-3 shows, on the other hand, a clear gradient with a highest water content of ~ 0.3 near the tunnel wall and the lowest of ~ 0.2 near the heater surface.

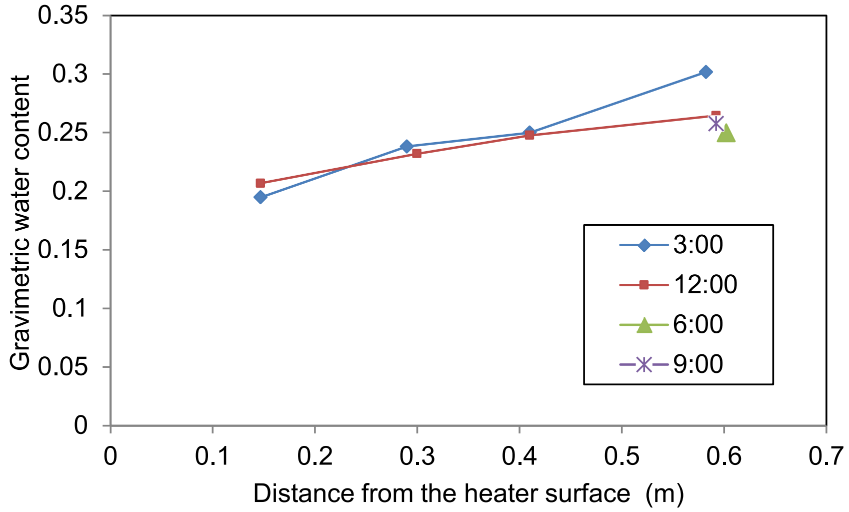


Fig. 5-3: Laboratory sample analysis results (Plötze 2016). Gravimetric water content as a function of distance from the heater. The legend indicates the transect position.

The dry density in Fig. 5-4 also showed a clear tend with the highest value of 1.75 Mg/m^3 near the heater surface and lowest of ~ 1.6 Mg/m^3 near the tunnel wall. The results from the 6 and 9:00 positions seem to be off-trend from the other two positions.

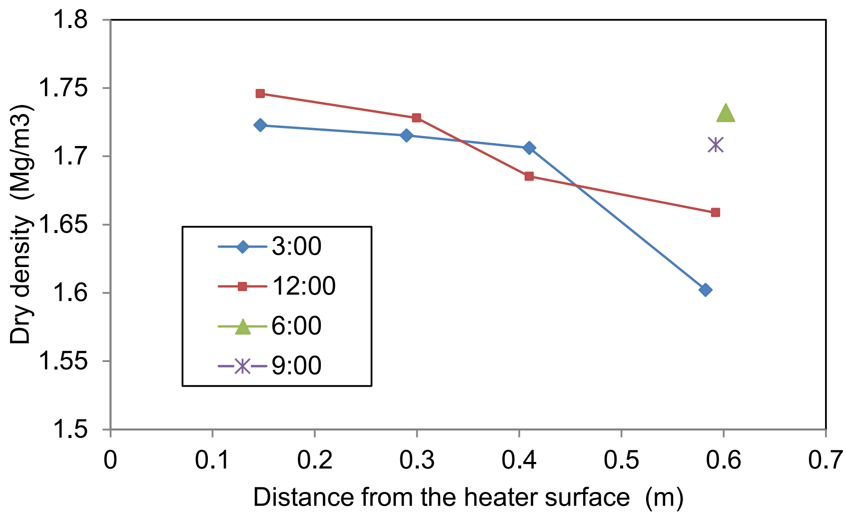


Fig. 5-4: Laboratory sample analysis results (Plötze 2016). Dry density as a function of distance from the heater. The legend indicates the transect position.

Based on the laboratory sample analysis results, porosity and volumetric water content were estimated assuming a bentonite grain density of 2.7 Mg/m^3 (Alonso et al. 2005). The porosity shown in Fig. 5-5 ranged from 0.35 to 0.41 with higher values near the tunnel wall.

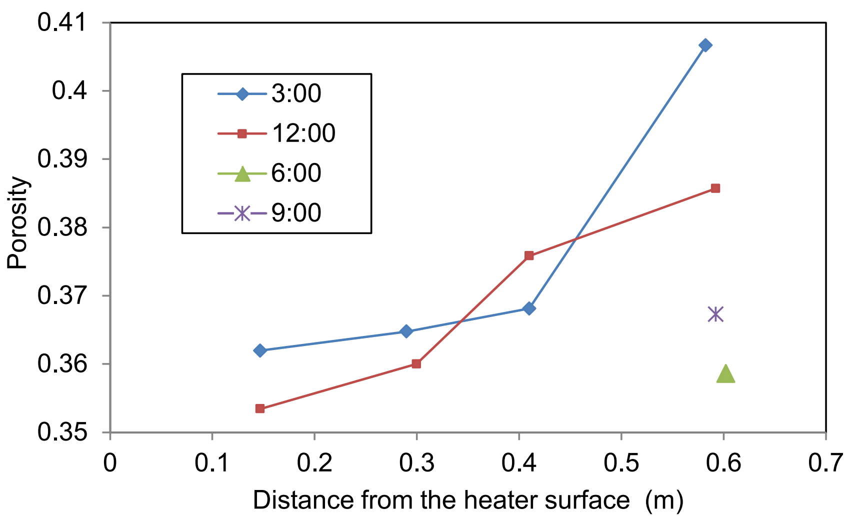


Fig. 5-5: Porosity as a function of distance from the heater (estimated from the results by Plötze 2016 using a grain density of 2.7 Mg/m3).

The legend indicates the transect position.

Fig. 5-6 shows the estimated *volumetric* water content of the samples. All the data points follow a similar linear relationship showing lower water content near the heater (approx. ~ 0.34) and higher water content near the tunnel wall (approx. ~ 0.45).

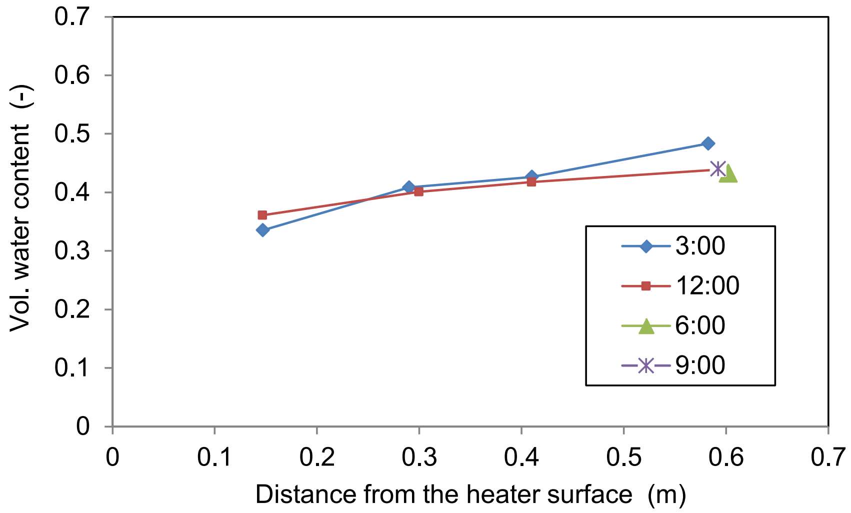


Fig. 5-6: Volumetric water content as a function of distance from the heater (estimated from the results by Plötze 2016 using a grain density of 2.7 Mg/m^3).

The legend indicates the transect position.

In Fig. 5-7, the TDR-estimated VWC values on April 24 (hot) and June 24 (cold) shown in Tab. 4-3 are compared. There is one outlier (TDR No. 9 near the heater at the 12 o'clock position) due to the overestimation described earlier. As noted with arrows, the VWC did change over this two month cooling period. During the partial dismantling in 2002, redistribution of water was observed likely due to vapour condensation (Huertas et al. 2006). The changes in VWC before and after cooling, however, seemed more distinct. It was suspected that the changes in VWC resulted largely from the long-term drift of the calibration including temperature correction.

The TDR-estimated VWC falls roughly in the range of the VWC of the samples in Fig. 5-6 except for the outlier due to the damage to the sensor. In the next section, the TDR-estimated VWC is further refined.

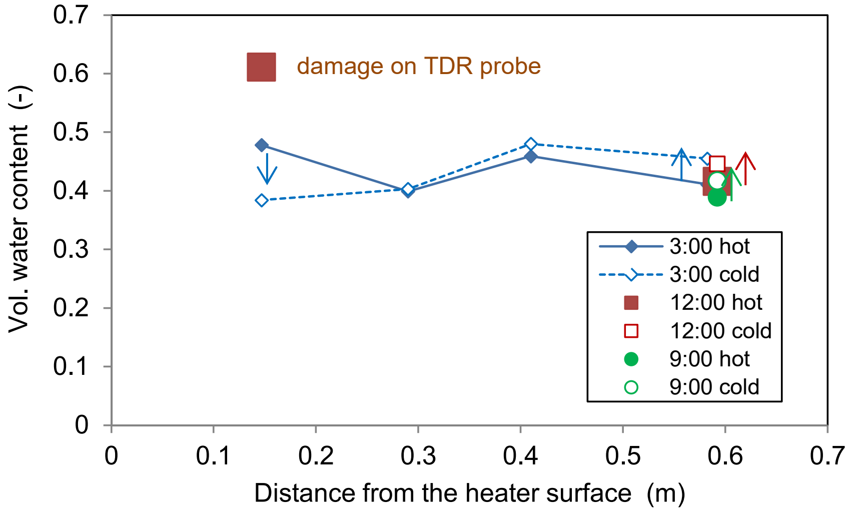


Fig. 5-7: TDR-estimated VWC values on April 24, 2015 (just before heater shut-off) and June 24, 2015 (samples were collected).

The legend indicates the transect position.

6 Re-scaling of TDR-measured volumetric water content

In the previous section, the VWC measured with the TDR probes in Section M2 were compared to the VWC values determined by laboratory analysis of the samples taken in the vicinity of the TDR probes. The TDR-measured VWC compared were those on June 24, 2015 when the temperature had come down. As in Tab. 4-3, the TDR-estimated VWC values did change after the heater was shut off on April 24, 2015. This change indicates that the temperature correction of the raw traveltime data to VWC had changed over the 18-year monitoring period and/or that the damage to the probes affected the signals. Therefore, the VWC shown in Fig. 4-3 can be further refined by re-scaling.

It has to be emphasised that the interpretation of VWC values in expansive materials such as bentonite is not as straightforward. A given gravimetric water content can correspond to different VWCs depending on the dry density of the bentonite. The same is true for the degree of saturation. In the case of the FEBEX in-situ test, exact dry density and gravimetric water content (from which VWC can be calculated) were measured only on three separate occasions:

1. At the beginning of the experiment where the initial VWC was 0.205 (Albert et al. 2003)
2. At the time of the first dismantling in 2002
3. At the time of the second dismantling in 2015

Using these exact VWC values, the TDR-estimated VWC shown in Fig. 4-3 was re-scaled as described in the following sections.

6.1 VWC measured around Heater #1 in 2002

The first dismantling was conducted only around Heater #1. Based on the sample analysis results (Villar 2006), the VWC values were computed for Sections 22, 27 and 31 that were in the vicinity of Section M1 and plotted in Fig. 6-1. The VWC near the rock wall had increased to about 0.45 whereas the innermost part near Heater #1 remained at the initial VWC of 0.205. The VWC distribution in the radial direction seemed to be well represented by a linear function which is also given in the figure.

It was then assumed that the moisture distribution in Section M2 (the section of interest in this report) at the same time was similar to that of Section M1 presented in Fig. 6-1.

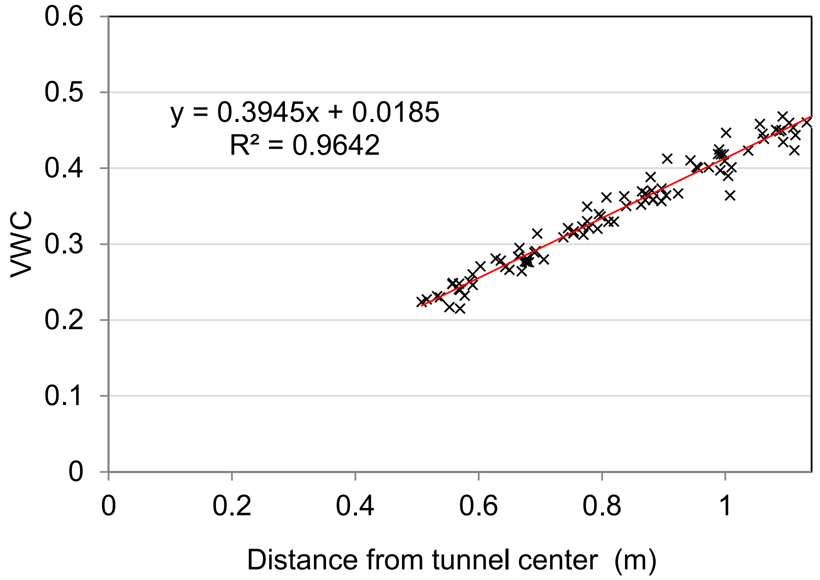


Fig. 6-1: Volumetric water content of samples around Heater 1 (Villar 2006).

6.2 VWC measured around Heater #2 in 2015

During the second dismantling of Heater #2, a set of sample analyses was also performed (Villar et al. 2017). Similarly, the VWC values were computed for Sections 45 and 49 that were in the vicinity of Section M2 and plotted in Fig. 6-2. The VWC near the rock wall was at about 0.45 as it was in 2002 whereas the innermost part near Heater #2 had increased approximately to 0.32. The VWC distribution in the radial direction seemed to be well represented by a linear function which is also given in the figure.

The data indicate that, after the dismantling in 2002, water kept migrating toward the heater and VWC increased from 0.205 to 0.32 over a period of 13 years.

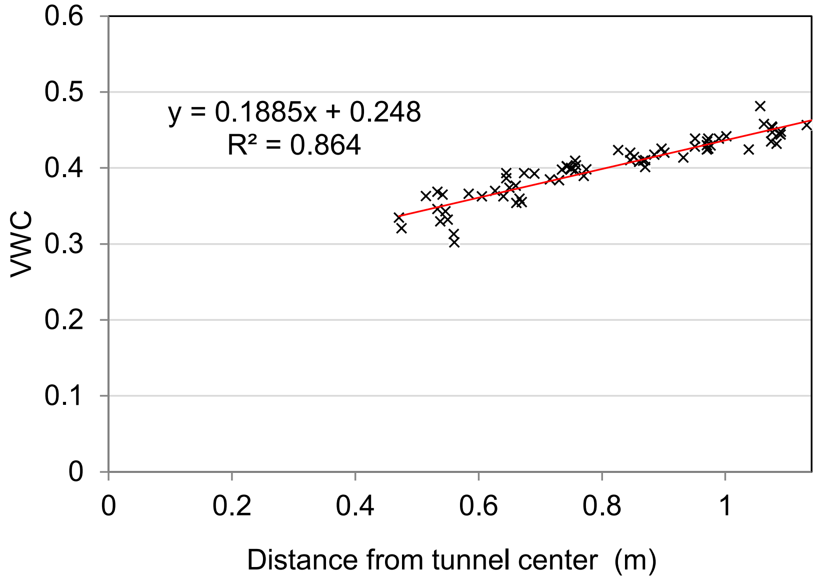


Fig. 6-2: Volumetric water content of samples around Heater 2 (calculated from Villar et al. 2017).

6.3 Re-scaled VWC around Heater #2

Based on the VWC data at different times presented above, and assuming that the VWC data near Section M1 shown in Fig. 6-1 are representative of those at Section M2 at the same time in 2002, the following conclusions can be drawn:

When the FEBEX experiment was started in 1997, the VWC of the bentonite blocks was 0.205 everywhere.

The radial distribution of VWC in 2002 was between 0.205 near the heater and 0.450 near the rock wall. The radial profile of VWR at a radius *r* was well expressed by a linear function VWC = 0.3945 *r* + 0.0185.

The radial distribution of VWC in 2015 was between 0.32 near the heater and 0.45 near the rock wall. The radial profile of VWR at a radius *r* was well expressed by a linear function VWC = 0.1885 *r* + 0.2480.

As noted earlier, the VWC data shown in Fig. 4-3 seem to have drifted due to unquantifiable changes in the temperature correction and/or the effect of damage to some of the probes over the long monitoring period. The exact values of VWC is known only in year 1997, 2002 and 2015. The VWC data were subjected to re-scaling so that their values at these three times satisfy the findings described above.

In particular, the VWC values in 2002 measured by the TDRs pass through the points estimated by "VWC = 0.3945 *r* + 0.0185" (*r* is the radial distance of each TDR). Similarly, the VWC values in year 2015 pass through the points estimated by "VWC = 0.1885 *r* + 0.2480". Fig. 6-3 through 6.5 shows the re-scaled VWC for each measurement transect.

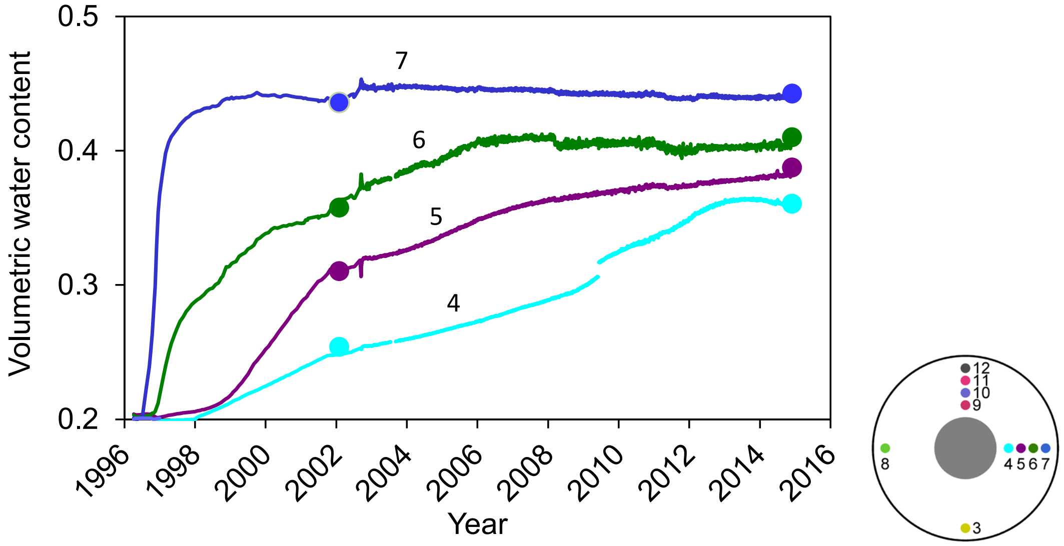


Fig. 6-3: Re-scaled VWC along the transect in the 3 o'clock direction.

The circles are the VWC estimated using the regression functions at the corresponding radial position.

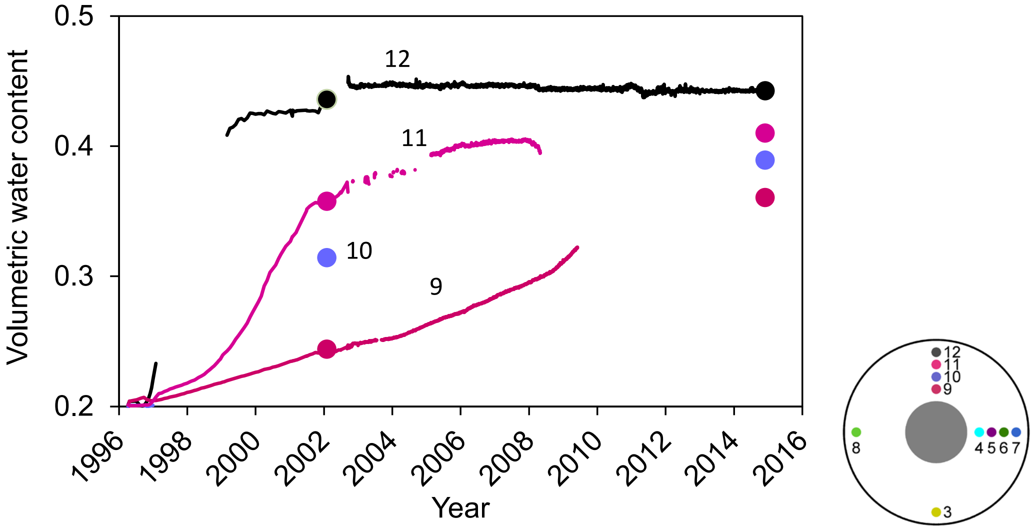


Fig. 6-4: Re-scaled VWC along the transect in the 12 o'clock direction.

Note that at No. 9, data after the overheating event in 2009 were not used due to erroneous behaviour of the sensor. The circles are the VWC estimated using the regression functions at the corresponding radial position.

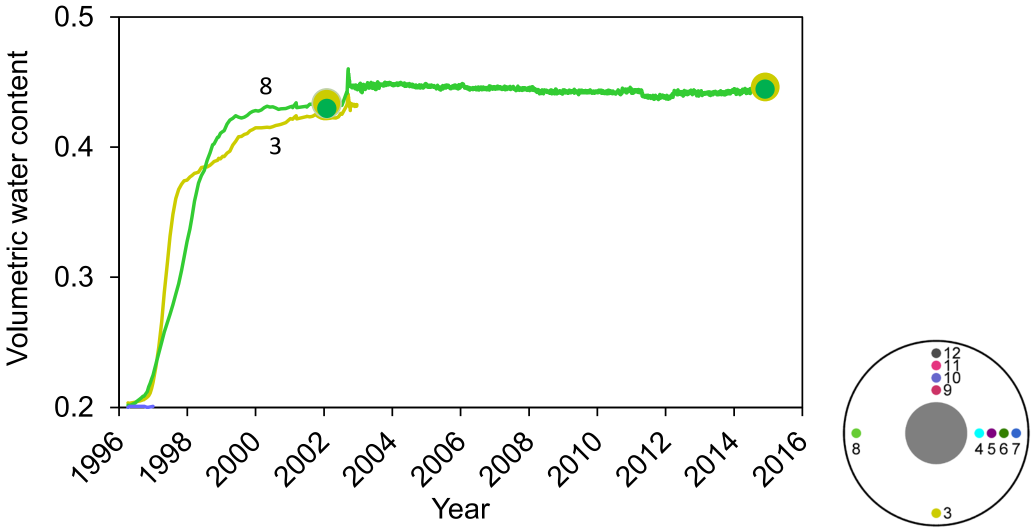


Fig. 6-5: Re-scaled VWC in the 6 and 9 o'clock directions.

The circles are the VWC estimated using the regression functions at the corresponding radial position.

The *re-scaled* VWC for all the TDRs in Section M2 is summarised in Fig. 6-6 together with the temperature evolution. Note here that the unrealistically high VWC at Probe No. 9 especially after the overheating event in 2009 was not used. The re-scaled time evolution of VWC can be considered as the best estimation of VWC over the 18-year monitoring duration.

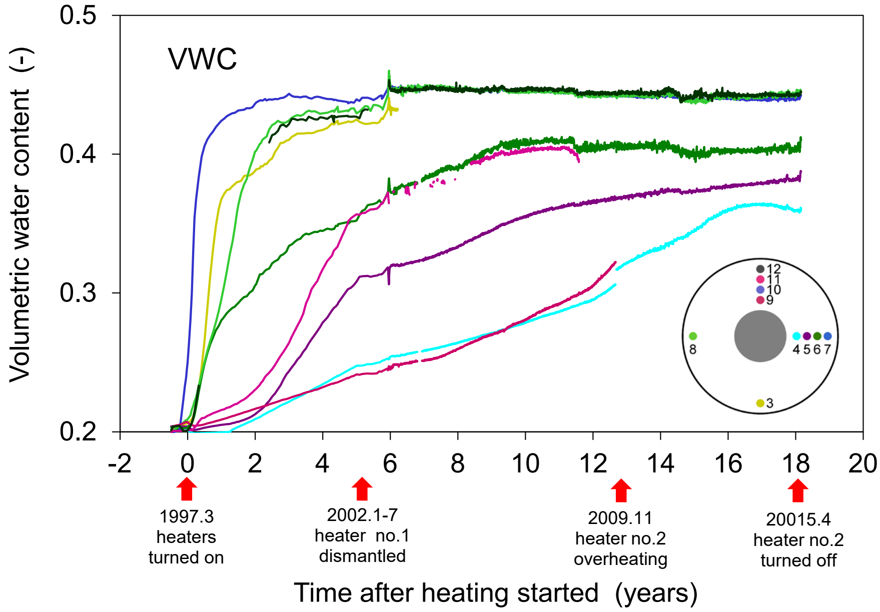
As noted in the early section, the temperature field reached a steady state a few months after the heaters were turned on whereas the moisture evolution took significantly longer.

The outermost block ring (probes No. 3, 7 and 8) absorbed water, swelled, and reached a VWC of about 0.44 within 1 – 2 years (saturation of 100 %, see Appendix C). The VWC increase at Probe No. 7 in the 3 o'clock transect took place earlier than the others.

The VWC values at the next set of probes 6 and 11 in the middle block ring stabilised at a VWC of about 0.4 (saturation of 100 %, see Appendix C) after 8-10 years. Probe No. 6 in the 3 o'clock transect showed a faster increase as observed in the outer ring.

Probe No. 5 installed at the inner part of the middle block indicated an arrival of water at about 2 years and the VWC stabilised at about 0.38 (saturation of ~ 95 %, see Appendix C) after 10 – 12 years.

The moisture migration toward the innermost block ring took significantly longer due to the large distance from the water-supplying tunnel wall as well as the heat from the heater which hinders the migration. As a result, the saturation increase at probes No. 4 and 9 were gradual and, at No. 4, VWC finally started to level off after about 16 years at a VWC of about 0.36 (saturation of ~ 90 %, see Appendix C).



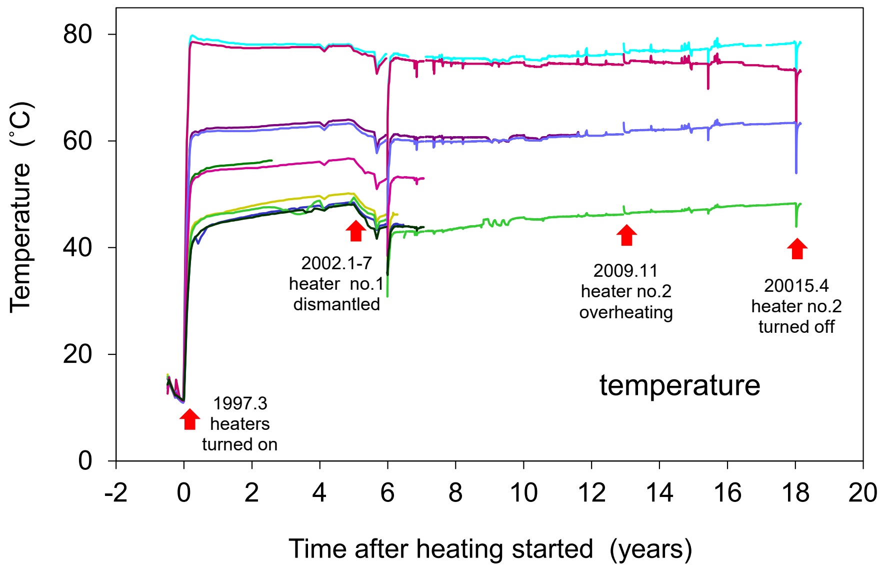


Fig. 6-6: Re-scaled VWC (top) and temperature (bottom) in Section M2 for the entire 18-year monitoring period.

Finally, the *re-scaled* VWC for all the TDRs in Section M2 is compared in Fig. 6-7 with the relative humidity (RH) evolution (Martinez et al. 2016, NAB 16-19). Although the position of the RH sensors was not identical to those of the TDR probes, a strong correlation is seen in these results, e.g., RH in the outer block ring reached saturation in less than two years, the middle ring took roughly eight years whereas the inner ring took significantly longer.

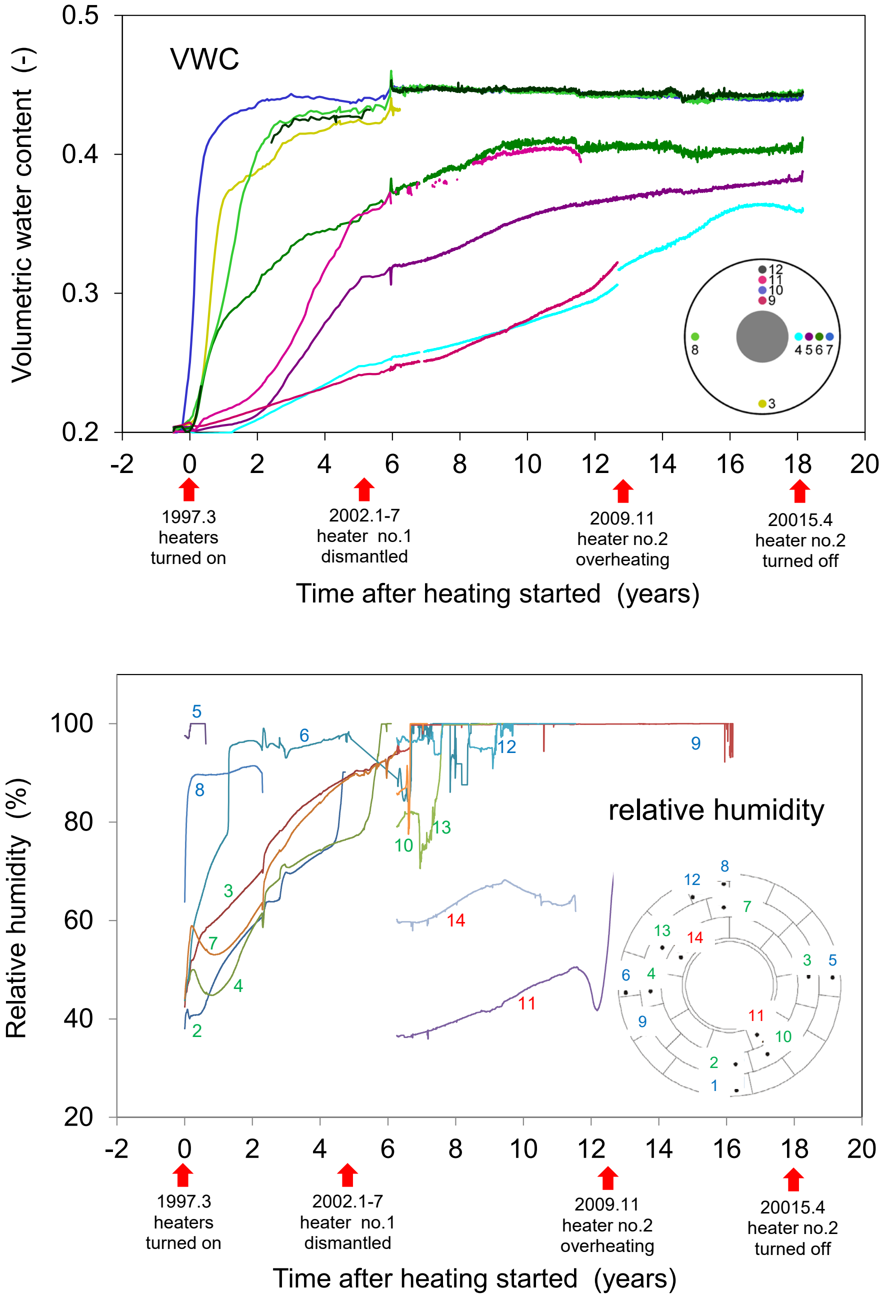


Fig. 6-7: Re-scaled VWC (top) and relative humidity (bottom, Martinez et al. 2016) in Section M2 for the entire 18-year monitoring period.

The RH sensor positions are not identical to those of TDR/temperature sensors. The RH sensor numbers in inner ring, middle ring and outer ring are denoted in red, green and blue, respectively.

7 Summary and conclusions

The FEBEX TDR probes in Section M2 (WT-M2-03 through 12) have been generating data on the evolution of VWC in the bentonite blocks around Heater #2 for 18 years (1997-2015). A few of the TDR probes and several temperature sensors failed during the course of the experiment. The TDR probes were retrieved in June 2015 and inspected in July 2015. The obtained data were closely analysed and interpreted based on the observations gathered from the TDR probe inspection.

The obtained VWC values were then evaluated and verified through a comparison with the laboratory sample analysis results. Finally, the TDR-estimated VWC, which seemed subject to sensor drift due to changes in calibration/temperature correction over the long term experimental duration, was re-scaled to match the available actual VWC of the samples. The key findings obtained through the monitoring, retrieval, inspection and re-scaling activities are summarised below.

Un-scaled TDR-estimated VWC

1. WT-M2-04, 05, 06, 07, 08 and 12 probes yielded final volumetric water content values in the range of 0.384 – 0.480 with a general trend of higher water content near the tunnel wall and lower values near the heater.
2. WT-M2-04 (15 cm from the heater) which showed a somewhat high final water content had a minor old crack on the surface coating.
3. WT-M2-09 (15 cm from the heater) which kept showing an increase in water content stopped yielding signals in late April, 2015 after the heater was shut off. The last water content estimated was 0.611 which did not match the sample results. This probe had a trace of water intrusion through the cracked coating film. The reading was likely affected by the moisture inside the probe.
4. In general, the TDR probes closer to the heater seemed to have been more affected or damaged by the heat from the heater. The surface coating film was more discoloured and cracked. The shear deformation seemed more on the probes in the inner ring and less in the outer ring. Swelling of the blocks might have been more uniform in the outer blocks.
5. The traveltime as well as VWC exhibited some changes between April 24, 2015 (just before the heater shut-off) and June 24, 2015 (when the samples were collected near the TDR probes). This was more pronounced for probes WT-M2-04 and 09 located close to the heater. This indicated that the calibration and temperature correction drifted over the longterm experimental duration.
6. More TDR probes in Section M2 (7 out of 10) survived than in Section M1 (3 out of 10). The coaxial cables in Section M2 were installed more loosely which likely contributed to the higher survival rate.

Samples analysis results

1. Bentonite samples were collected in Section M2 (dismantle Section 46) in the vicinity of the TDR probes for laboratory analysis. The results showed a general trend of high water content, high porosity, low density toward the tunnel wall.
2. VWC of the samples varied between 0.335 (near the heater) and 0.483 (near the tunnel wall) which matched well with similar results from adjacent Sections 45 and 49 (Villar et al. 2016) as can be seen in Appendix C.

Re-scaling of TDR-estimated VWC

1. The TDR-estimated VWC was further adjusted by using the outcome of laboratory volumetric water content analyses at the time of the two dismantling operations in 2002 and 2015. A set of sample analysis results for the 2002 dismantling from Sections 22, 27 and 31 near Section M1 were selected (Villar 2006). For the 2015 dismantling, data from Sections 45 and 49 near Section M2 were selected (Villar et al. 2016). In addition, a VWC of 0.205 was used as the initial condition according to Albert et al. (2003).
2. This re-scaling allowed the TDR-estimated VWC values to match the sample data VWC values at three different times.
3. The re-scaled VWC was then compared with the relative humidity (RH) measurement results (Martinez et al. 2016). The general trend/timing of RH reaching saturation at different distances from the heater is highly correlated to the evolution of VWC.

Overall conclusions

1. In general it can be concluded that the TDR probes have been generating valuable VWC data for more than 18 years under harsh conditions.
2. The readings from probes WT-M2-04 and 09 near the heater were likely affected by the cracks in the probe coating film. These cracks may have been caused by the overheating incident that took place in 2009. The event led to a temperature increase of 16 °C at the heater surface for about 62 hours and a 6.6 °C increase at the probes' position. Given the discontinuous increase in VWC recorded at the time of the overheating, this possibility cannot be excluded.
3. The TDR-estimated VWC presents the qualitative trend of its time evolution well. The quantitative accuracy of the VWC was, however, further refined by "re-scaling".

Recommendations for future VWC measurements

1. Due to the swelling and movement of bentonite blocks, the probes extending through multiple blocks should be designed to accommodate shear deformation. The probes used in FEBEX were able to deform with the blocks without losing their functionality.
2. The notable difference in the TDR probe survival rates in Sections M1 and M2 indicated that the loosely routed co-axial cable had a significantly higher durability against the swelling for a long duration. The RG213 low-loss co-axial cable survived well under the harsh conditions for a long term. The design of the connection between the co-axial cable and the probe could be improved for further strength.
3. The probes are calibrated before installation using a known VWC and density as well as standard materials with known dielectric properties such as air, water, glass beads, and

quartz sand. A temperature correction also needs to be taken into account. However, in a swelling material such as bentonite for the extremely long experimental duration as was the case at GTS, the density of the material changed as VWC changed, the state of the probes can also change due to damage. As calibration cannot be done for all possible conditions, it is recommended that the estimated VWC is refined when actual values become available. In this report, it was done via re-scaling using known VWC values from initial state and the two dismantling campaigns.

4. The reliability of the estimated VWC results can further be confirmed through comparison to other quantities such as relative humidity, water suction, swelling pressure, deformation depending on their availability and accuracy. In this report, the VWC was compared to relative humidity.

8 References

Albert, W., Weber, H., Meier, E. & Dubois, D. (2003): Grimsel Test Site. Febex II: Excavation of TDR probes, Section M1. Laboratory analyses of bentonite samples. New calibration + calculation of water content from TDR data. Unpubl. Nagra Interner Bericht NIB 03-03.

Alonso, E.E., Alcoverro, J., Coste, F., Malinsky, L., Merrien-Soukatchoff, V., Kadiri, I., Nowak, T., Shao, H., Nguyen, T.S., Selvadurai, A.P.S., Armand, G., Sobolik, S.R., Itamura, M., Stone, C.M. (2005): The FEBEX benchmark test: case definition and comparison of modelling approaches. International Journal of Rock Mechanics and Minings Sciences, Vol. 42, No. 5-6, pp. 611-638.

Bárcena, I. & García-Siñeriz, J.L. (2015a): FEBEX-DP (GTS) Full Dismantling Sampling Plan. Nagra Arbeitsbericht NAB 15-14.

Bárcena, I. & García-Siñeriz, J.L.(2015b): FEBEX-DP (GTS) Full Dismantling Test Plan. Nagra Arbeitsbericht NAB 15-15.

Bárcena, I., Fuentes-Cantillana, J.L. & García-Siñeriz, J.L. (2003): Dismantling of the Heater 1at the FEBEX "in situ" test. Description of operations. Enresa Technical Report 9/2003, Enresa, Madrid.

Enresa (1998): FEBEX Full-scale engineered barriers experiment in crytalline host rock: Bentonite – Origin, properties and fabrication of blocks. Publicación tecnica num. 05/98. Enresa, Madrid.

Fuentes-Cantillana, J.L. & García-Siñeriz, J.L (1998): "FEBEX Full-scale Engineered Barriers Experiment in Crystalline Host Rock. Final Design and Installation of the "In Situ" Test at Grimsel ". Enresa Technical Report 12/98, Enresa, Madrid.

Fuentes-Cantillana, J.L., García-Siñeriz, J.L., Franco, J.J., Obis, J., Pérez, A., Jullien, F., Alberdi, J., Barcala, J.M., Campos, R., Cuevas, J., Fernández, A.M., Gamero, E., García, M., Gómez, P., Hernández, A., Illera, A., Martín, P.L., Melón, A.M., Missana, T., Ortuno, F., Pardillo, J., Rivas, P., Turrero, M.J., Villar, M.V., Mingarro, M., Pelayo, M., Caballero, E., Cuadros, J., Huertas, F., Huertas, F.J., Jiménez de Cisneros, C., Linares, J., Bazargan-Sabet, B., Ghoreychi, M., Jockwer, N., Wieczorek, K., Kickmaier, W., Marschall, P., Martínez, M.A., Carretero, P., Dai, Z., Delgado, J., Juncosa, R., Molinero, J., Ruiz, A., Samper, J., Vázquez, A., Alonso, E., Carrera, J., Gens, A., García-Molina, A. J., Guimera, J., Guimaraes, L.do N., Lloret, A., Martínez, L., Olivella, S., Pintado, X., Sánchez, M., Elorza, F.J., Borregón, J.L., Canamon, I., Rodriguez Pons-Esparver, R., Fariña, P. & Farias, J., Huertas, F., 2000: FEBEX full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock Final Report. Enresa, Technical Report 1/2000.

Fuentes-Cantillana, J.L., García-Siñeriz, J.L., Obis, J., Pérez, A., Alberdi, J., Barcala, J.M., Campos, R., Cuevas, J., Fernández, A.M., Gamero, E., García, M., Gómez, P., Hernández, A., Illera, A., Martín, P.L., Melón, A.M., Mingarro, M., Ortuno, F., Pardillo, J., Pelayo, M., Rivas, P., Rodríguez, V., Turrero, M.J., Villar, M.V., Caballero, E., Jiménez de Cisneros, C., Linares, J., Martínez, M.A., Samper, J., Delgado, J., Juncosa, R., Molinero, J., Alonso, E., Carrera, J., Gens, A., García-Molina, A.J., Guimera, J., Guimaraes, L.do N., Lloret, A., Martínez, L., Elorza, F.J., Borregón, J.L., Fariña, P. & Farias, J. (1998). "FEBEX Full-scale Engineered Barriers Experiment in Crystalline Host Rock. Pre-operational Stage Summary Report". Enresa Technical Report 1/98, Enresa, Madrid.

García-Siñeriz Martinez, J.-L., Abós. H., Martínez, L.V., De la Rosa, C., Mäder, U., Kober, F. (2016): FEBEX DP: Dismantling of heater 2 at the FEBEX "in situ" test: Description of operations. Nagra Arbeitsbericht NAB 16-11.

Huertas, F., Fariñas, P., Farias, J., García-Siñeriz, J.L. Villar, M.V., Fernández, A.M., Martín, P.L, Elorza, F.J, Gens, A., Sánchez, M., Lloret, A., Samper, J., Martínez, M.A. (2006): "Full-scale Engineered Barriers Experiment. Updated Final Report 1994 – 2004" December 2006. Enresa, Technical Report 05-0/2006.

Marschall, P., Kickmaier, W., Kirchner, R., Meier, E. & Schubert, E. (1997): GTS/FEBEX: Water content measurements using Time Domain Reflectometry: Construction of probes, instrumentation of the site and data transfer. Unpubl. Nagra Interner Bericht NIB 96-80.

Martinez, V., H. Abós and J.L. García-Siñeriz (2016), FEBEXe: Final Sensor Report (FEBEX "in situ" Experiment). Nagra Arbeitsbericht NAB 16-19.

Plötze, M. (2016): FEBEX DP Bentonite characterization, IGT Report CL 1053/1, pp. 14.

Rey, M., Sanz, F-J. & Martínez, V. (2016): (AITEMIN) FEBEXe/FEBEX-DP Post-mortem analysis: sensors. Nagra Arbeitsbericht NAB 16-20.

Schlaeger, S., Sakaki, T., Kober, F. & Gaus, I. (2016): Grimsel Test Site: FEBEX-e Water content measurements using the TDR technique - Raw data report January 2014 to June 2015 Final report. Nagra Aktennotiz 16-706.

Villar, et al. (2017, in prep.): FEBEX-DP Postmortem THM/THC Analysis Report. Nagra Arbeitsbericht NAB 16-17.

Villar, M.V. & Iglesias, R.J. (2016): FEBEX-DP: onsite determinations report, Nagra Arbeitsbericht NAB 16-12.

Villar, M.V. (eds.) (2006): FEBEX Project Final report, Post-mortem bentonite analysis, Enresa publicación técnica 05-1/2006, pp 183.

Appendix A: Detailed photographic record of the TDR probes after their retrieval

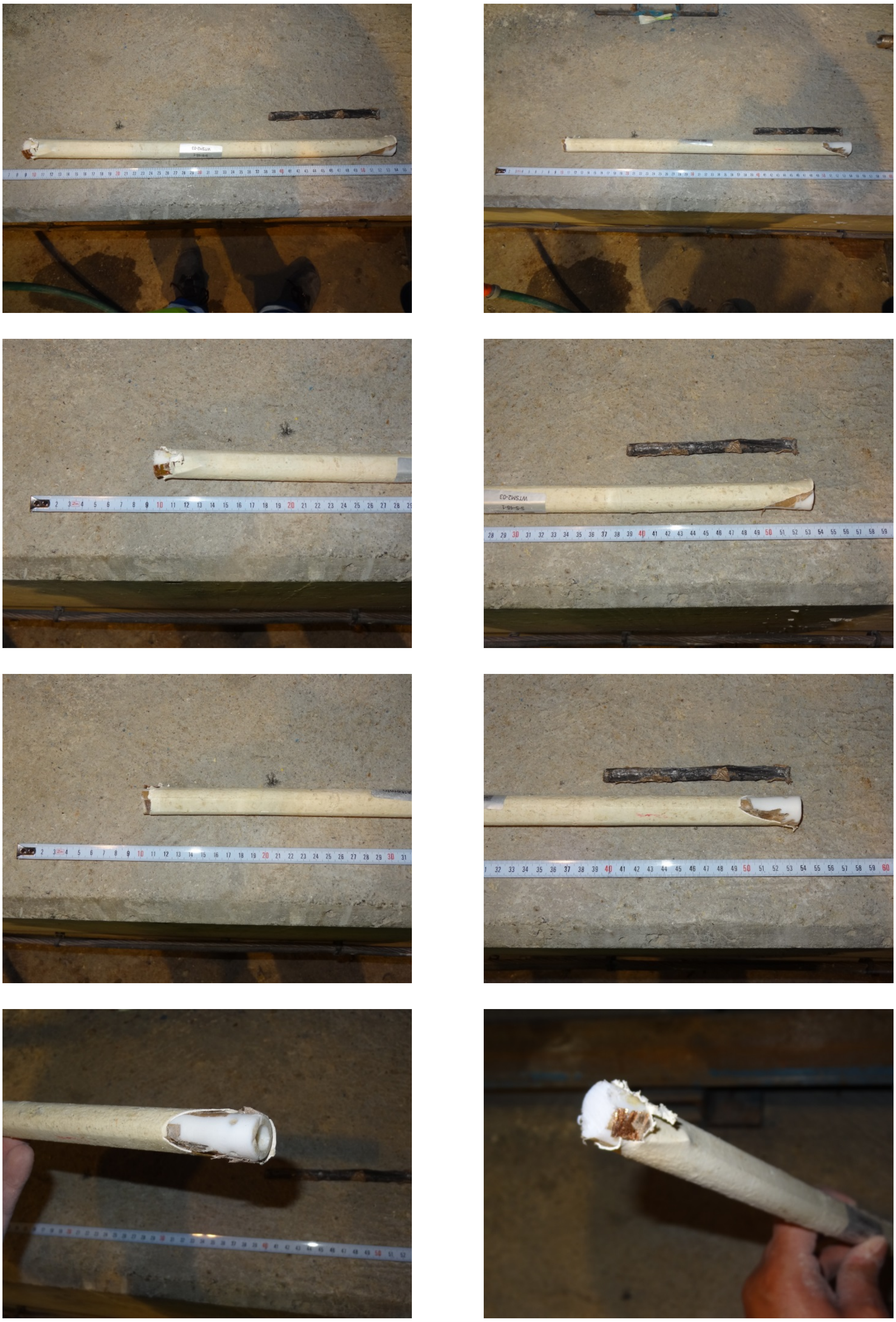


Fig. A-1: State of the bentonite TDR probe WT-M2-03 after retrieval.

Fig. A-2: State of the bentonite TDR probe WT-M2-04 after retrieval.

Fig. A-3: State of the bentonite TDR probe WT-M2-05 after retrieval.

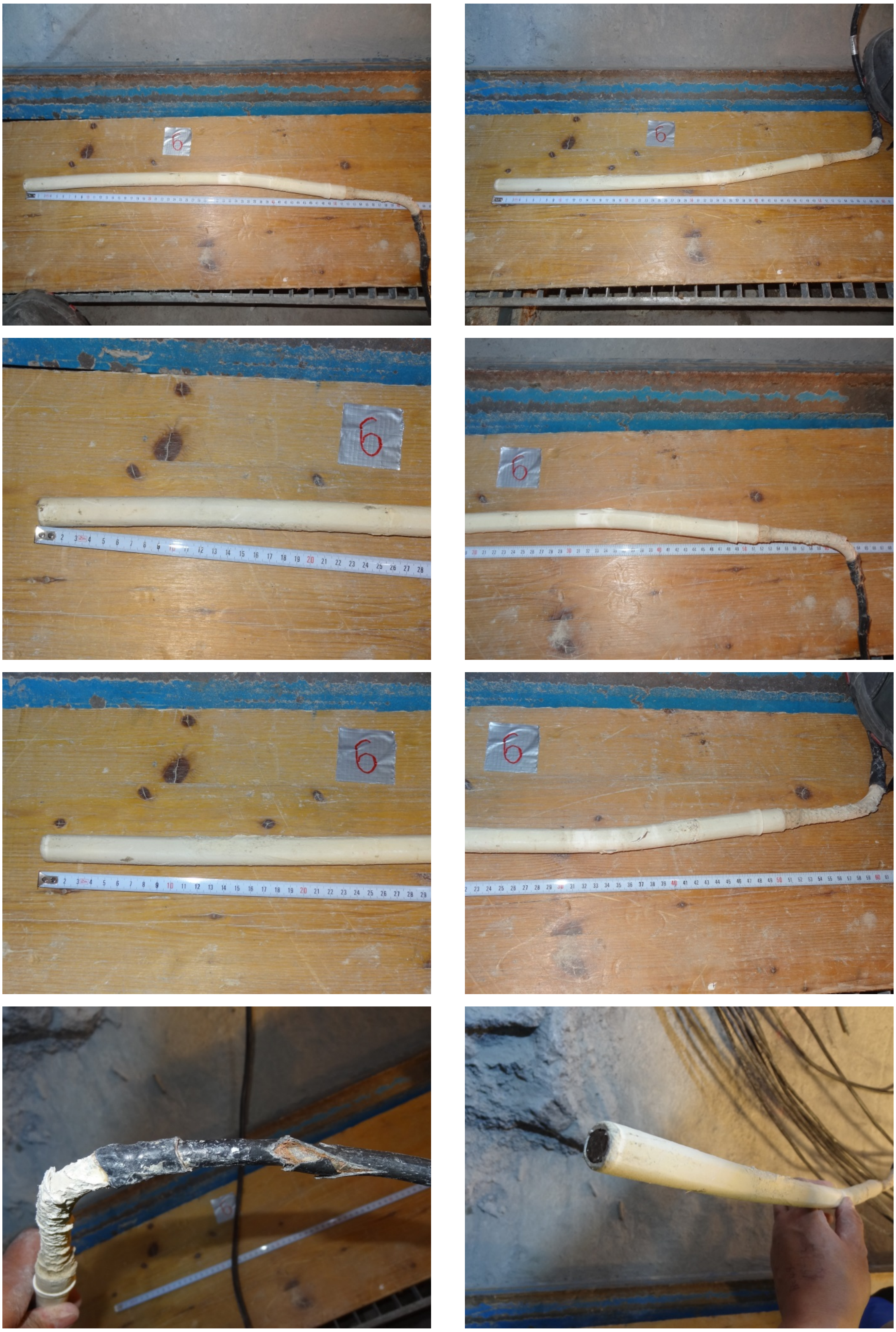


Fig. A-4: State of the bentonite TDR probe WT-M2-06 after retrieval.

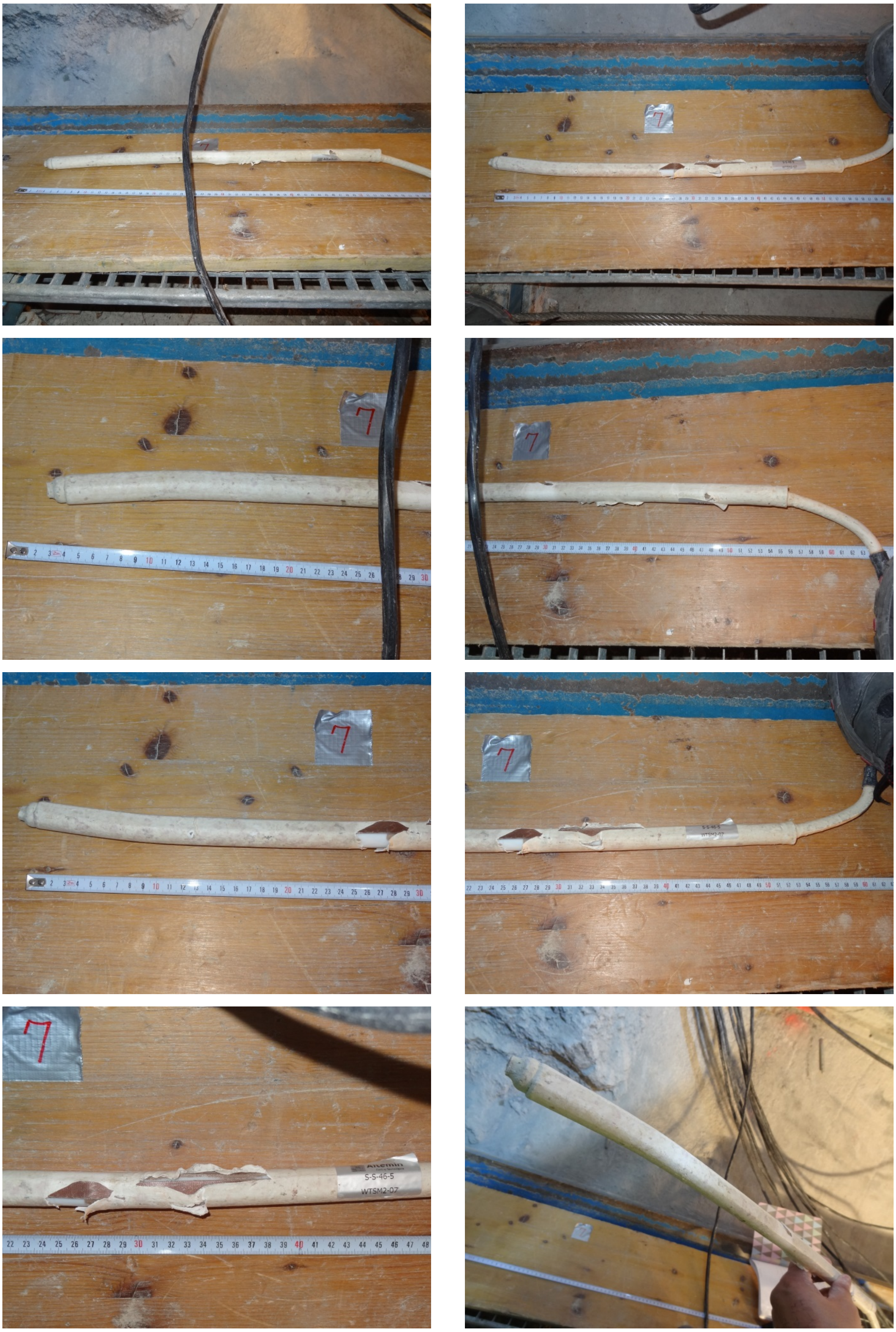


Fig. A-5: State of the bentonite TDR probe WT-M2-07 after retrieval.

Fig. A-6: State of the bentonite TDR probe WT-M2-08 after retrieval.

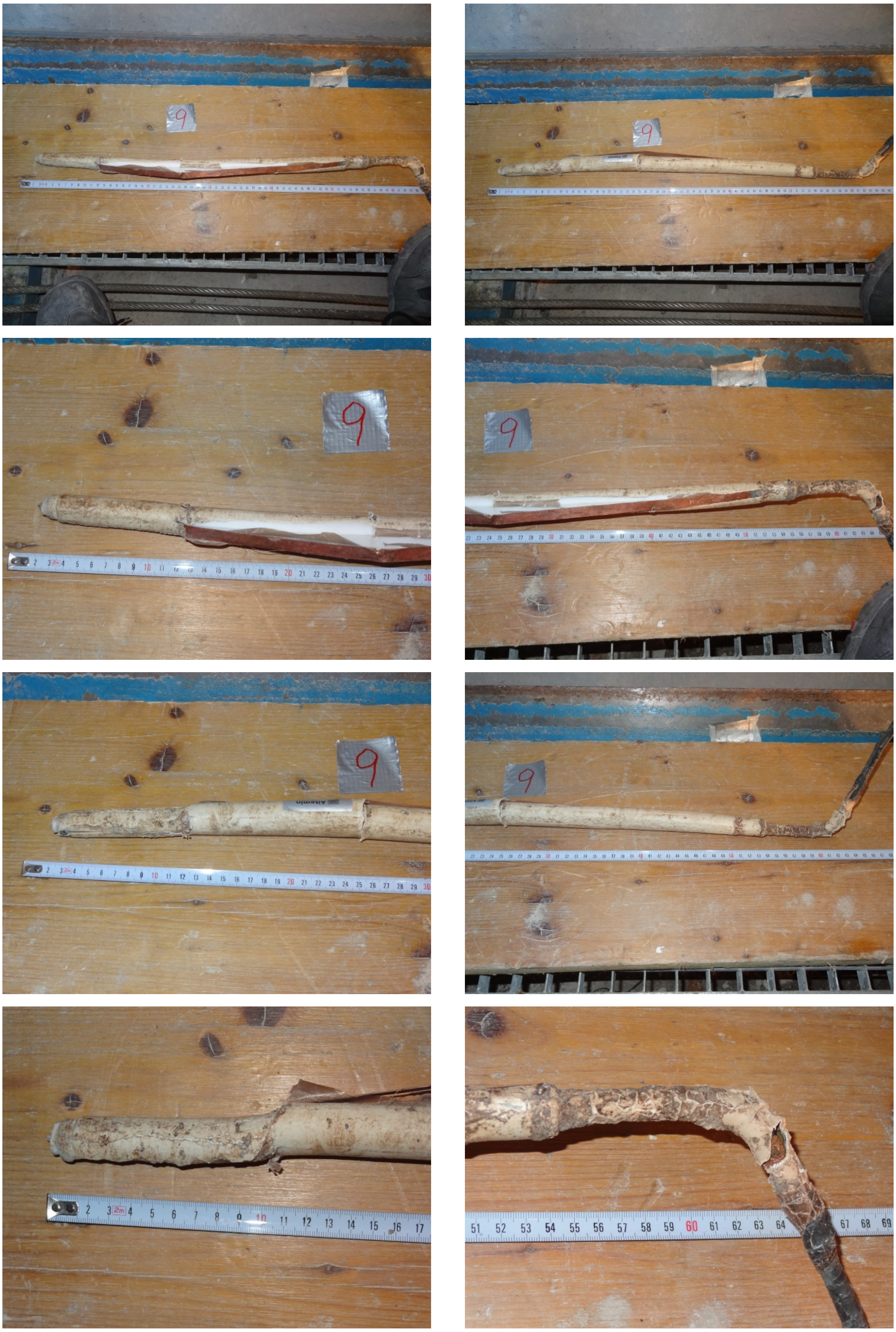


Fig. A-7: State of the bentonite TDR probe WT-M2-09 after retrieval.

Fig. A-7: Cont.

Fig. A-8: State of the bentonite TDR probe WT-M2-10 after retrieval.

Fig. A-8: Cont.

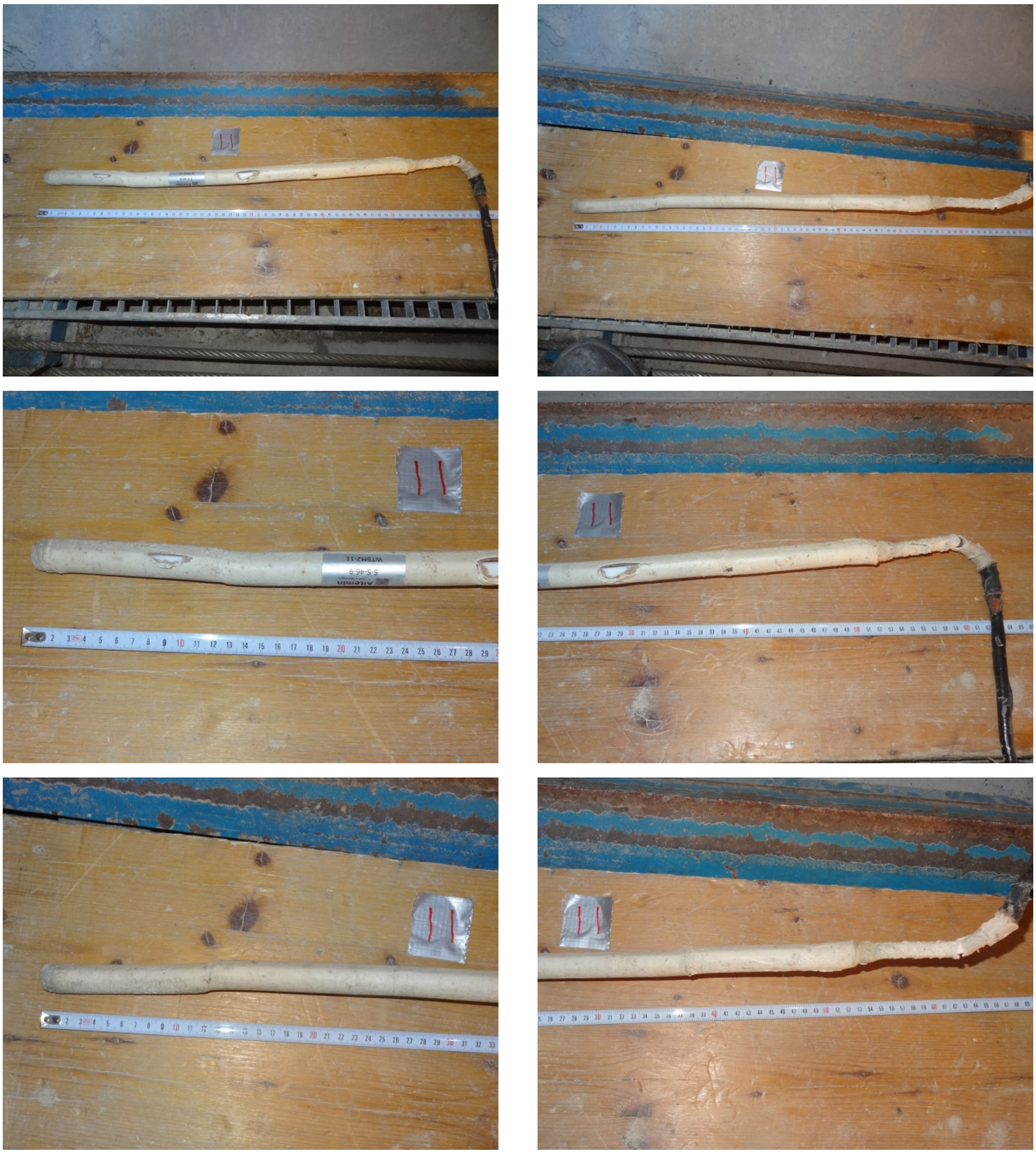


Fig. A-9: State of the bentonite TDR probe WT-M2-11 after retrieval.

Fig. A-9: State of the bentonite TDR probe WT-M2-11 after retrieval.

Fig. A-10: State of the bentonite TDR probe WT-M2-12 after retrieval.

Appendix B: Scaling performed at the time of the first dismantling in 2002

Only three out of ten TDR probes WT-M1-06, 09 and 11 installed at Section M1 still functioned at the time of the first dismantling in 2002. As temperature sensor No. 11 was not functional, only two TDR probes No. 06 and 09 were generating the necessary data for temperature correction.

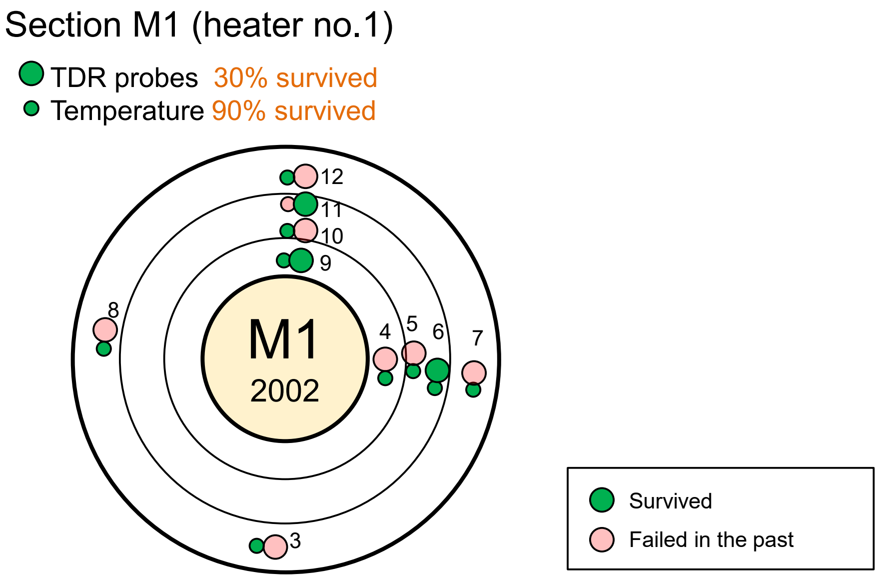


Fig. B-1: Status of the TDR probes and temperature sensors at Section M1 at the time of the first dismantling in 2002 (Albert et al. 2003).

A set of bentonite samples was collected from the vicinity of the TDR probes for laboratory analyses. In addition, the *initial* water content of an original bentonite block was re-investigated and found to be 0.205.

Fig. B-2 shows the time evolution of VWC together with the laboratory quantified VWC values near probes No. 06, 09 and 11 on the right side. The shown VWC was "scaled" based on the initial VWC of 0.205 and the laboratory determined VWC of the samples taken at the time of the partial dismantling. More information on the TDR results and scaling at the first dismantling can be found in Albert et al. (2003).

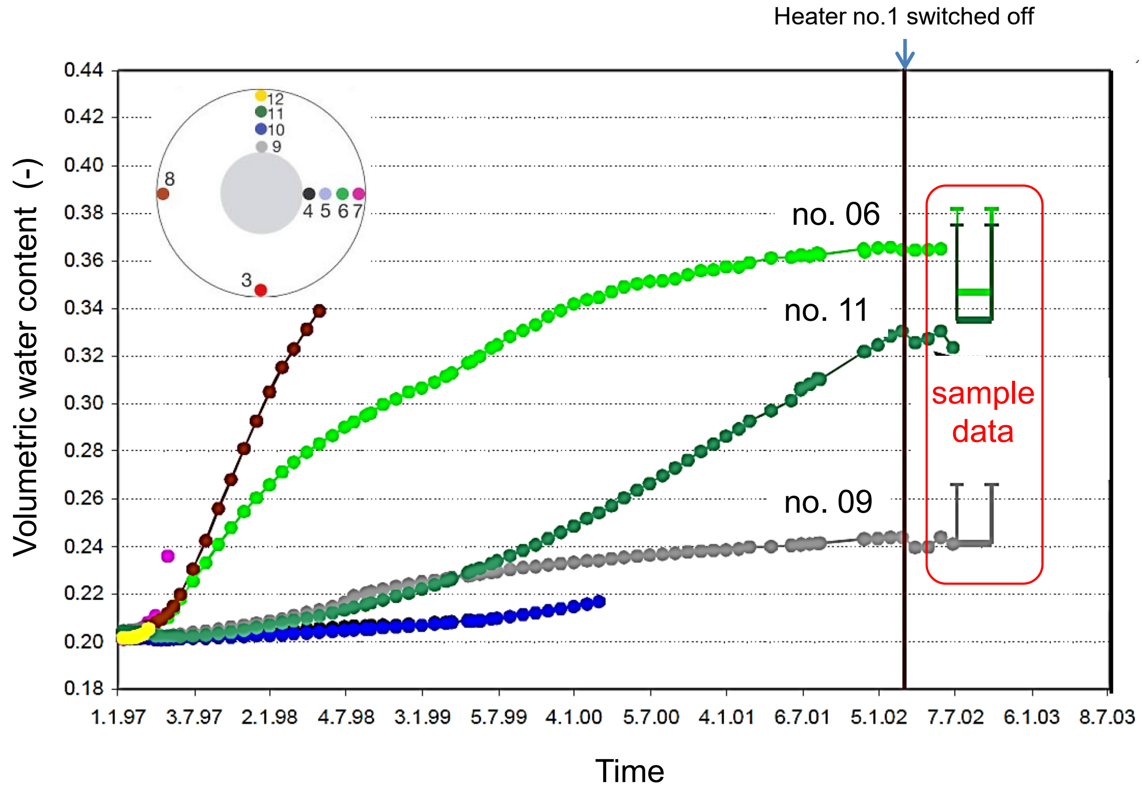


Fig. B-2: Volumetric water content evolution as well as the sample results at the time of the first dismantling in 2002 (figure taken from Albert et al. and revised 2003).

Appendix C: Sections for TDR measurement and sample comparison

Fig. C-1 shows the approximate position of the sections that were referred to in the main part of this report.

Sections M1 and M2 are those where the TDR probes were installed. Sample analysis results from Section 22, 27 and 31 around Heater #1 (Villar 2006) were used to predict the VWC near Heater #2 in 2002. The results for the samples taken from Sections 45 and 49 (Villar & Iglesias 2016) were used to compute VWC around Heater #2 in 2015. Finally, the actual VWC were used to re-scale the TDR-measured VWC.

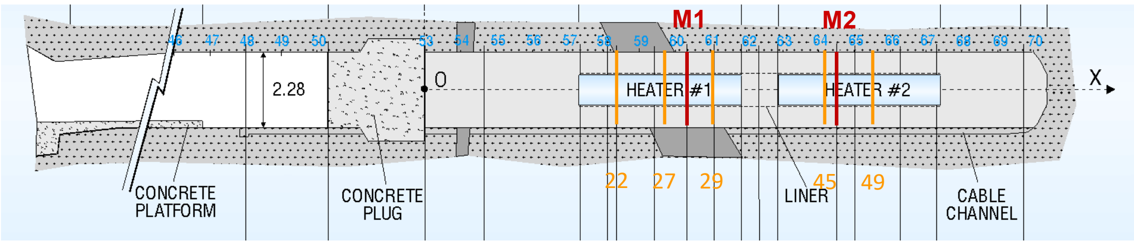


Fig. C-1: Position of sampling sections for the laboratory analyses (Villar 2006, Villar & Iglesias 2016).

Fig. C-2 through A3.5 respectively illustrate the changes in dry density, gravimetric water content, volumetric water content and degree of saturation in the radial direction between 2002 and 2015.

The dry density remains nearly unchanged after 2002 whereas moisture migrated further toward the heater. Near the heater, VWC of 0.32 in 2015 indeed shows that the bentonite is highly saturated (S = ~ 0.9) due to the higher density.

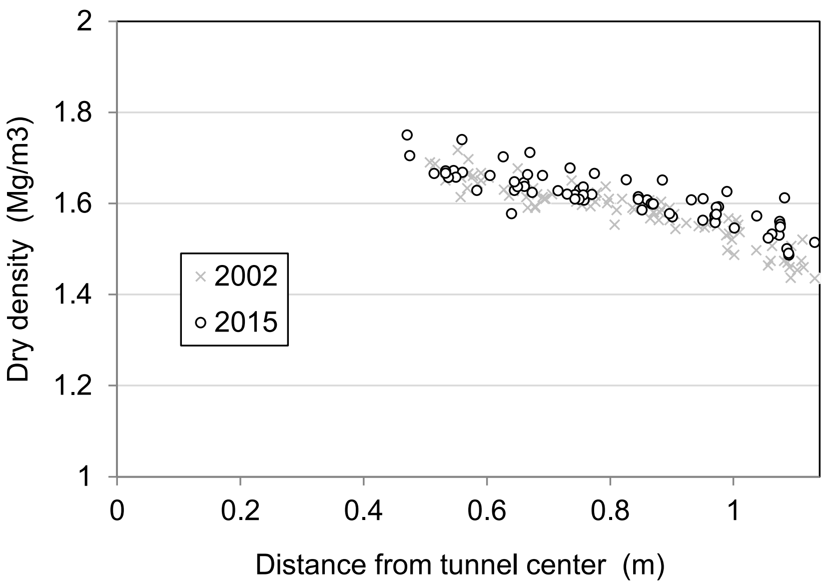


Fig. C-2: Sample analysis results in 2002 and 2015 (dry density).

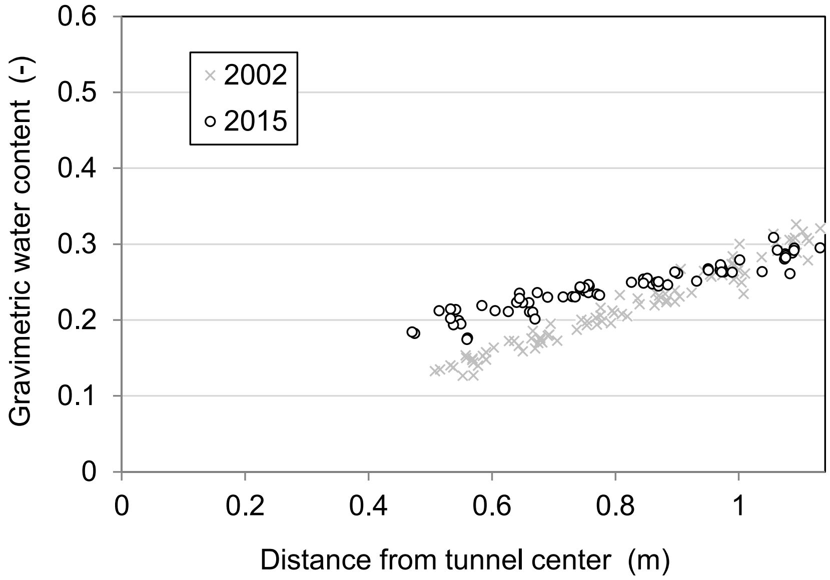


Fig. C-3: Sample analysis results in 2002 and 2015 (gravimetric water content).

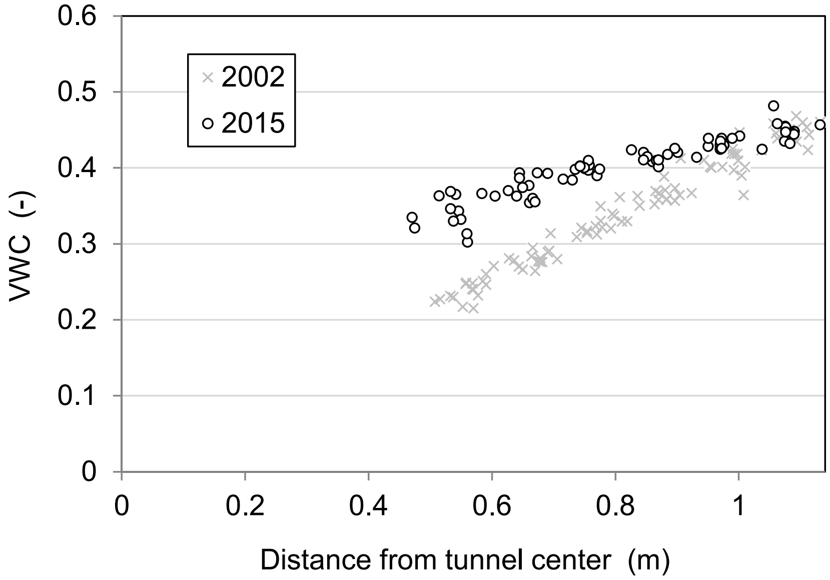


Fig. C-4: Sample analysis results in 2002 and 2015 (VWC).

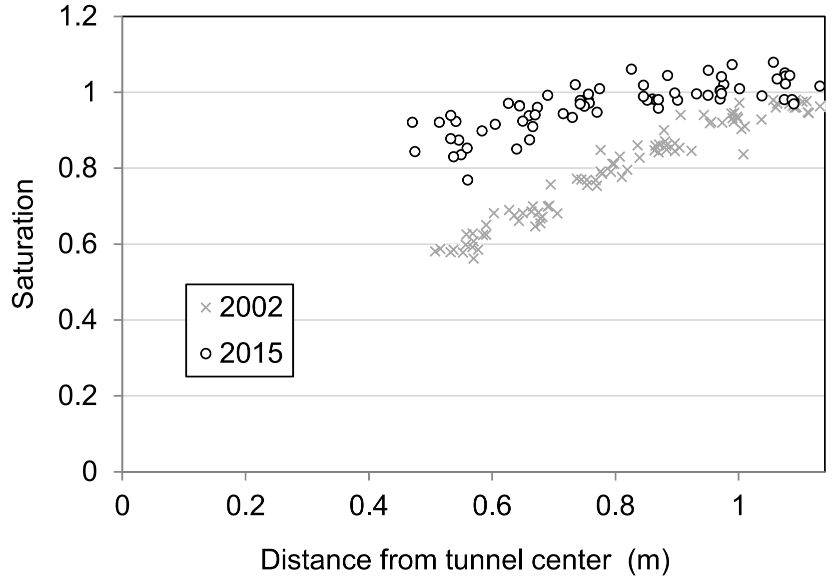


Fig. C-5: Sample analysis results in 2002 and 2015 (saturation).

Finally, Fig. C-6 presents the VWC of the samples taken in the vicinity of the TDR probes (denoted as Section 46) compared with those from adjacent sections.

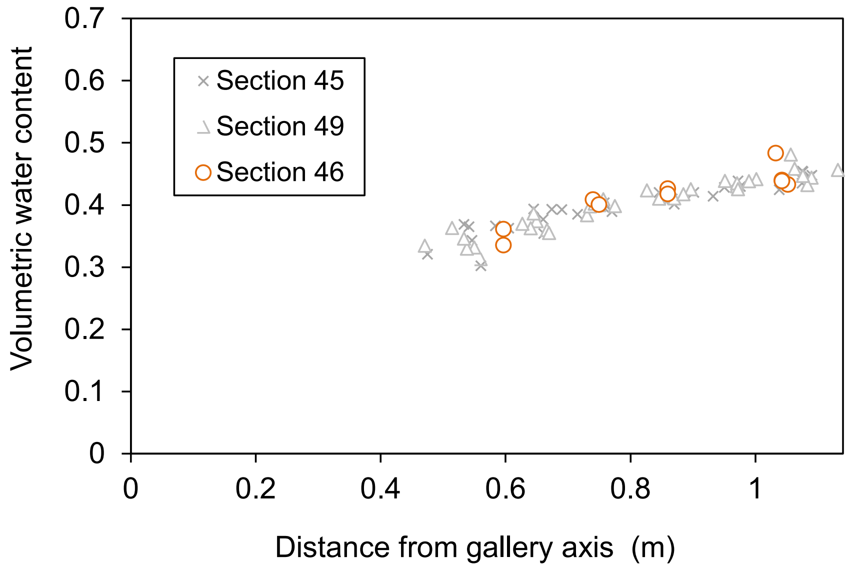


Fig. C-6: Sample analysis results in 2015 (VWC).

Analysis of Sections 45 and 46 was performed at CIEMAT (Villar & Iglesias 2016). Section 46 samples were analysed at ETH (Plötze 2016).