Contract Number: 622177

Deliverable D4.1: EBS monitoring plan - Spent fuel disposal concept at crystalline host rock

Work Package 4

Project Acronym	Modern2020
Project Title	Development and Demonstration of Monitoring Strategies and Technologies
Start date of project	01/06/2015
Duration	48 Months
Lead Beneficiary	Posiva
Contributor(s)	Edgar Bohner, Harri Kivikoski, Kalle Raunio, VTT Johanna Hansen, Mika Niskanen, Pasi Rantamäki, Posiva David Luterkort, Lars-Erik Johannesson, SKB
Contractual Delivery Date	Month 45 (February 2019)
Actual Delivery Date	31/05/2019
Reporting Period	3
Version	Final

<table>
<tr><td colspan="3">Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme</td></tr>
<tr><td colspan="3">Dissemination Level (for this draft of the report)</td></tr>
<tr><td>PU</td><td>Public</td><td>x</td></tr>
<tr><td>PP</td><td>Restricted to other programme participants (including the Commission Services)</td><td></td></tr>
<tr><td>RE</td><td>Restricted to a group specified by the partners of the Modern2020 project</td><td></td></tr>
<tr><td>CO</td><td>Confidential, only for partners of the Modern2020 project</td><td></td></tr>
</table>

History chart			
Status	Type of revision	Partner	Date
Draft 1	Draft for review by WP4 leader	Euridice	15/03/2019
Draft 2	Draft for review by Modern 2020 coordinator	Andra	
Final version	Version ready to submit to the database	Posiva	31/05/2019

Reviewed by:

This report has been reviewed according to the Modern2020 Quality Plan and the Deliverables Review Procedure therein. Formal review according to a Review Plan has been undertaken by Jan Verstricht (WP4 leader) and documented in Review Statements.

Approved by:

This report has been approved by:

- Jan Verstricht, Work Package 4 Leader, *31.5.2019*
- Johan Bertrand, the Modern2020 Project Co-ordinator (on behalf of the Modern2020 Project Executive Board), *31.5.2019*

List of Acronyms

ADR:	Azimuthal deep resistivity
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation damage zone
FEPs:	Features, events and processes
HLW:	High-level waste
ILW:	Intermediate-level waste
ILW-LL	Long-lived intermediate-level waste
LiDAR:	Light Detection and Ranging
L/ILW:	Low- and intermediate-level waste
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
Modern2020:	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal
PARS:	Phenomenological Analysis of Repository Situations
QA:	Quality assurance
QC:	Quality control
RD&D:	Research, development and demonstration
RSC:	Rock Suitability Classification
RTD:	Resistance temperature detector
THMCR:	Thermal, hydraulic, mechanical, chemical and radiological
URL:	Underground research laboratory
URCF:	Underground rock characterisation facility
WMO:	Waste management organisation
WP:	Work package
ZFD:	Discrete fracture zone, part of the excavation damage zone (in French)

List of Modern2020 Project Partners

The partners in the Modern2020 Project are listed below. In the remainder of this report each partner is referred to as indicated:

Partner name	Short name	Country
Agence Nationale pour la Gestion des Dechets Radioactifs	Andra	France
Amberg Infraestructuras	Amberg	Spain
Arquimea	Arquimea	Spain
AREVA NC SA[1]	AREVA NC SA	France
CeskeVysoke Uceni Technicke v Praze	CTU	Czech Republic
DBE Technology GmbH	DBETEC	Germany
Electicite de France	EDF	France
Agenzia Nazionale per le Nuove Tecnologie, L'Energia e lo Sviluppo Economico Sostenibile	ENEA	Italy
Empresa Nacional de Residuos Radiactivos S.A.	ENRESA	Spain
Eidgenoessische Technische Hochschule Zuerich	ETH Zurich	Switzerland
European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment	EURIDICE	Belgium
Galson Sciences Limited	GSL	UK
Institut de Radioprotection et de Surete Nucleaire	IRSN	France
Nationale Genossenschaft für die Lagerung radioaktiver Abfälle	Nagra	Switzerland
Nidia SRL	Nidia SRL	Italy
Nuclear Research and consultancy Group	NRG	The Netherlands
Nationale Instelling voor Radioactief Afval en Verrijkte Splijstoffen	NIRAS	Belgium
Posiva Oy	Posiva	Finland
Radioactive Waste Management Limited	RWM	UK
Radioactive Waste Management Funding and Research Center	RWMC	Japan
Svensk Karnbranslehantering AB	SKB	Sweden
Radioactive Waste Repository Authority	RAWRA/SURAO	Czech Republic

[1] In January 2018, Areva was renamed Orano.

Partner name	Short name	Country
Technicka Univerzita v Liberci	TUL	Czech Republic
Universiteit Antwerpen	UAntwerpen	Belgium
Goeteborgs Universitet	UGot	Sweden
Universite de Mons	UMons	Belgium
Universite de Limoges	ULim	France
University of Strathclyde	UStrath	UK
Teknologian tutkimuskeskus VTT Oy	VTT	Finland

Table of Contents

1 Introduction

1.1 Background

Posiva is creating an EBS monitoring plan, which is used to support the development of the monitoring strategy for EBS components in real repository for disposal of spent nuclear fuel. To demonstrate the applicability of EBS monitoring strategies for long-term monitoring setups there are several options as indicated in Modern 2020 WP2 Deliverables D2.1 and D2.2. As part of the Modern 2020 WP2 Posiva did made a study how to apply methodologies identified in Task 2.1 (Deliverable D2.1) when identifying EBS and host-rock monitoring parameters. The results of the work are reported in Modern 2020 D2.2 test case study for Posiva. The results points out that the direct monitoring of EBS's during operational phase is challenging, while the operational phase is short in comparison to long-term evolution of the EBS and the site, and therefore monitoring activities can only provide limited information on the long-term behaviour of the repository system.

The EBS concept and the disposal facility are designed in robust manner providing passive safety, without a need for monitoring or maintenance for EBS components during operational period or post-closure period. Due to this passive safety approach, mainly full-scale and/or in-situ tests with related QA/QC procedures can provide data on achievement on initial state and early evolution of EBS components and near field host rock.

The overall objective of Posiva's and VTT's work in this task is to demonstrate the applicability of EBS monitoring strategies for long-term monitoring setups used for the operation of spent fuel disposal activities in planned final disposal facility in Olkiluoto, Finland. It focuses on showing compliance with the safety case and covers primarily long-term monitoring aspects. It requires the planning and design of a monitoring system that meets the needs defined and identified in Modern 2020 WP2 and includes the newest technologies, developed in Modern 2020 WP3.

This deliverable D4.1 EBS monitoring plan will be used as a background for Posivas full scale tests and demonstrations planned to be performed by Posiva in its underground rock characterisation facility ONKALO™ or in future disposal facility. This Deliverable D4.1 describe a plan, which role is to show the needs how the monitoring could look like in a full scale test. The plan is based on a Posiva, VTT and SKB work and does represent the ideas for implementation. Since this plan is not executed within Modern 2020 project, its feasibility is not verified and therefore it cannot be used as such for the final monitoring programme of EBS components.

The first part of the work is to perform an investigation of the latest EBS monitoring technologies in order to identify the potentials, limitations and restraints of different available techniques, equipment's and/or procedures with respect to their use, applicability and functionality. The review will include an assessment of the technology readiness level (TRL).

The assessment work will focus in particular on the applicability of the selected techniques to be developed within WP3. A further aspect is the identification of optimal local point measurements (e.g. information from temperature or humidity sensors) to complement the information from applied spatial monitoring systems, like e.g. ERT (electrical resistance tomography).

The second part of the work focuses on the development and design of a monitoring plan. The new monitoring systems need to be designed with respect to long-term applications needed for the operational phase of the repository. In order to integrate these systems, the design and setup of the in-situ EBS system test, including traditional monitoring concepts, need to be adapted and modified to provide optimal monitoring conditions. An important objective for planning and design work is that the monitoring demonstration does not reduce the overall level of operational, environmental and post-closure safety of the facility.

The development of the monitoring plan within this project includes the design of a detailed instrumentation and test plan (sensor type, sensor location, wiring, etc.). The EBS monitoring plan is done for a section of tunnel and in this case the selected tunnel is located in ONKALO demonstration area, which is well studied and known area and host 4 demonstration tunnels, which will be used later for testing the EBS concept. This plan is made for a section with three deposition holes and around 50 meters of deposition tunnel located in crystalline host rock at the depth of 420 meters below the surface. The EBS concept does include engineered barriers like modified copper canister equipped with heaters, buffer bentonite with precompacted blocks and backfill with clay blocks and pellets and dome type plug with filter and seal layer. The Safety case work used as background for selection of parameters to be monitored is the same which is used for construction licence application during 2012 (Posiva 2012a).

Posiva Oy (Finland), SKB Ab (Sweden), and VTT Technical Research Centre of Finland (Finland) produced this plan jointly. The initial investigation of the EBS monitoring technologies is done in equal shares. In the second part of the work Posiva will focus on the general design of the monitoring plan and the performance modelling, and the SKB is describing the reasoning for processes to be monitored, while VTT will mainly work on technical aspects of the monitoring plan and the design of the instrumentation and test plan

1.2 Disposal concept and site to be monitored and general monitoring aspects

Posiva's safety concept for the geologic disposal of spent nuclear fuel is based on the KBS-3 design of the geologic repository and the characteristics of the Olkiluoto site, which have been studied since 1980's and monitored more than 20 years (Posiva 2012 b). In the KBS-3V design (Figure 1-1), the spent nuclear fuel assemblies are placed into copper canisters with cast iron load-bearing inserts, and the canisters are emplaced vertically in individual deposition holes bored in the floor of the deposition tunnels excavated in Olkiluoto crystalline host rock more than -420 meters below surface. The canisters are surrounded by a swelling clay buffer material that separates them from the bedrock. The deposition tunnels, central tunnels, access tunnel and other underground openings are backfilled with natural materials and plugged with manmade structures ensuring the favourable conditions for host rock and for the other engineered barriers. Engineered barrier system (EBS) includes canister, buffer, backfill and deposition tunnel plug, and closure, with its different backfill and plug types. Within Modern 2020 Task 4.1 the monitoring plan is compiled for one deposition tunnel like conditions or more detailed to a section of deposition tunnel including canister, buffer and backfill. The same basis for an EBS plan can be used to monitor also in-situ or full scale tests of EBS concept.

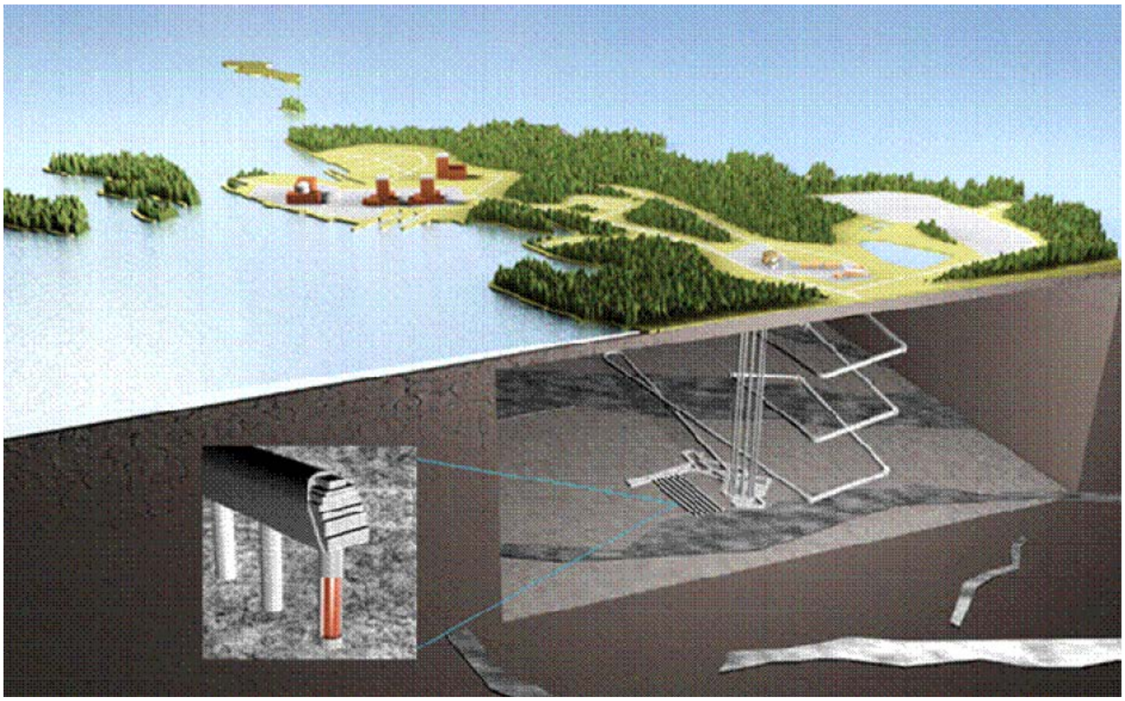


Figure 1.1. KBS-3 concept for engineered barrier system for Olkiluoto host rock.

In this report the EBS monitoring plan is compiled for an illustrative deposition tunnel using real site information and component specification from Posiva plans for final disposal of spent nuclear fuel. The site information is gathered from Posiva's ongoing site investigations and monitoring programme and models for EBS component behavior.

Posiva's current monitoring programme (Posiva 2012b) concentrates to follow up the site properties and changes in those caused by disposal facility construction activities. Later on the follow up of influences caused by disposal activities are added to the programme and therefore the monitoring of engineered barriers are handled within the Posiva monitoring programme. The monitoring of EBS components are still in R&D phase and the plans are produced as part of the operational monitoring programme, which is planned to be ready by the end of 2020. The current monitoring programme at Posiva includes the following five sub-sections:

- Hydrogeochemistry
- Rock mechanics

- Surface environment
- Hydrology and hydrogeology
- EBS-monitoring (under development).

This report concentrates on EBS component monitoring and considerations how EBS components can be monitored. The report does use the background from other monitoring areas for describing the site, and utilize the existing monitoring process used at Posiva.

1.3 Objectives and delimitations of this Report

The main objectives of the EBS monitoring plan are:

a) to get and overview on available methods and sensors feasible to be used in underground conditions to achieve the readiness level required for use of method in real systems;
b) to describe “Repository monitoring” as defined in the European Commission project Modern2020: Monitoring during the operational period to support decision making and to build further confidence in the post-closure safety case (Modern2020 D2.2). How the parameters for monitoring related to this were chosen is described in Chapter 2:
c) to develop further the monitoring strategy for EBS components, by understanding the limitations and constraints of using proposed or selected methods and to distinguish the methods between real operational conditions and tests conditions.

The quality control and the quality assurance of the rock excavations and the EBS are not included in the monitoring, but they are often used in order to verify that the components and production fulfils the requirements and works as a supporting element for EBS Monitoring plan. The use of monitoring data for conventional environmental controls or workers safety is not included in this monitoring program. Radiation aspects are not included in the monitoring plan. They are part of the radiation protection programme, which will be used in encapsulation facility and in underground disposal facility and are based on existing and tested methods and procedures. The chemical interactions between the engineered barrier components are not suitable to monitor in a full scale test and this is not included in the EBS monitoring plan. The reason is that there are extra disturbances due to sensors, heaters etc. Other more precise tests to measure corrosion or other processes in situ, e.g. the Minican tests performed by SKB (Aggarwal et al. 2015) are more suitable for addressing these issues. Monitoring of chemical interactions between disposal components is not part of the monitoring programme, it is more part of the performance assessment studies. Tests and demonstrations might serve as a platform for studying boundaries and interactions between EBS components and host rock. The monitoring programme might give background information on conditions to be able to study the interactions. The test set up needs to be considered carefully if chemical interactions will be analysed. In case chemical interactions need to be studied in full scale the monitoring information (like pressure, temperature, moisture conditions, groundwater composition from nearby) are essential. Therefore, the full scale monitoring at a site might have also a role to give the boundary conditions for different tests.

This report describes a suitable monitoring programme for fulfilling the listed objectives. This report concentrates on few selected methods, which have been developed as part of the Modern 2020 WP3.

This report does propose the main processes to be monitored and the programme to implement monitoring based on ideas from earlier tests and demonstrations done in different organisations. The proposal is not binding and the actual monitoring programme content and extent have other boundaries as well to take into consideration.

2 Rationale for chosen monitoring parameters

2.1 Screening of parameters for monitoring

A large part of Posiva's work regarding monitoring has been made after site selection for spent nuclear fuel disposal 2001. The monitoring programme has developed further from the baseline conditions first from surface and when excavations have progressed also from ONKALO™. Posiva has followed closely the international co-operation in the field of monitoring ex. European Commission Seventh Framework programme MoDeRn (2015) Monitoring Developments for Safe Repository Operation and Staged Closure, available at: http://www.modern-fp7.eu/ [20180221] and its continuation Horizon 2020 project Modern2020 (Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal). So far, Posiva has concentrated on site monitoring and since the changes in Safety authority guidance (YVL D.5 published in 2013) also the establishment of a research and monitoring programme for the construction and operation of the disposal facility shall include the monitoring of the performance of engineered barriers.

The Radiation and Nuclear Safety Authority in Finland (STUK) published the latest version of D.5 guidelines 13.2.2018. Chapter 5 (Planning and design of the disposal facility and disposal operations) describes among other the monitoring needs in the following way:

"During the construction and operation of the disposal facility, a research and monitoring programme shall be executed to ensure that the site and the rock to be excavated are suitable for disposal and to collect supplementary information about the safety-relevant characteristics of the host rock and the performance of the barriers. This programme shall at least include:

a. the characterisation of the rock volumes intended to be excavated;

b. the monitoring of rock stresses, movements and deformations in rock surrounding the emplacement rooms;

c. the hydrogeological monitoring of the host rock surrounding the emplacement rooms;

d. the monitoring of groundwater chemistry;

e. the monitoring of the performance of engineered barriers; and

f. the monitoring of surface environment." (YVL D.5 Nuclear Safety Guidance, Chapter 5, Clause 506)

The overall aim of the Modern2020 Project is to provide the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account requirements of specific national programmes.

As a part of this the Modern2020 project a Screening Methodology to provide guidance on the steps that a WMO may take in identifying and managing a list of repository monitoring parameters was developed, see Figure 2.1. Seven test cases where the screening methodology was tested were run. One of the test cases was Posiva’s 2012 safety case for disposal of spent fuel in crystalline rock based on the EBS concept (Posiva 2012c).

The work with application of the screening methodology within Modern 2020 should be considered as a training exercise and not as Posiva statements. The work carried out is comprehensive and considers what is suitable to monitor in a full scale test. It is hence used as a background to set the rationale for Posiva’s planned Full scale test of EBS system called FISST (Full scale in situ system test) monitoring programme.

Posiva established a working group to perform screening using the Modern2020 Screening Methodology, and developed a template for recording the results. Posiva’s safety case for the spent fuel repository at Olkiluoto was being updated at the time of the test run, therefore most information and references supporting the test case are from the earlier TURVA 2012. However, updated requirements, where available, were used as input.

The starting point for the screening was the performance targets set for each component of the EBS within Posiva’s requirements management system. These performance targets have been defined in such a way that, if they are met, the safety functions will be fulfilled.

For each performance target, the relevant EBS component was identified, together with one or more relevant process(es). An assessment was then made of whether there is relevance and value for post-closure safety. One or more parameter(s) that could be used to monitor each process were identified, and a high-level, qualitative expected evolution defined for the process/parameter(s) in question. A short description of how monitoring could be done was then developed (if several options exist, all were described), and technical feasibility assessed for each option (recorded as “yes” or “no” with associated discussion). An overall assessment of whether the parameter should be monitored was then determined, together with identification of key uncertainties and how they can be resolved, and discussion of how the monitoring results could be used to elucidate EBS behaviour.

Results are presented in the test case report in three tables relating to different EBS components:

- Canister, for which six performance targets were considered.
- Buffer, for which eight performance targets were considered.
- Backfill, including the deposition tunnel plug, for which five performance targets were considered.

Once each performance target was screened, the resulting processes and parameters were compiled in a table listing the processes of relevance to the performance targets, associated parameters of interest and, for each parameter the result of the screening (Table 2.1)

- The parameter is parked.
- The parameter will be investigated through quality assurance (QA)/quality control (QC), full-scale test/demonstrator, or in situ single component tests.

- The parameter will be monitored during the operational phase.
- For the canister, buffer and backfill, all parameters will be investigated through QA/QC, full-scale demonstrators and in situ tests (i.e. no direct operational monitoring). Groundwater flow and chemistry (parameters indirectly related to the canister, buffer and backfill) will be monitored throughout construction and operations. Additionally, seismicity and temperature in tunnels (parameters indirectly related to the canister and buffer), will be monitored throughout construction and operations.

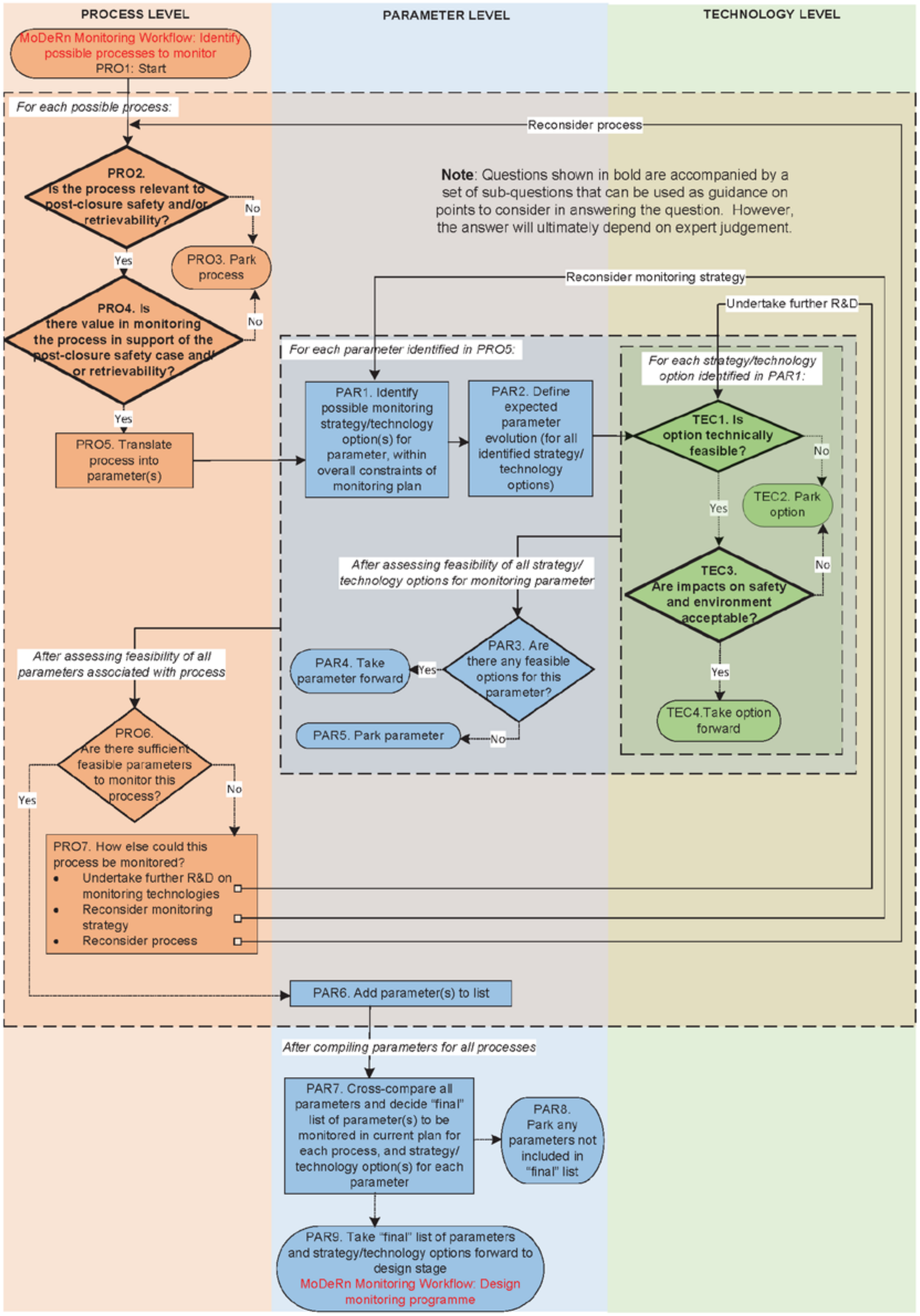


Figure 2.1. The Modern2020 Screening Methodology (Modern2020 D2.2).

Table 2.1 lists processes and associated parameters identified in the Modern2020 test case (modified from Modern2020 D2.2). Parameters in parentheses would be monitored indirectly with respect to the full-scale or *in situ* test (e.g. in surrounding groundwater). The parameters chosen for EBS Monitoring plan are marked with bold text and commented in green.

Table 2.1. Modified after M2020 Posiva test case report for Modern2020 D2.2.

Process	Parameter	Component	Result of Screening: How Addressed				
			Parked	QA/QC	Full-Scale Test	Single Component *In Situ* Test	Operational Monitoring
Seismic events, Reactivation/ displacement	Seismicity monitoring	Canister					X
	Rock displacement	Canister		X			X
	Rock displacement velocity*	Canister	X				
Metal corrosion	Groundwater chemistry (sulphides, oxygen, etc.)	Canister			(X)	(X)	X
	Corrosion potential	Canister	X				
	Composition	(Canister) buffer and backfill		X	X	X	
Glaciation	Maximum long-term pressure load, design issue	Canister		X			
Stress redistribution	Canister geometry changes.	Canister			X	X	
Heat transfer	**Temperature**	Canister		X	X	X	X
Mineral alteration	Buffer composition	(Canister)/ Buffer		X	X	X	
Water uptake and swelling (density homogenisation)	**Geometry** (Buffer upward swelling,)	Buffer		X	X	X	
		Backfill			X	X	
	Density (dry and bulk) At installation and at dismantling	Buffer		X	X	X	
		Backfill		X	X	X	
	Water content, degree of saturation. At installation and at dismantling	Buffer		X	X	X	
	Swelling pressure	Buffer			X	X	
		Backfill			X	X	
	Mineralogy	Buffer		X			
		Backfill		X			

Process	Parameter	Component	Result of Screening: How Addressed				
			Parked	QA/QC	Full-Scale Test	Single Component *In Situ* Test	Operational Monitoring
	Piping and erosion Observed at dismantling, may however be hard to investigate in a full scale test	Backfill			X	X	
	Pore structure	Buffer		X	(X)	(X)	
Water uptake and swelling (saturation)	**Water content and distribution** At installation and at dismantling	Backfill			X	X	
	Relative humidity	Backfill			X	X	
	Pressure (in different parts of backfill)	Backfill			X	X	
	Mineralogy	Backfill		X			
	Dry density	Backfill		X			
	Water content	Backfill		X			
Water uptake and swelling (swelling pressure development)	**Pressure** (Swelling pressure)	Backfill			X	X	
	Pressure (plug lead through)	Backfill	X		X		
Erosion	**Density** (at start and in dismantling) Observed at dismantling, may however be hard to investigate in a full scale test	Buffer			X	X	
		Backfill			X	X	
	Leakage water quantity and composition (through/past plug)	Backfill			X		X
	Groundwater composition	Backfill			(X)	(X)	X

Process	Parameter	Component	Result of Screening: How Addressed				
			Parked	QA/QC	Full-Scale Test	Single Component *In Situ* Test	Operational Monitoring
	Not deemed an possible way to measure erosion						
	Swelling clay content	Backfill		X			
	Geometry	Backfill		X			

2.2 Considerations on EBS monitoring

There are number of advantages and disadvantages with extensive instrumentation including sensors in canister, buffer and backfill and plug. Instrumentation needs and implementation depends on purpose where and why instrumentation is used and the Table 2.1 gives guidelines for different reasons from monitoring point of view. The instrumentation is always site specific and gives very local information and therefore the amount of instruments needs to be considered carefully. On other hand too intensive instrumentation might slow down the emplacement, might cause extra pathways and disturbances to the natural system. The planning of instrumentation requires careful considerations with test design and installation. The fact is that monitoring set up in full scale alone might not be the reality due the cost, resource and location aspects. Therefore, usually the monitoring and instrumentation is only one part of the full scale testing, which has several other objectives.

For this study Posiva had two alternatives of selecting the scope for the EBS monitoring plan. Posiva wanted to create an EBS monitoring plan for realistic underground conditions, where it could be utilized later for other purposes (as part of the full scale test or part of the strategy for R&D work for monitoring of engineered barriers). First alternative was to use a full scale demonstration of EBS component installation for an EBS monitoring plan. Second alternative was to use one specific deposition tunnel in operation and design a full scale EBS monitoring plan for that tunnel or parts of it.

Posiva has selected to use the EBS monitoring plan as design example for monitoring of a full scale experiment of a full scale test of EBS system to be installed at ONKALO™. It has been considered that following advantages and disadvantages needs to be handled when planning the full scale installation test and instrumentation related to the test.

The role of the monitoring and related instrumentation is to:

- learn about interactions between installed components after installation and getting design information;
- increase the knowledge of the THM processes for EBS components;
- increase chances of identifying expected or unexpected evolution of EBS components at an early stage; and

- learn to understand the EBS component system interactions with site conditions.

This list does not answer directly to the question of fulfilment the safety case specifications, while the processes are so slow that with a full scale test the processes will go beyond the relevant test time.

Disadvantages of extensive instrumentation:

- Complicated installation (risk for delay and increasing cost and possibly that the installation cannot be done according to the plans).
- The track record of measurements is not expected to be high, there is always a risk that a number of the installed sensors malfunction or give incorrect readings.
- More disturbances to the system due the wires and cables (causing more pathways for water and possibility for chemical interactions with components).
- The amount of data increases, which might cause complicated interpretation and modelling.

Disadvantages of non-extensive instrumentation:

- The instrumentation does not provide the whole picture of processes, which take place in the tunnel section.
- A small amount of measurement data might lead to wrong interpretations.
- High risk for loss of data due to sensor malfunctioning or failure.

The monitoring strategy for a test is always a compromise of different factors. Since Posiva is aiming to prepare the EBS monitoring plan for a full scale EBS installation test the objectives set for a test influence to the instrumentation design. An important objective of the planned full scale experiment could be: “To show that the EBS components can be installed with prototype equipments and the initial state can be reached within set time limit, excluding the experiment preparation related time”. To reach this objective the strategic decision should be to limit the number of sensors installed in the buffer and the backfill.

Another topic is to understand whether extensive instrumentation in full scale tests is an efficient way to build knowledge on evolution. It is important to consider what are the available methods.

Based on the abovementioned factors the following processes are planned to be monitored in the EBS monitoring plan:

- Heat transfer from canister
- Water uptake and swelling of buffer and backfill

The monitoring methods and instrumentation are described in the following Chapters. It is obvious that several methods can be used for monitoring purposes, but the EBS monitoring plan concentrates on few methods, which mainly have been developed further in Modern2020 WP3. The chapters below describe shortly about other methods as well. This report concentrates on methods based on the assessment work, which is described later. Some of the methods under development have been not selected, like the use of fibre optics since the strain conditions in crystalline rock are not measured as part of the EBS components and the temperature information is gathered as a by-product from other selected methods instead of using fibre optics.

2.2.1 Temperature

Apart from the purpose of measuring temperature as a part of evaluating the THM evolution of the bedrock, the resulting temperature evolution in space is monitored. The purpose is to evaluate the prediction of temperature evolution that depends on the thermal properties of the bedrock, buffer, canister and more marginally backfill. Based on the results the input to the model can be improved. The updated model can be used for optimising the distance between disposal canisters in the repository.

2.2.2 Water uptake and swelling of the buffer (density homogenisation)

No technically feasible method of directly measuring density change during the test implementation has been identified. The Toolbox for following swelling and density change comprises of measurements of:

- Resistivity
- Total pressure
- Pore pressure
- Relative humidity

Also the temperature can be measured in this context as it influences the hydraulic and mechanical processes.

The design of the monitoring program has been focused on the processes currently deemed to have significant influence on the resulting density and swelling pressure of the buffer. Therefore, a sensor that is able to directly measure the displacement of the buffer backfill interaction would be a good addition to the measurements.

It is the saturation and subsequent swelling of the buffer that causes the upward swelling and compression of the backfill on top of the deposition hole. In order to follow the saturation process with as little disturbance to the buffer and backfill, and more importantly to the installation process a measurement system should be applied that provides volumetric information of the water uptake inside buffer and backfill, e.g. ERT (Electric Resistivity Tomography). Using such a measurement system the variation in water content and degree of saturation of the bentonite in the buffer and backfill can be derived in 3D. In order to provide information on the water uptake and swelling of the buffer and backfill sensors for measuring the relative humidity (section 5.5), total pressure (section 5.3) and pore water pressure (section 5.4) are also installed in a few locations. The results from these sensors can be used for getting information of the evolution in the measurement positions.

2.2.3 Saturation and deformation of the backfill

The saturation and homogenisation of the backfill close to the tunnel roof influence the buffer upward swelling. The backfill material in this region might also be sensitive to processes like piping and erosion (the initial ones are mechanical processes). The same strategy as for the buffer will be used for following the hydro mechanical evolution. A volumetric measurement system for following the water uptake and swelling processes (e.g. ERT) in the backfill is combined with total pressure and pore water pressure sensors. No measurements of relative humidity are made in the backfill. The relatively rapid changes in resistivity that are anticipated as water from fractures enters the pellet filling is predicted to be due to the change in water ratio and this process should be possible to follow. The swelling of the buffer will then lead to a compression and subsequent increase in pellet fill dry density. The results from the displacement measurements will be used for assessing when in time the compression takes place. If the upward movement of the buffer is separated from the saturation the change in resistivity may be separated to change in water ratio and change in density.

3 Expected evolution of EBS and rock

It is helpful to know the expected evolution of the site, EBS and sensor readings for planning and executing the monitoring. In this case the expected evolution has been derived from thermo-hydraulic (TH) simulations for the in-situ EBS system test. This chapter provides only a short overview of the expected evolution and more details of the site and model are given in (Kristensson 2015). The model is presented in Figure 3.1 and fractures intersecting the test tunnel in Figure 3.2. Simulations were run both for fractured case and unfractured case, the unfractured case being relevant if groundwater flow would be disturbed or stopped for some reason.

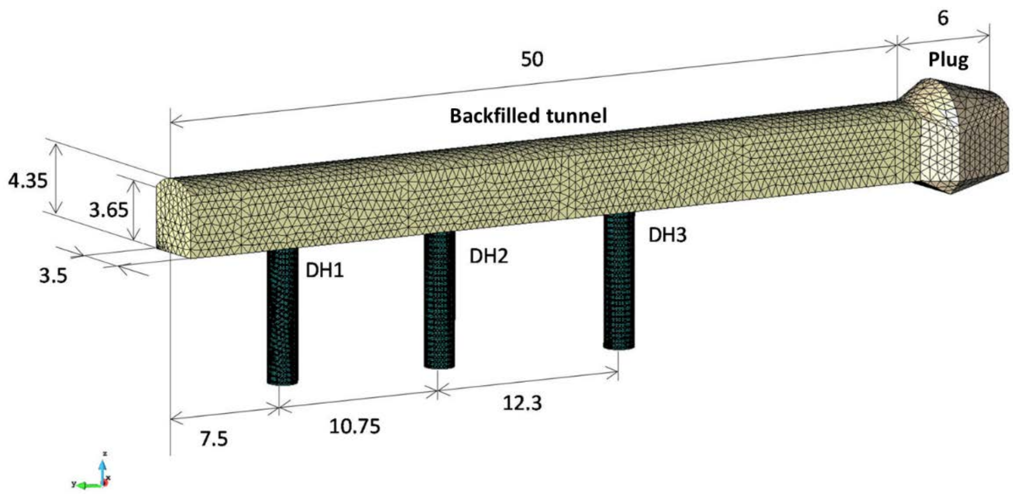


Figure 3.1. Experiment-tunnel geometry and dimensions (Kristensson 2015). Each deposition hole (DH) contains a canister surrounded by a bentonite buffer.

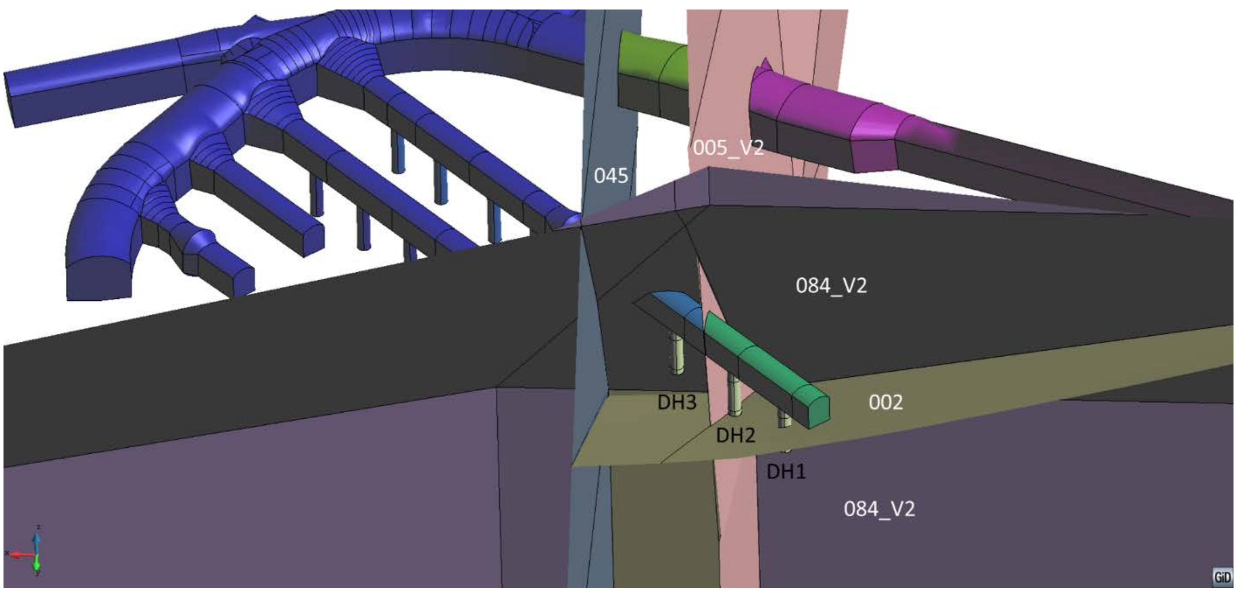
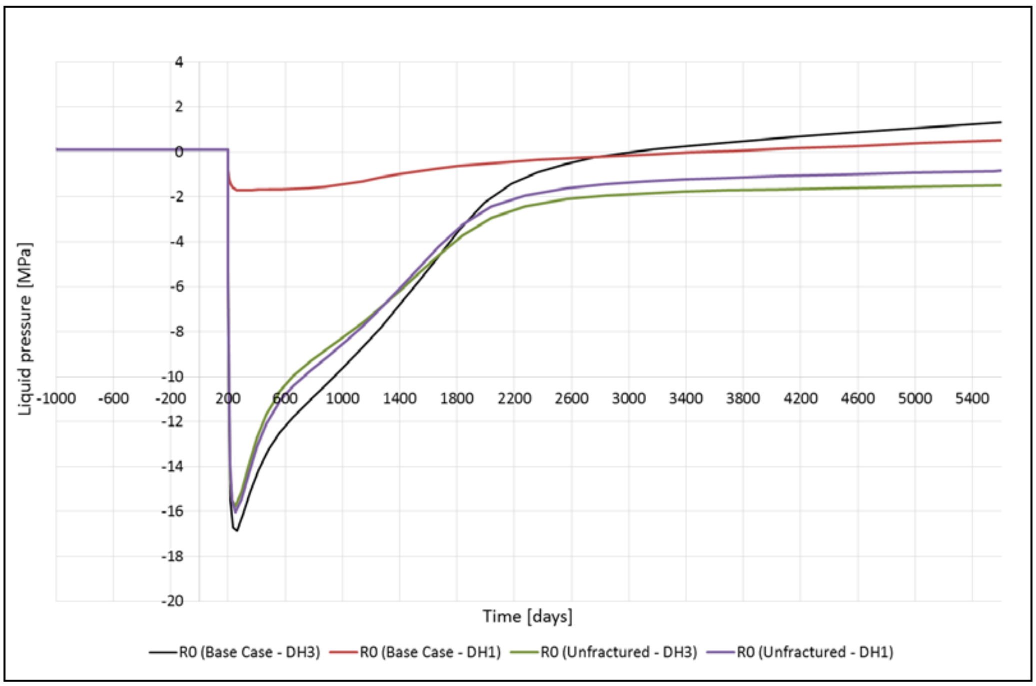


Figure 3.2. Fracture geometry. The close-up at the bottom demonstrates the fracture positions with respect to the deposition holes (the fractures are only partially drawn to better

illustrate this point). Fracture 002 intersects DH1. Note that the reference labels of the fractures have since been revised (Kristensson 2015).

3.1 Liquid pressure (saturation) in the rock

The host rock slowly desaturates after excavation. This effect was studied by mapping liquid pressure in the rock at rock-test deposition hole interface (R0) and 2 meters inside the host rock towards other test deposition holes (Figure 3.3). Positive liquid pressure means real pressure whereas negative values depict suction and mean that the host rock is desaturated. Important events in the time scale are: tunnel was excavated at t = -1000 days, open tunnel has a relative humidity of 100%), t = -800 days open tunnel the relative humidity was set to 90%. t = 200 days all EBS components are installed and heating is turned on.



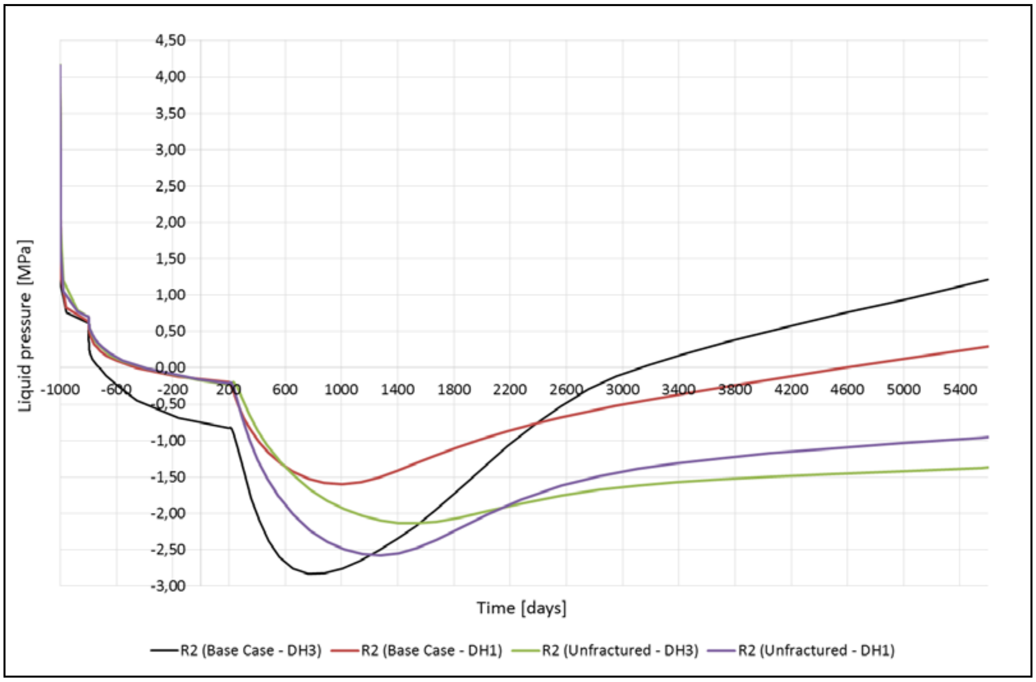


Figure 3.3. Evolution of liquid pressure in the rock: point R0 at rock wall (top) and point R2 at 2 m radial distance from the rock wall (bottom) (Kristensson 2015).

3.2 Temperature in the rock

Temperature in the host rock was evaluated more closely in the rock at rock-test deposition hole interface (R0) and 2 meters inside the host rock towards other test deposition holes (Figure 3.4). Moreover, temperature at vertical cross-section of the tunnel is shown at t = 560 days and t = 5600 days in Figure 3.5. The canisters were expected to output 1700W power.

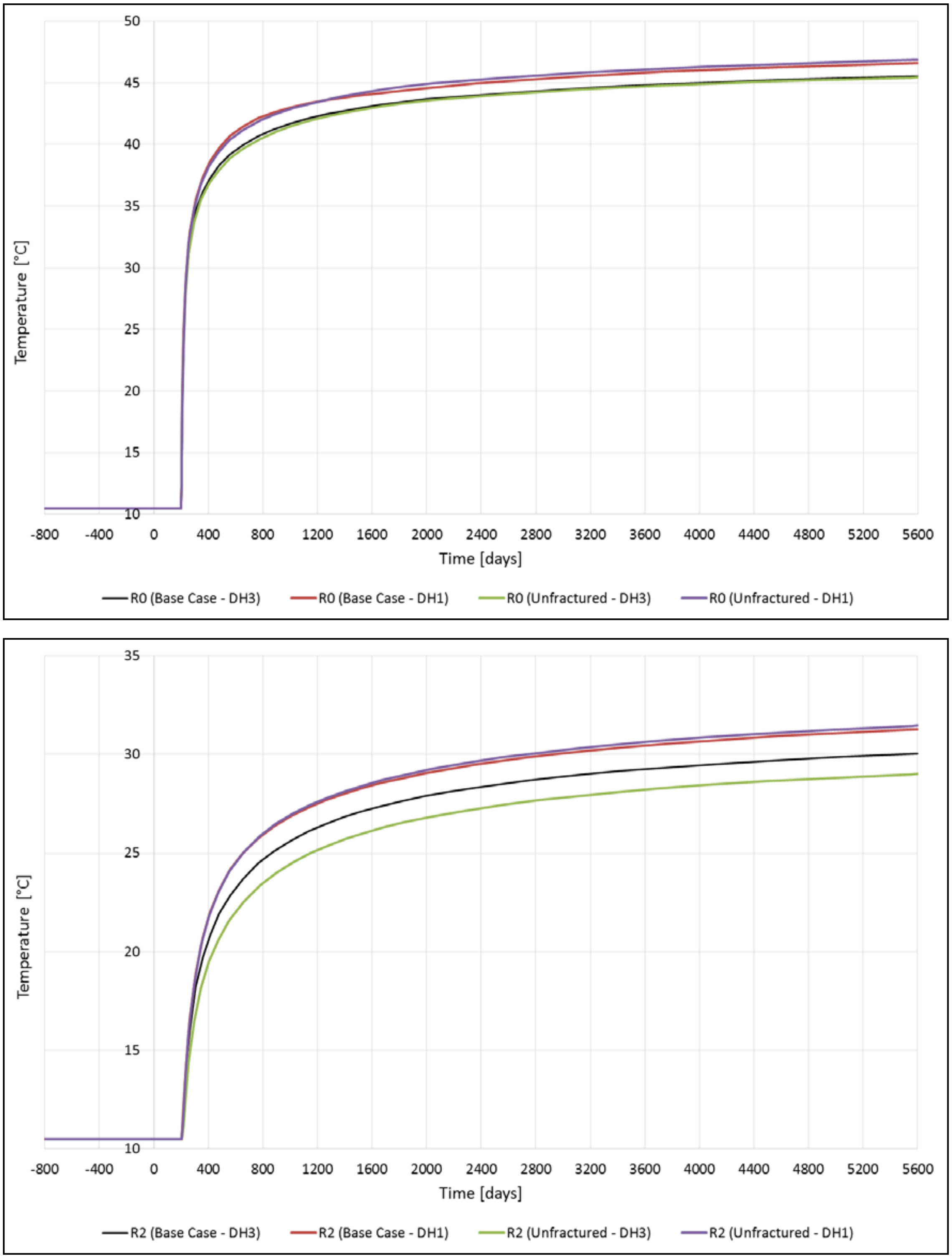
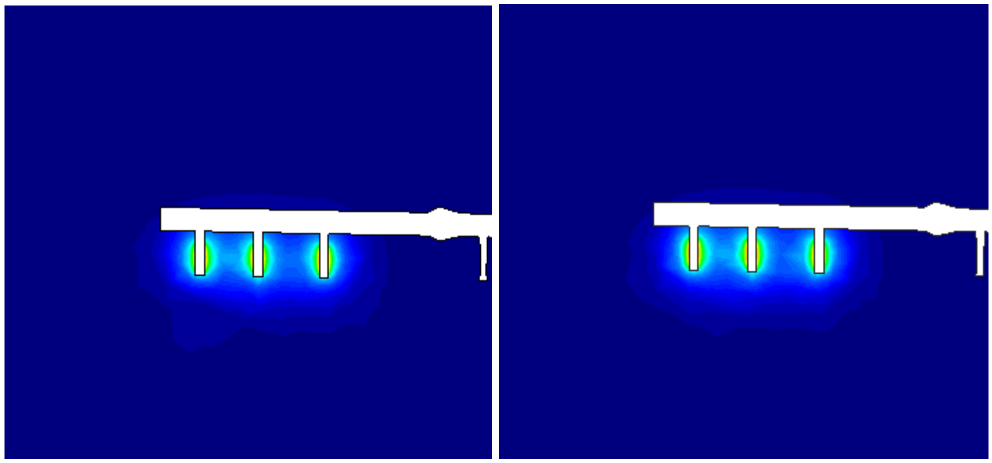
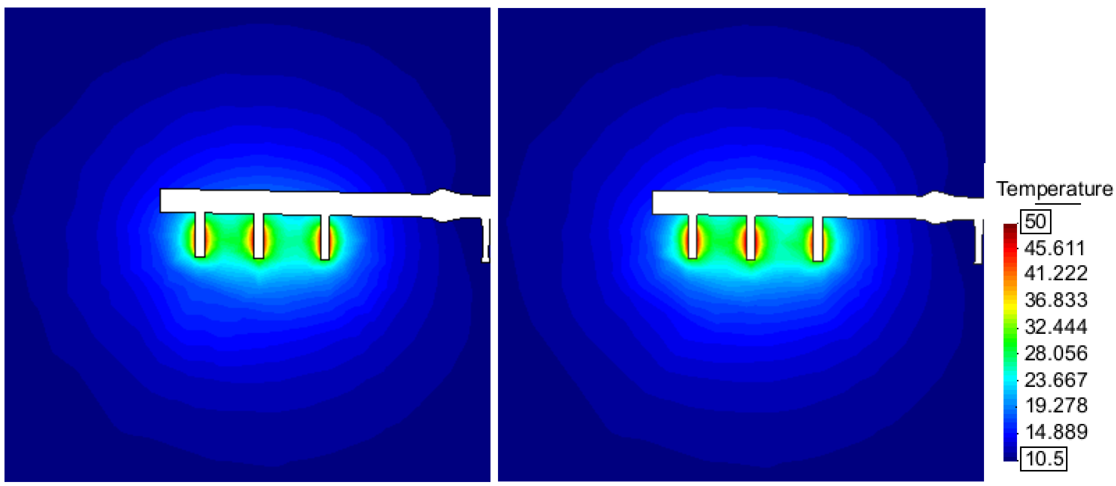


Figure 3.4. Evolution of temperature in the rock: point R0 at rock wall (top) and point R2 at 2 m radial distance from the rock wall (bottom) (Kristensson 2015).



360 days (t = 560 d)



5400 days (t = 5600 d)

Figure 3.5. Distribution of temperature (°C) in the rock at 360 days and 5400 days after installation. Vertical cross-sections for the normal case (left) and unfractured case (right) (Kristensson 2015).

3.3 Degree of Saturation in Buffer and Backfill

The degree of saturation in the buffer is presented in Figure 3.6. The results at points B1 and B2 are taken on nodes on the top and bottom of canister/buffer interfaces, the point B3 lies close to the vertical canister/buffer interface on the buffer side and point B4 is located radially in the middle of the buffer. The difference in location with respect to the closest interface may contribute a small difference in the time evolution of saturation at points B1, B2 and B3.

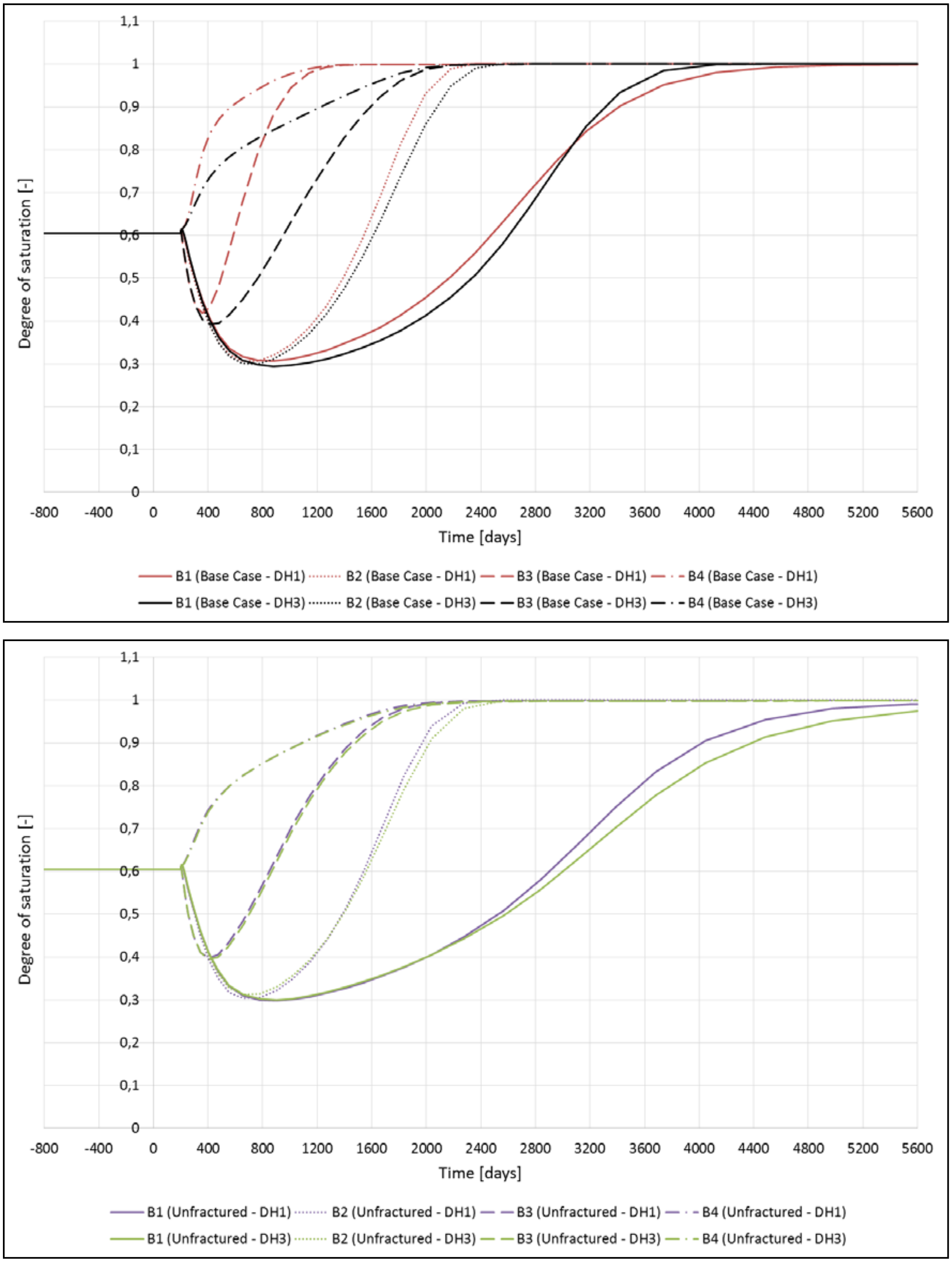


Figure 3.6. Evolution of the degree of saturation in the buffer at points B1, B2, B3 and B4. Results in DH1 and DH3 are presented both for the normal case (top) and unfractured case (bottom) (Kristensson 2015).

The degree of saturation in the buffer and backfill is presented in Figure 3.7 and Figure 3.8. The figures present a vertical cross-section of the backfilled deposition tunnel. The depicted area is as follows: The highest point in the rock is approximately 15 m above the highest point of the tunnel (located at tunnel end) and the lowest point in the rock is approximately 19 m below the lowest point of the tunnel (on the tunnel/plug interface). The horizontal distance from the tunnel end to the furthest point in the rock is approximately 10.5 m. All in all, the area is roughly 39.5 m in height and 55.5 m in length.

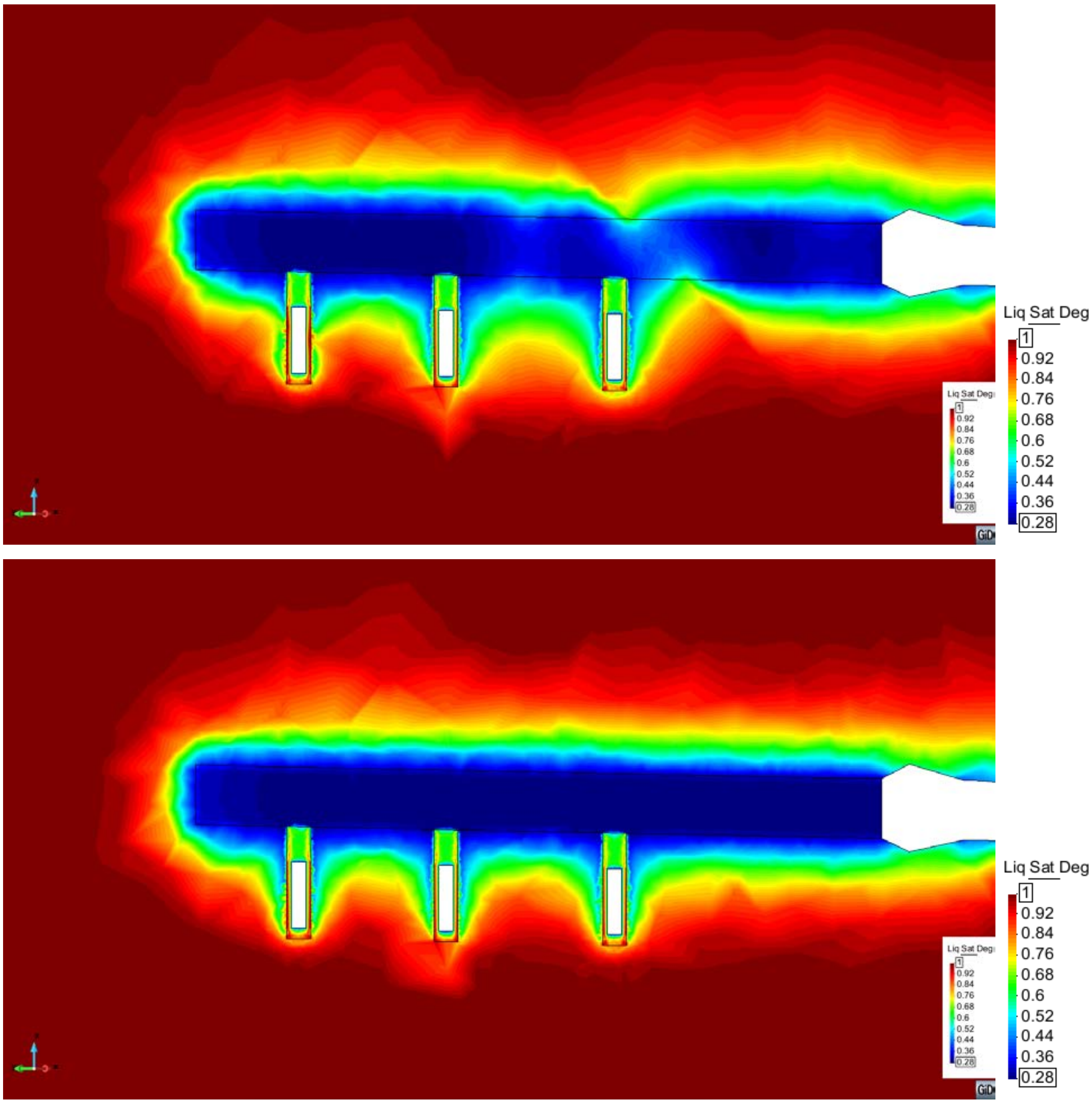


Figure 3.7. Saturation degree in the buffer and backfill at 360 days. Vertical cross-sections for the normal case (top) and unfractured case (bottom) (Kristensson 2015).

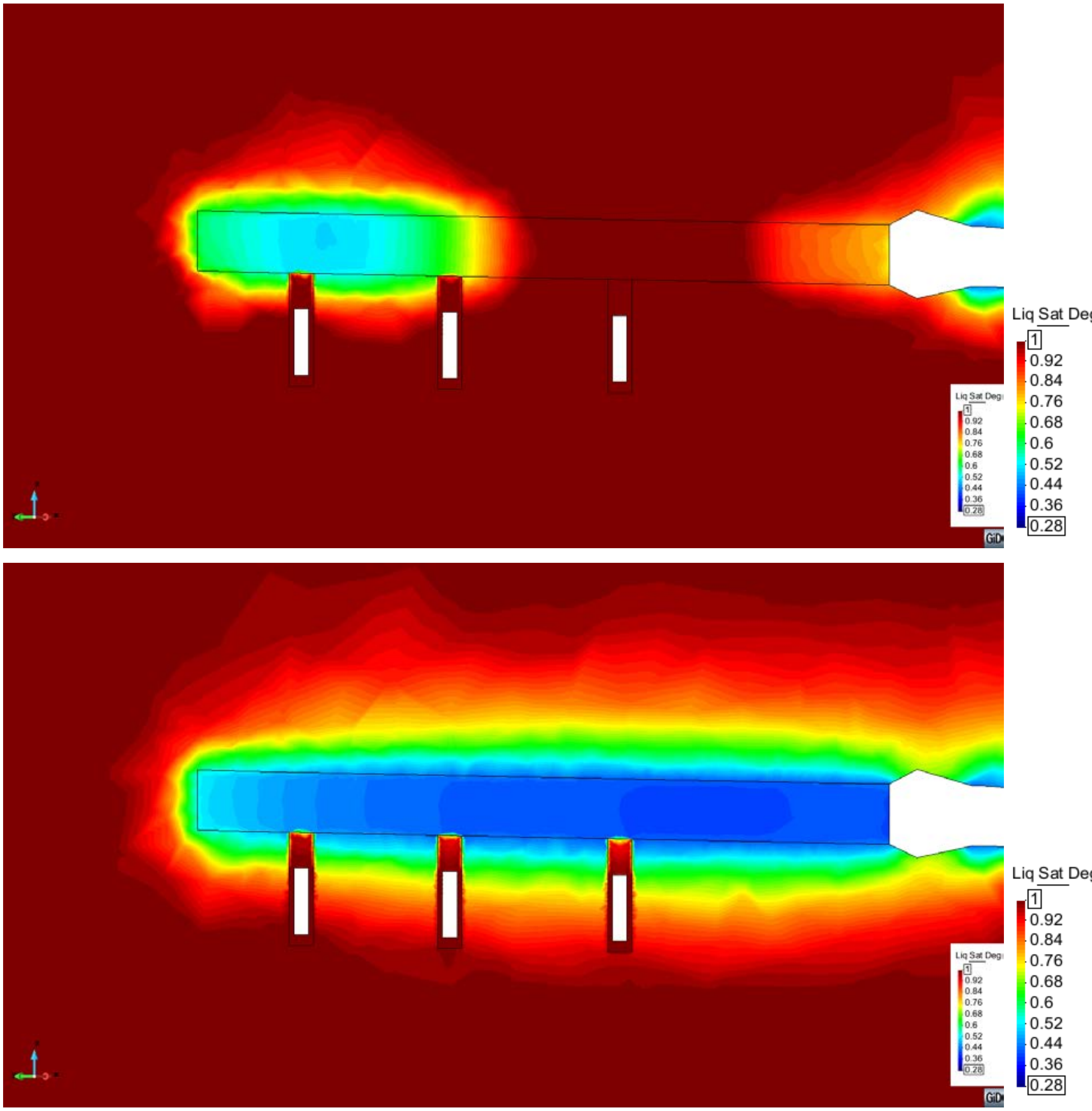


Figure 3.8. Saturation degree in the backfill at 5400 days after installation. Vertical cross-sections for the normal case (top) and unfractured case (bottom) (Kristensson 2015).

3.4 Temperature in Buffer

The temperature in the buffer is presented in Figure 3.9. The results at points B1 and B2 are taken on nodes on the top and bottom of canister/buffer interfaces, the point B3 lies close to the vertical canister/buffer interface on the buffer side and point B4 is located radially in the middle of the buffer. The difference in location with respect to the closest interface may contribute a small difference in the time evolution of temperature at points B1, B2 and B3.

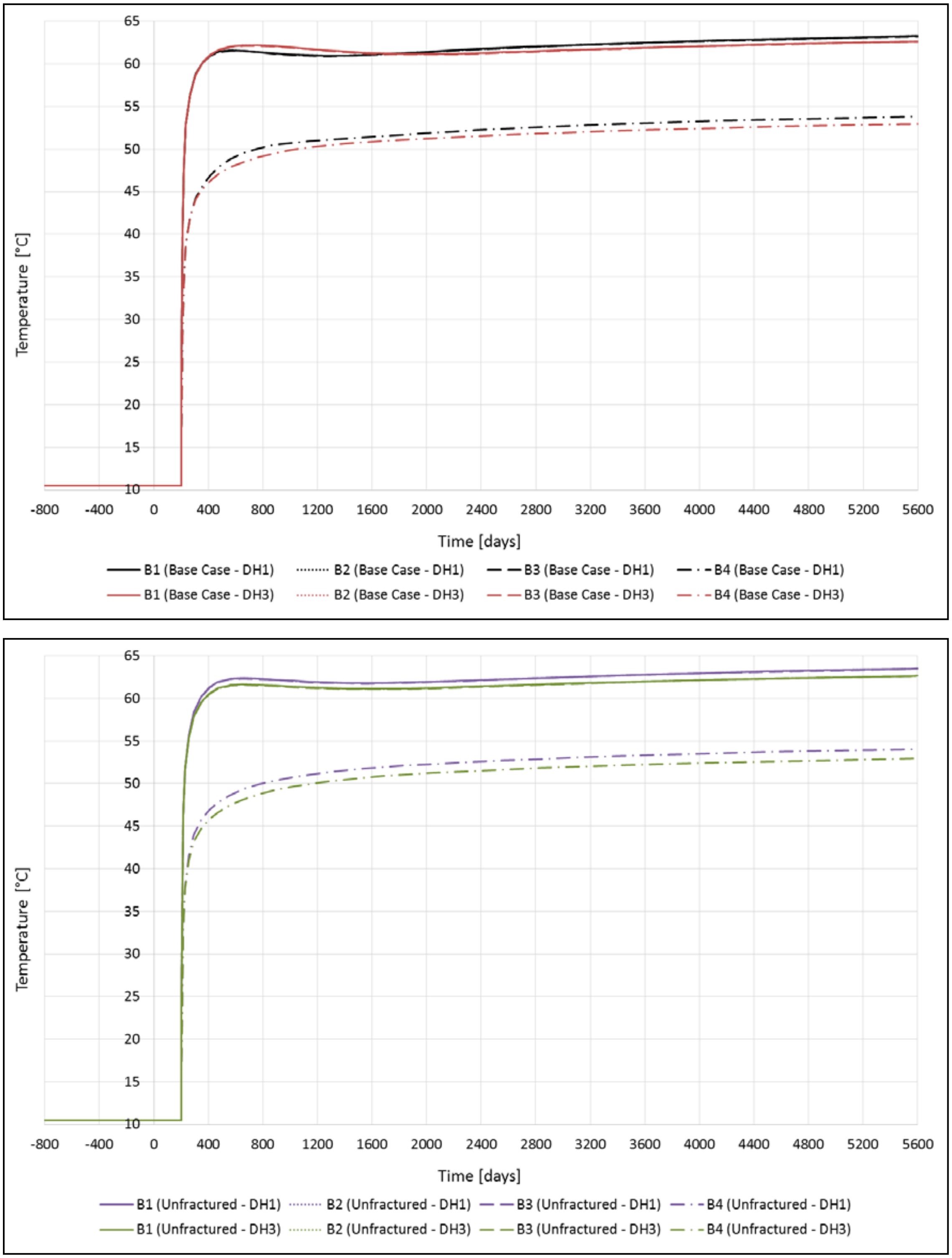


Figure 3.9. Evolution of temperature in the buffer at points B1–B4. Results in DH1 and DH3 are presented both for the normal case (top) and hypothetical unfractured case (bottom) (Kristensson 2015).

4 Assessment of EBS monitoring technologies

After parameters and processes to be monitored are identified, it is necessary to assess the monitoring technologies to be used for measurements inside the EBS. There is a wide range of sensors available, but only few are able to meet the requirements given in a geological repository.

4.1 Objectives

The objective of this work was to perform an assessment of EBS monitoring technologies as a state-of-the-art review in order to identify the potentials of different available techniques, equipment and/or procedures. The review included an assessment of the technology readiness level TRL (United States Department of Defence, 2011) of these items, with regard to the EBS monitoring plan established within this project for ONKALO™.

The assessment feeds into the work done in Modern2020 Task 3.1. However, results from Task 3.1 are expected only at the end of the Modern2020 project. Therefore, the assessment performed within this Task 4.1 of the Modern2020 project was focusing on the KBS-3V disposal concept for crystalline rock and were needed prior the expected outcome of Modern2020 Task 3.1 in order to be able to provide the detailed EBS monitoring and instrumentation plan.

The assessment focused only on EBS components as part of the EBS monitoring plan, including the copper canister and clay/bentonite of the buffer and backfill. Consequently, the monitoring of the near-field rock, tunnel characterisation or site condition monitoring was not part of this study.

The work included or addressed the following aspects:

- Determining existing monitoring methods, techniques and/or tools.
- Identifying limitations and restraints on the technology readiness, use, applicability (such as operating environment), functionality (such as duration) and/or feasibility of the methods.
- Noting references for location of earlier monitoring techniques.
- Focusing on monitoring technologies that are applicable for the operational phase of the repository (10 to 100 years or more), but may also address shorter-term (1 to 10 years) applications.
- Considering accessibility of the monitoring equipment and instrumentation, for e.g. maintenance measures, change of sensors, batteries, power supply.

The review process started from the existing experience and documentation inside Posiva. It also included the results of the Euratom FP7 MoDeRn project (MoDeRn Project, 2013) and previous assessments done by VTT, in particular work already performed during the past years regarding single component buffer and plug demonstration tests at ONKALO™, e.g. Kivikoski et al. 2014, Holt et al. 2016. The results and findings in these earlier studies were updated and re-evaluated on the basis of new information, including latest publications or other accessible sources for available data.

The assessment study does not include any financial aspects or cost estimates for the referred monitoring technologies and does not prioritize the different technologies for use or cost but provides an assessment of their readiness for implementation.

4.2 Work description

The work started with a survey of the state-of-the-art of measuring and sensing technologies. The focus was on the measuring parameters that are given in Chapter 2 as "process" to be monitored. The relevant information for the state-of-the-art research was collected from literature, available internal and external research and working reports as well as from interviews of several VTT experts. The results were summarized and listed in Table A1 in the Appendix of this report.

Technical information and aspects that are of special interest with regard to an implementation in an EBS monitoring system, are part of the list:

- technology and/or working principle of the sensor, or measuring technique respectively
- measuring range and accuracy of the sensor
- durability and reliability (differentiated for a service life of the sensor of 1 to 10 years, or 10 to 100 years respectively)
- applicability for wireless sensing, i.e. if the signal transmission and operation of the measuring device can be handled based on a wireless system
- technology readiness level TRL (United States Department of Defence, 2011)
- references.

Certain technologies and techniques that show obvious constraints that do not allow their application for this purpose were not listed. Such constraints are e.g. a measuring range far out of the range needed, very large dimensions of the measuring apparatus/sensor or techniques that can only be operated under special laboratory conditions.

Selected were only relevant, feasible and preferred sensors and technologies that are most promising for an implementation in tests, in-situ demonstrations and during operation of EBS in the repository. The selection was performed based on a defined decision making process, which is described in the following Chapter.

The selected technologies are described in this report by taking into account some of the following aspects, as far as they are of relevance:

- history and background of sensor development
- working principle of the selected sensor
- signal type
- existing experiences with the technology; references from preferably long term measurements where the sensor or technology has been used

- advantages, disadvantages and further remarks about the use and operation of the sensor.

4.3 Decision making process for technology selection

By means of a decision making process the sensors and monitoring technologies were selected, that are most promising for an implementation in the EBS monitoring plan, i.e. for use during the operation of the repository.

All sensors and technologies that are listed in Table A1 in the Appendix of this report were assessed on the basis of a rating process following seven specific criteria listed below. The definition of the criterions was made together with Posiva for the case of KBS-3V and is focused on EBS monitoring plan in this task. The process does utilise the outcome from Task 3.1, and is not handled more for Task 4.1.

The sensors and technologies with the best rating result were chosen to be described in more detail in this report.

The different criteria that were used for the assessment are given in Table 4.1. Each criterion A-G (see Table 4.1) is rated for the different sensor/technology using

“1” for a low/poor/negative,

“2” for a moderate or unknown and

“3” for a high/good/positive

performance or assessment of a specific influence on the monitoring result.

Additionally the relevance of each criterion for the selection of the sensors is taken into account by a specific percentage, which acts as a weighting factor. The total sum of all weighing factors is 100%. Regarding the weight factor, the accuracy of certain sensors was ranked lower than valid references, which show that certain technologies are tested and validated. For an assessment of condition, performance and evolution in Posiva’s case, the criterion were chosen based on an internal discussion and assessment procedures as explained above. It is not generally valid and needs re-assessment if changes in the monitoring concept and the monitoring case apply.

Table 4.1. Criteria and corresponding weighting factors used for the decision making process.

Criterion	**weighting factor** f_i **[%]**
A effect of cable length on signal	5
B dimension of sensor and ease of installation	10
C accuracy of measurement	5
D durability, reliability	30
E applicability for wireless sensing	5
F TRL, references	25

G specialty, singularity, novelty, uniqueness	20
	∑ 100

The overall rating result R of a monitoring technology/sensor can be calculated by the sum of the individual products calculated by the ratings and weighting factors for each criterion A-G using the following formula:

$$R = A \cdot f_A + B \cdot f_B + C \cdot f_C + D \cdot f_D + E \cdot f_E + F \cdot f_F + G \cdot f_G \qquad (4\text{-}1)$$

Consequently, the best rating a technology/sensor can achieve is “3”, and the worst is “1”.

4.4 Assessment results

4.4.1 Survey of measuring and sensing technologies

The main result of this project is a table where processes or properties desired to be monitored are listed with the parameters through which the property can be evaluated and measured (see Table 4.2). Based on a survey performed as a review of literature and available internal and external research and working reports as well as interviews of several VTT experts, relevant measuring technologies and sensor were listed in Table A1 in the Appendix of this report.

Table A1 includes as well the result of the rating of each criterion mentioned in Table 4.1. and thus lists the overall results of the decision making process described in Chapter 4.3.

4.4.2 Overview of selected sensors and technologies

The sensors and technologies to measure key parameters in the copper canister and buffer/backfill that were selected based on the decision making process (see Chapter 4.3) are presented in Table 4.2.

Thermocouples and resistance temperature detectors were selected for all temperature based parameters. Vibrating wire-based sensors were chosen for mechanical and pore water pressure measurements. The decision making process showed as well that ERT is the technology of choice since it is the only technology that is available to provide an overall picture of the changes in water content in a large volume. Where complementary point measurements are of interest, psychrometers and electronic capacitive hygrometers for moisture determination should be used. Inclinometers are the primary choice for measuring the possible upheave of the buffer.

Table 4.2. Selected sensors and measuring technologies for key parameters in the canister (copper) and buffer/backfill (bentonite).

EBS component	Process/property to be monitored	Parameter	Technology	Durability, Reliability	Applicability for wireless sensing	Technology Readiness Level (TRL)	Evaluation - decicion making process
				Service Life 10 to 100 years		1-3: basic/ conceptual 4-6: proof of concept in lab or relevant environment 7-9: prototype demonstration to succesful operation	R evaluation result, rating
							100 %
Canister (copper)	Radiogenic heat production	Surface temperature	**Thermocouple**	medium	high	9	**2,80**
	Radiogenic heat production	Surface temperature	**Resistance temperature detector (RTD)**	high	high	9	**2,80**
Buffer & backfill	Heat transfer	Temperature	**Thermocouple**	medium	high	9	**2,80**
	Heat transfer	Temperature	**Resistance temperature detector (RTD)**	high	high	9	**2,80**
	Water uptake	Moisture - water content	**ERT/IPT**	high	low	7-9	**2,80**
	Water uptake	Moisture - relative humidity	**Psychrometer**	low	medium	8	**1,95**
	Water uptake	Moisture - relative humidity	**Electronic capacitive hygrometer**	low	high	8	**2,05**
	Swelling	Pressure, mechanical	**Vibrating wire sensor**	medium	medium	9	**2,85**
	Swelling	Pore water pressure	**Vibrating wire transducer**	low	medium	9	**2,85**
	Swelling	Displacement profile	**Inclinometer chain**	medium	high	7	**2,35**

4.4.3 Characteristics of the selected sensor and measuring technologies

4.4.3.1 Thermocouple

Thermocouple is one of the oldest measurement instruments that is still in everyday use today. It is based on thermoelectric effect discovered by Thomas Johann Seebeck where a temperature gradient causes a voltage over a metallic conductor. The magnitude of the voltage is dependent on the material used in the conductor, thus using two different metals, a voltage or current dependent on the temperature gradient can be measured.

Thermocouples create a millivolt-range signal, which is relatively easy to measure. By measuring the current flow through a known resistor, the length of the thermocouple wire has no effect on the measurement.

When sheltered correctly, thermocouples can be made robust and to withstand harsh environmental conditions. Thermocouples are made of two metal conductors and the plastic shield around them. As long as the conductors stay intact and maintain contact in the measuring point only, the sensor will stay operational.

4.4.3.2 Resistance Temperature Detector (RTD)

RTD is the generic expression for sensors that changes their resistance according to the temperature. RTD's are more stable and linear than thermocouples and are therefor more accurate. RTD's can be used in a wide range of temperatures -250°C to 600°C, but the range is a bit more narrow than the range of thermocouples. In continuous measurement RTD's start to heat due to bypassing current trough the resistor. This error called self-heating should be kept minimum by using excitation current less than 1mA.

There are three wiring topologies used to measure RTD's: Two-Wire, Three-Wire, and Four-Wire. The two-wire configuration is the least accurate since lead wires resistance adds error to the measurement and cannot be removed afterwards. In three-wire configuration lead wire resistance can be effectively cancelled. The four-wire configuration is the most accurate using own lead pairs for the excitation and for the measurement (Wu, 2018).

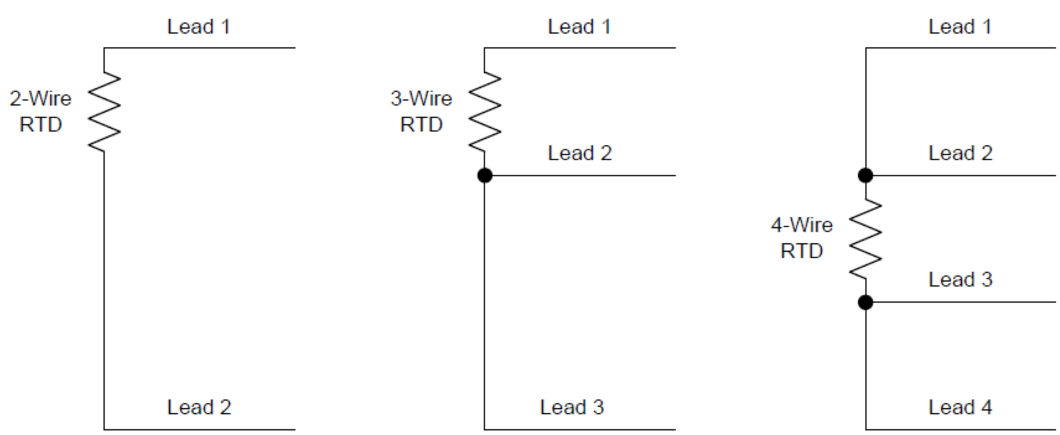


Figure 4.1 Two-Wire, Three-Wire, and Four-Wire RTD configurations (Wu, 2018).

4.4.3.3 Vibrating wire sensor

Vibrating-wire technology is widely recognised as the preferred choice for long-term monitoring of the stability of dams, tunnels, foundations, bridges etc. (Yu & Gupta 2005, Benmokrane et al. 1995, Coutts et al. 2001). The technology has been in use since the late 1970s (Tyler, 1976).

For example, the operation principle of a pore pressure vibrating wire is as follows. The vibrating-wire piezometer contains a magnetic, high-tensile-strength stretched wire, one end of which is anchored and the other end fixed to a diaphragm. The diaphragm deflects in response to applied pore water pressure, changing the tension in the wire and its resonant frequency. Calibration of the piezometer establishes the relationship between pore water pressure and resonance frequency. To operate the piezometer, the wire is plucked by sending a broadband signal down the piezometer cable to a coil magnet assembly beside the wire. When the plucking signal is turned off, the wire continues to vibrate at its resonance frequency, which induces an alternating current in the coil magnet. This signal can be read at the other end of the cable and then converted to units of pressure (User's manual Vibrating-wire piezometers, 2008). Other vibrating wire sensor types use the same principle of operation. The internal structure of a pore pressure vibrating wire sensor is illustrated in Figure 4.2 (Instruction manual, Model 4500 series vibrating wire piezometers, 2014).

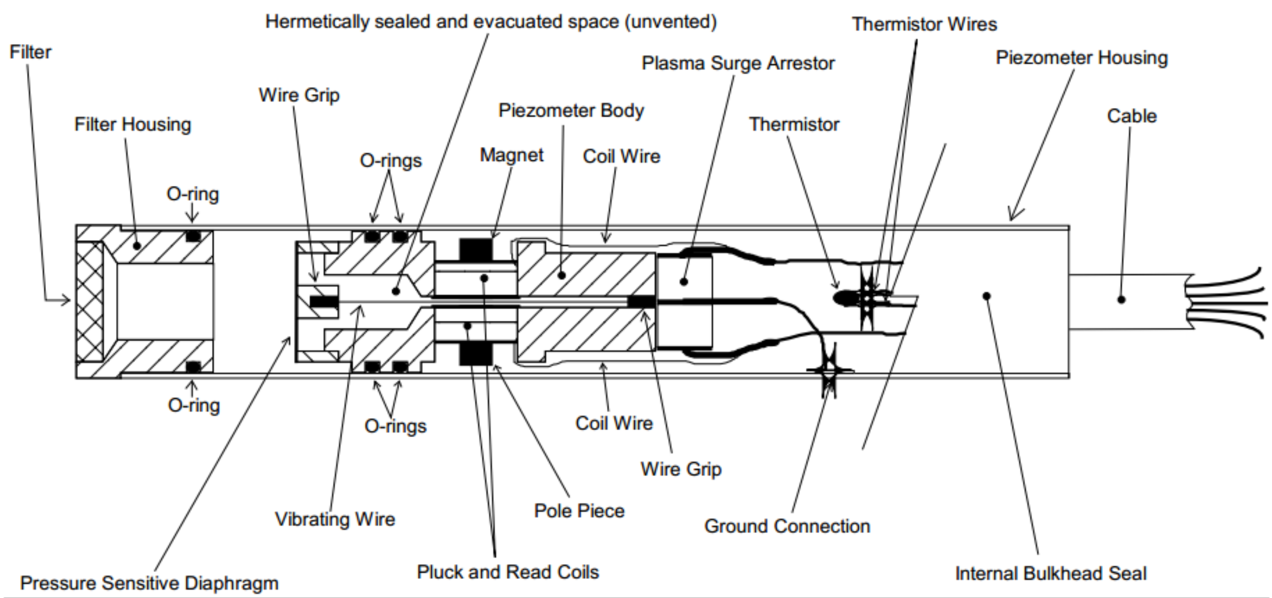


Figure 4.2. Vibrating wire pore pressure sensor (Instruction manual, Model 4500 series vibrating wire piezometers, 2014).

Vibrating wire sensors have been successfully used to measure pore water and soil pressure inside bentonite in repository conditions (Kivikoski et al. 2014, Holt & Koho, 2016).

4.4.3.4 Electronic capacitive hygrometer

In 1937 an electrolytic humidity sensor based on lithium chloride (LiCl) developed by Dunmore (Dunmore, 1938) became the first and only electrical moisture sensor available until around the middle of the 1970s (Faharani et al., 2015). In 1973, Vaisala introduced a HUMICAP thin-film capacitive humidity sensor (Vaisala, 2015).

Humidity can be measured with various types of sensors. Sensing principle for the humidity sensors can be capacitive, resistive, mechanical, and oscillating types. Capacitive sensors are often preferred, because of their low power consumption and linear output response (Kang & Wise, 2015). Earlier, hysteresis was a serious drawback in capacitive sensors. Later cross-linking methods have helped to reduce and eliminate the hysteresis (Matsuguchi et al., 2015). Resistive humidity sensors tend to have higher temperature dependence, which drives the selection to a capacitive sensor. Another categorization for humidity sensors could also be made of the sensor's sensing material type (Faharani et al., 2015). Breakdown of a capacitive and a resistive relative humidity sensor can be seen in Figure 4.*3* (Globalspec, 2015).

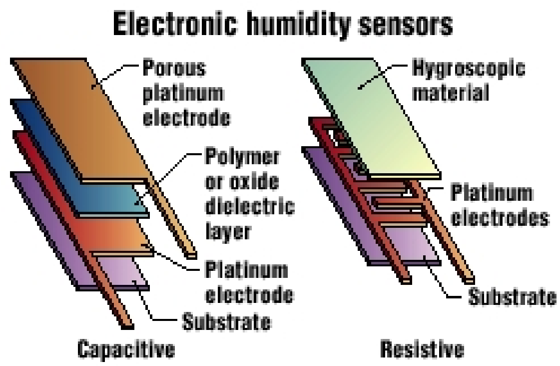


Figure 4.3. Breakdown of a capacitive (on the left) and a resistive RH sensor (Globalspec, 2015).

The typical configuration of a capacitive humidity sensor can be a sandwiched structure with two electrode surfaces on each side. Other possibility for the manufacturing is to use an interdigitated structure. In the sensor, the material between the electrodes will either absorb or release water vapour changing the capacitance of the sensor. These capacitance changes are measured and converted to the relative humidity (RH) values.

Relative humidity sensing has been widely used in consumer, industrial, automotive and weather monitoring applications; e.g. Vaisala has been using the capacitive humidity sensors since its introduction in 1973 in weather monitoring and other environmental monitoring both outdoor and indoor.

Measuring range for the capacitive humidity sensors can be 0–100% (RH) and the accuracy ±1% (RH). Different application areas usually have their own temperature ranges, like e.g. weather radiosonde (-50 to +40 ºC), food processing (+50 to +100 ºC), automotive (-20 to +80 ºC) (Fenner & Zdankiewicz, 2001).

4.4.3.5 Psychrometer.

Ernst Ferdinand August from Germany invented the psychrometer in 1818. The Psychrometer is a humidity measurement device where the humidity can be calculated from a dry air and wet air temperature difference (K. A. Teague, N. Gallicchio, The Evolution of Meteorology: A Look into the Past, Present, and Future of Weather Forecasting ,Wiley Online Library, 2017).

Total water potential can be measured with thermocouple psychrometer. In psychrometric wet bulb method a thermocouple is cooled below the dew point and water drop condenses on the junction of two dissimilar metals. When water is evaporating from the thermocouple junction, the temperature decreases and keeps almost constant for few seconds (wet bulb plateau) before all water has evaporated. The thermocouple output voltage is measured at this point and at point when the ambient temperature is reached again (Water Potential System Users Manual,, 2004).

The relative humidity is calculated as suction pressure from the measured thermocouple output voltage. The measurement range for Wescor PST-55 sensor is from -0.05 to -6.2 MPa that equals to relative humidity from 95% to 99,96%. The Wescor PST-55 psycrometer has been used in SKB’s Prototype Repository and the sensors have measured successfully suction pressure until they reached full saturation (Prototype Repository – Sensor data report, SKB, 2019).

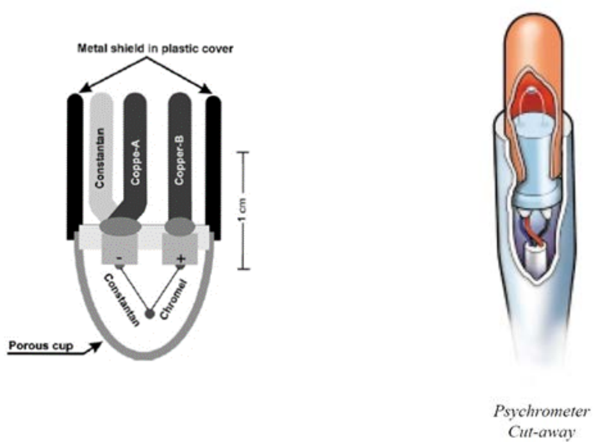


Figure 4.4 Psychrometer sensor (W. Skierucha, 2004; Water Potential System Users Manual, 2004).

4.4.3.6 Electrical resistance tomography (ERT)/Induced polarization tomography (IPT)

The ability of ERT to show the movement of water in rock was first demonstrated during the Single Heater Test in volcanic tuff. This was one of the in-situ thermal tests being conducted in the Exploratory Studies Facility at Yucca Mountain, Nevada. The purpose of the test, which took place in 1996 to1997, was to monitor the movement of liquid water and condensate in welded tuff around a single heater emplaced in a horizontal borehole. Emphasis was placed on measuring the movement of condensate out of the system. Two-dimensional resistivity tomographs were derived from data collected before, during, and after the heating episode.

ERT is based on conventional resistivity methods: two grounded metal electrodes are supplied with a known electric current which causes an electric potential field in the sub-surface. The potential field depends on the yet unknown resistivity distribution. This potential distribution is characterized for each current dipole by measuring the electric potential difference (voltage) between a large number of metal electrode pairs, i.e., each ERT data point requires just a simple current and potential measurement. Once a complete dataset has been acquired it can principally be inverted for the unknown 3D-resistivity distribution without extensive data processing. More details can be read from (Korkealaakso & Marjavaara, 2014).

VTT has gained extensive expertise in ERT/IPT from three decades of research work (Saksa et al. 1986, Korkealaakso & Saarenpää 1998, Korkealaakso 1998, Korkealaakso 2013).

The main advantage of the ERT/IPT technology is its ability to globally visualize (in 3D timehistory) the resistivity map inside the material being measured whereas other sensors and technologies offer only local values. Spatial resolution is determined case-by-case basis and values for the parameters responsible for changes in resistance are model-based. For example, accompanying temperature measurements help to remove the effect of temperature changes from the results.

Using ERT the variation in resistivity in the buffer and backfill can be derived in 3D. For a fixed density, temperature and chemistry in the pore water, the resistivity can be used for calculating a water content or degree of saturation of the bentonite. The method of calculating water content from the sensor readings is complex, requires fairly high computing power and has many degrees of freedom. Many factors going into the calculations can be adjusted to arrive at the correct water ratio. To receive good results from the measurements, a high and fairly unique competence and skill for calculating the water ratio is required. There will not be any direct water content or moisture analysis from laboratory conditions to compare the sensor results and their interpretations with. Therefore it is recommended to complement the ERT with a few sensors in the buffer and backfill that provide reference values for water ratio. Based on this the ERT output can be calibrated.

4.4.3.7 Inclinometer chain

In principle, the inclinometer measures its orientation angle respect to the earth's gravity plane. Nowadays inclination is measured using proven capacitive MEMS technology. MEMS inclinometer is based to capacitive accelerometer where gravity effects to a tiny movable spring element. Capacitance of the sensor changes when distance between fixed electrodes and electrodes attached to movable spring element deflect.

The inclinometer chain includes biaxial inclination sensors, which are installed into a flexible tube and protected with cast in resin. The free space between inclination sensors is filled with elastic mass. The measuring axes of the sensing elements are parallel to the mounting plane and orthogonal to each other. The displacement profile is calculated from the information provided by the inclination sensors and the distances between sensors inside the tube. Measuring range for the biaxial inclination sensors can be ± 90°. The output is dependent also to the environment temperature and variation is approximately ±1° in temperature range -50°C to +120°C. The inclination sensor has high stability over temperature and time.

5 EBS instrumentation plan for a full scale test

Experience from earlier full scale tests, e.g. Prototype Repository (Pusch R, Börgesson L, Svemar C (eds), 2004) and Febex (ENRESA, 2006) indicates that unpredicted events do occur and that it is necessary to be prepared for them. The measuring system needs to be designed to store sufficient measurement data measured with a relatively high frequency for long time of periods. If unexpected events occur the data can be saved. Processes in full scale are always related to the site conditions and models provide information of the expected behavior in different engineered barriers and surrounding host rock and might indicate which measurement frequencies to apply. The measuring system are not necessarily capable to monitor everything and therefore it is important to assess afterwards whether the selected monitoring set up has been performing according to its planned purpose.

5.1 Planned sensor locations

Selecting the locations of sensors, cables and wires requires an optimisation process. In this process a good balance between maximising the monitoring information and minimising the disturbance of the barriers has to be reached. If direct measurements are necessary the sensors need to be as close as possible to the points of interest, which are derived from the modelling work of the expected evolution of the EBS and the rock (see Chapter 3). As a result of the assessment of sensing technologies (see Chapter 4) the detailed location and the surrounding medium, in which the sensor is placed, can be selected.

The temperature measurements at the canister are done inside the canister, i.e. in the interface between copper overpack and cast iron insert, as well as at the heating elements. The latter is necessary to receive a direct response of the heater functionality. Due to the high thermal conductivity of the copper, it is possible to place the temperature sensors inside the canister, to avoid any damaging of them when installing the canister with the automated canister emplacement vehicle. Further temperature sensors are installed at the rock surface of the deposition hole, often as part of sensors measuring other parameters like pressure or humidity. Different locations from the bottom of the deposition hole until its top are selected. In order to obtain information about the temperature gradient within the buffer, few sensors are placed inside the buffer block, at a defined distance between rock surface and canister. Similar to the temperature at the rock surface of the deposition holes, the temperature distribution is measured with single localised sensors at the deposition tunnel surface. Additional temperature information is received through pressure sensors, humidity sensors and ERT electrodes. Temperature profiles in the host rock are measured by means of multipoint temperature sensors placed in boreholes inside the rock.

The same principles as for selecting the locations of the temperature sensors are applied when choosing the best locations for the total pressure and pore pressure sensors for the buffer and backfill. The buffer and backfill blocks are placed with automated robots, which may harm the sensors and wires. Therefore, there are no instruments inside the blocks, except the relative humidity sensors and few temperature sensors inside the buffer, as mentioned above. The sensors are distributed to cover the full height and width of the buffer, and the full length, width and height of the tunnel backfill respectively. Certain sensors are placed at the roof of the tunnel directly on top of the deposition holes, in order to receive pressure information caused inside the backfill by the buffer upheave.

ERT measurements are done by means of electrode chains. They are mounted inside grooves at the rock surface of the deposition holes and directly on top of the rock surface of the deposition tunnel.

For measuring the upheave of the buffer, inclinometer chains are placed horizontally on the top of the buffer elements. One side of each chain is fixed to the rock surface of the tunnel bottom.

5.2 Temperature measurements

Temperatures are measured in the canister surfaces both for canister insert and copper shell with two different type of sensors. The temperature is mainly measured in the buffer and backfill in conjunction of pressure and relative humidity measurements. Also few cored holes at the tunnel are equipped with temperature sensors to be able to measure the host rock temperature.

5.2.1 Temperature measurements in the canister

Pt100 sensors are installed inside the canister into the 12 heaters located inside the canister's iron insert. These measurements are needed to provide feedback to temperature controlling system. Also the overall performance and possible failure of individual resistors can be monitored this way. K-type thermocouples are installed to the surface of the BWR insert. The distance between sensors are 90˚and the sensors are located in the middle height of the BWR insert.

The copper canister's temperature profiles are measured on the inner surface of the canister with separate multipoint thermocouples. The multipoint thermocouple is housed inside smooth inconel tubing and there are 10 separate sensing areas along vertical line. The installation of the temperature profile will be done by mounting them inside a machined groove (8 mm).

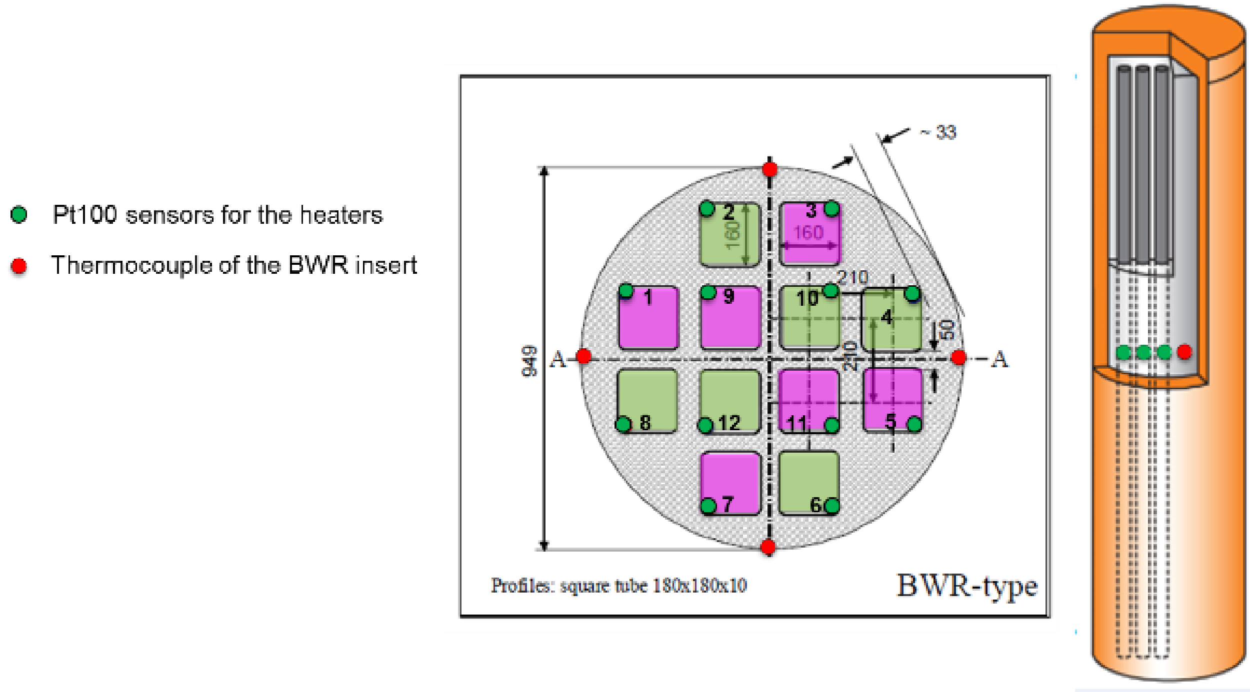


Figure 5.1. Pt100 sensors inside the canister and K-type thermocouples on the surface of the BWR insert.

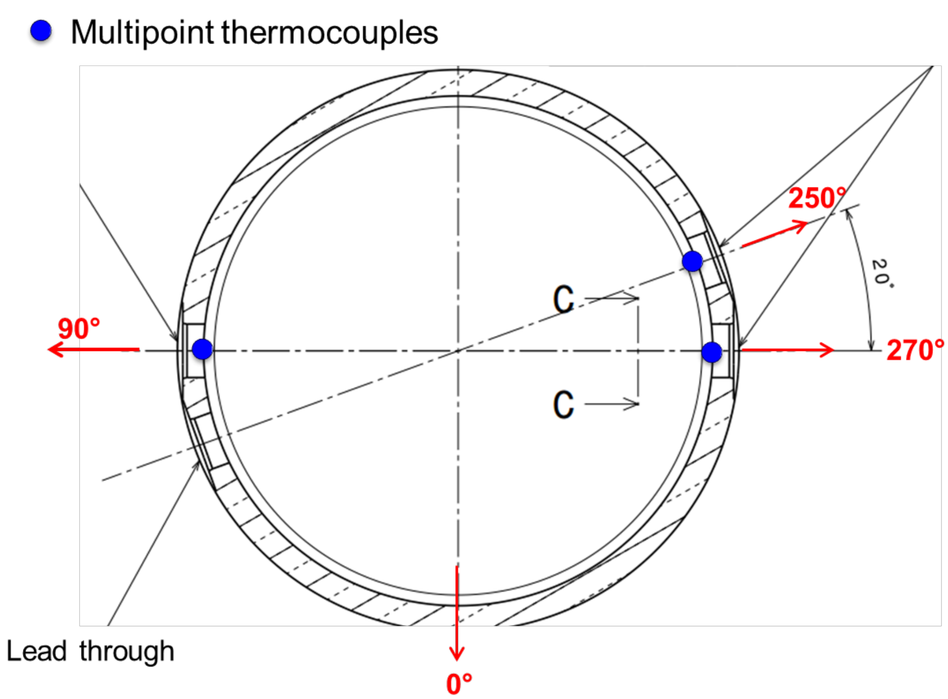
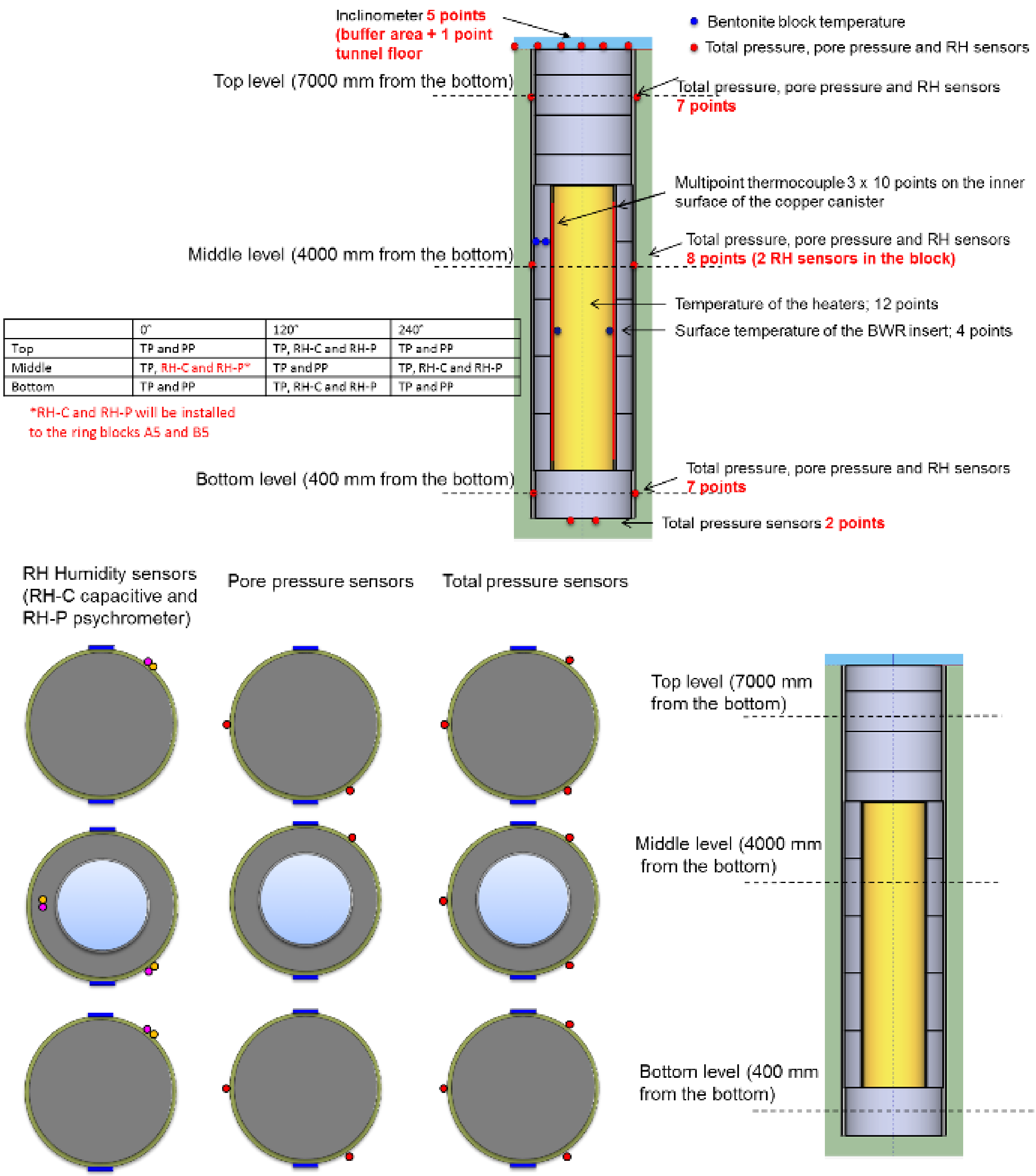


Figure 5.2. Multipoint thermocouples on the inner surface of the copper canister.

5.2.2 Temperature measurements in the experimental deposition holes

Temperature is measured in each experimental deposition hole on the surface of the rock with thermocouples, total pressure sensors, pore pressure sensors, relative humidity (RH) sensors and inclinometers (Figure 5.3).



	0°	120°	240°
Top	TP and PP	TP, RH-C and RH-P	TP and PP
Middle	TP, RH-C and RH-P*	TP and PP	TP, RH-C and RH-P
Bottom	TP and PP	TP, RH-C and RH-P	TP and PP

Figure 5.3. Temperature is measured in the experimental deposition hole on the surface of the rock with thermocouples, total pressure sensors, pore pressure sensors and RH sensors.

5.2.3 Temperature and relative humidity measurements in the buffer block

The temperature of the buffer block is measured with thermocouples and RH sensors in the upper part of the ring block (Figure 5.4).

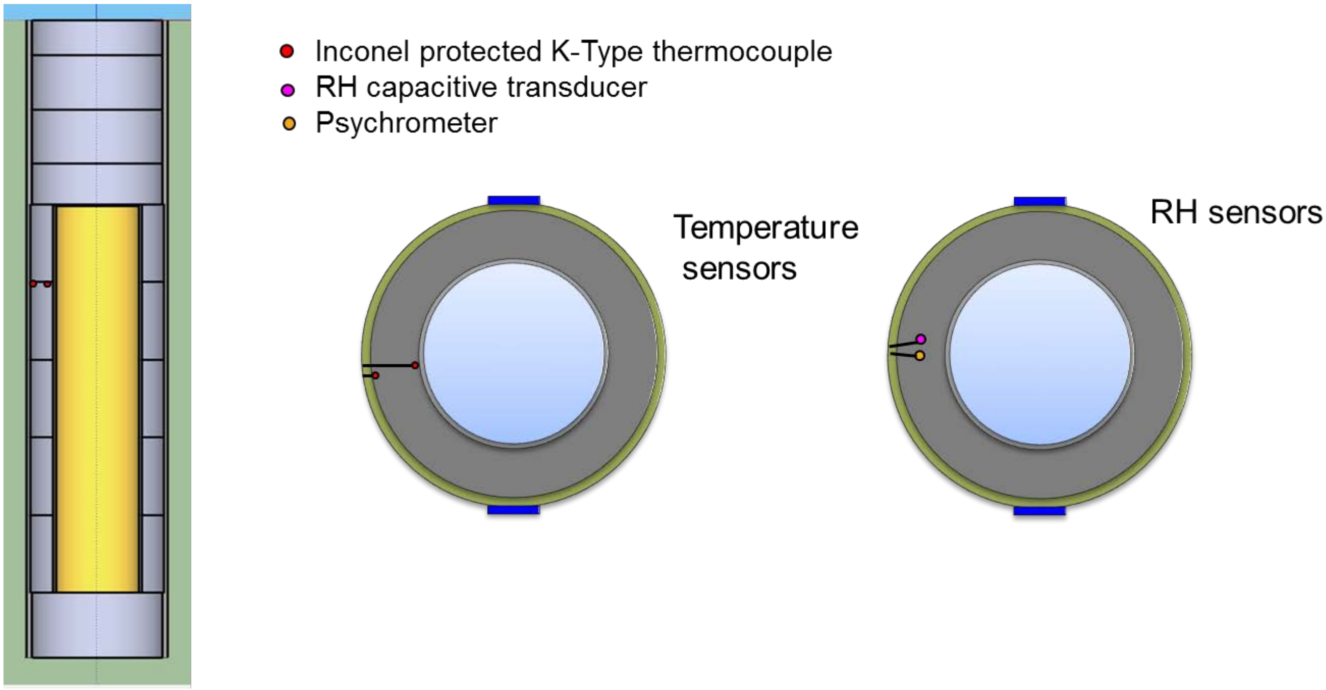


Figure 5.4. Temperature measurements in the buffer block.

5.2.4 Temperature measurements in the rock

Temperature profiles in the rock are measured in the vertical holes between experimental deposition holes and in the hole on the wall. Each of these multipoint temperature sensors are 9 meters long and the distance between individual sensors is 1 meter. The multipoint temperature sensors are installed into core holes and filled with low pH concrete.

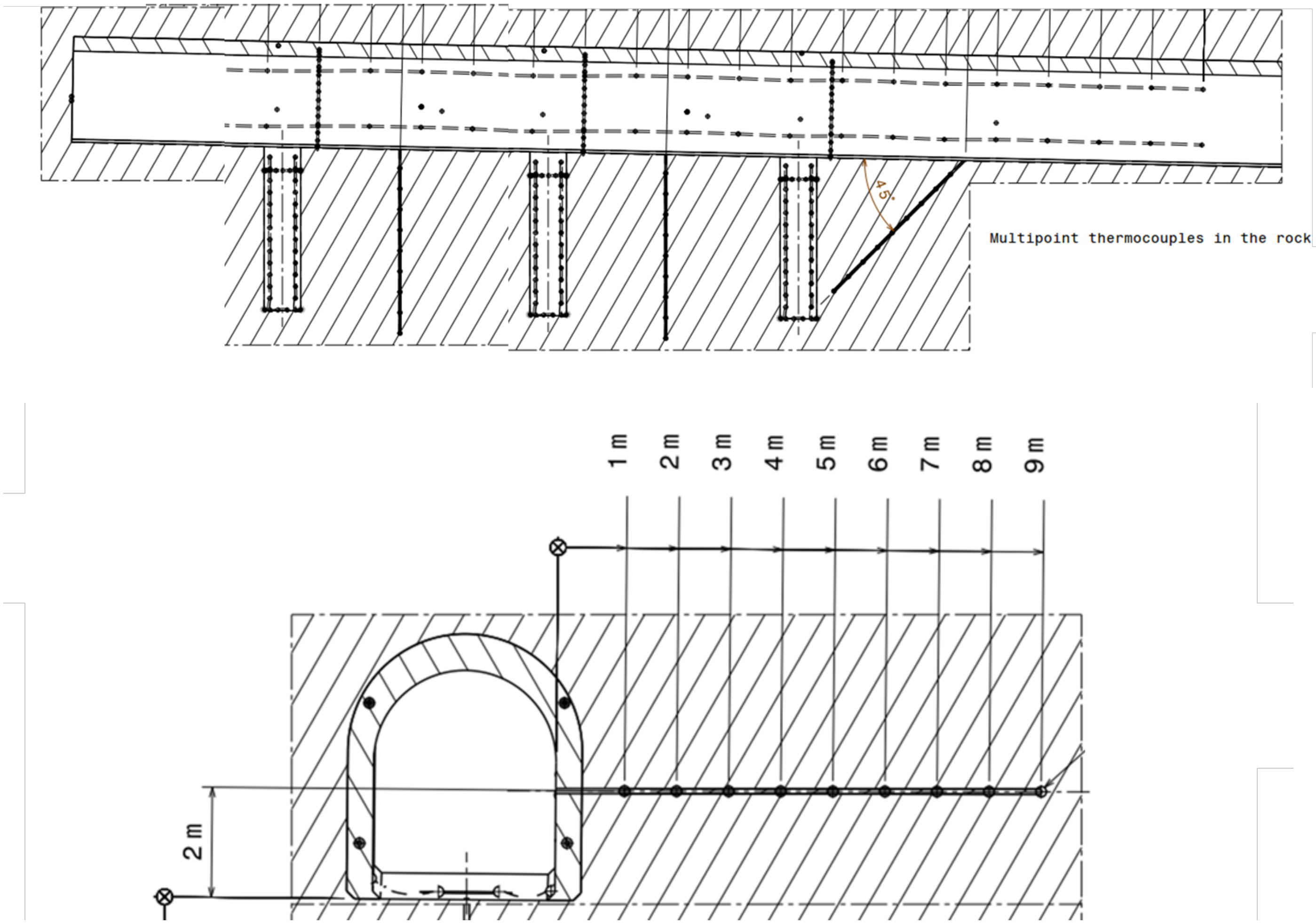


Figure 5.5. Temperature profiles in the rock.

5.2.5 Temperature measurements in the deposition tunnel

Temperature is measured in the backfill with thermocouples (for example in the ERT-chains, Figure 5.6), total pressure sensors and pore pressure sensors.

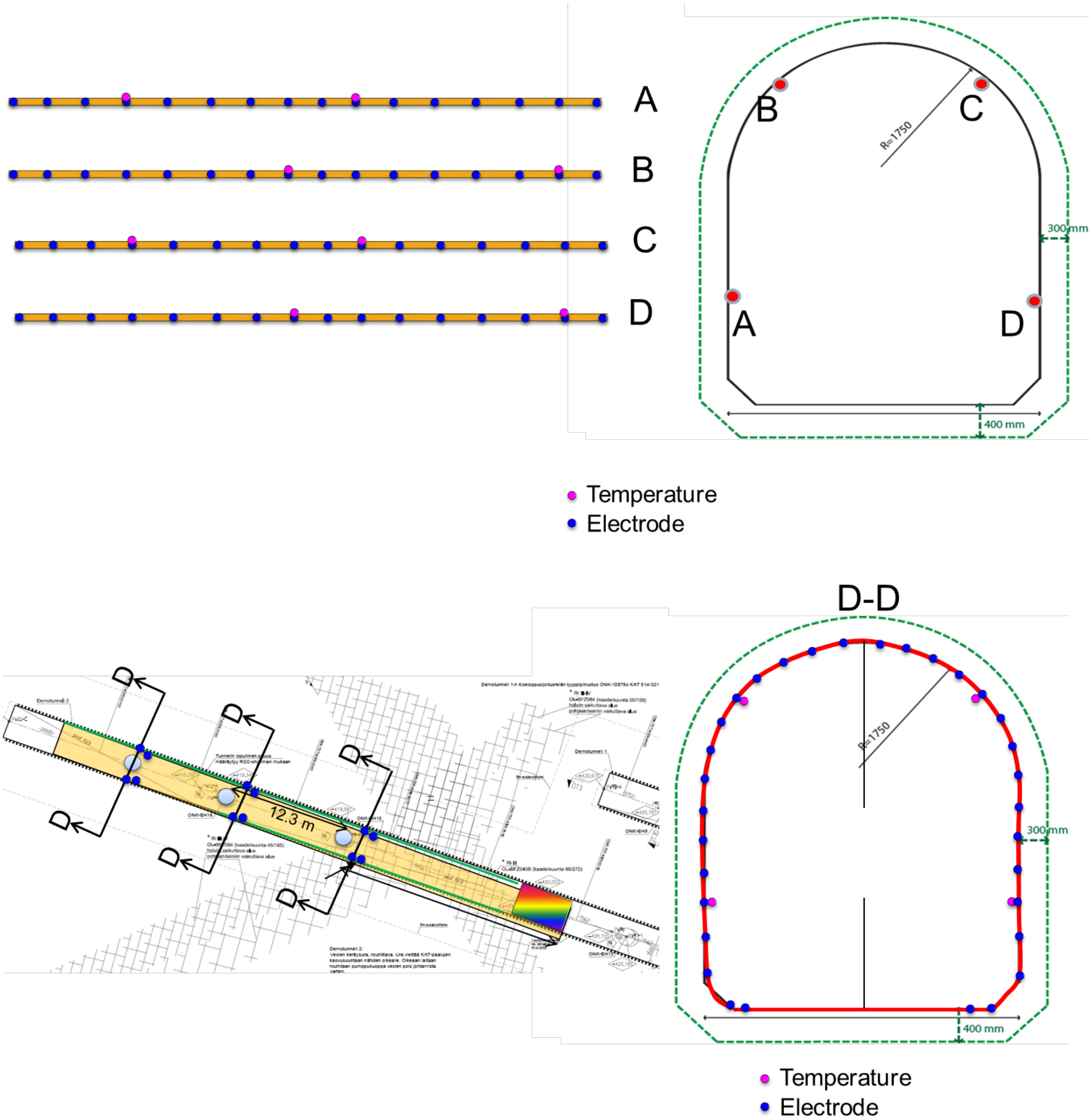


Figure 5.6. Temperature measurements in the backfill tunnel.

Temperature is also determined with total pressure and pore pressure sensors.

5.3 Total pressure measurements

Total pressure is measured in several locations in experimental deposition holes. Total pressure sensors are also installed to the bottom of the experimental deposition hole (Figure 5.7).

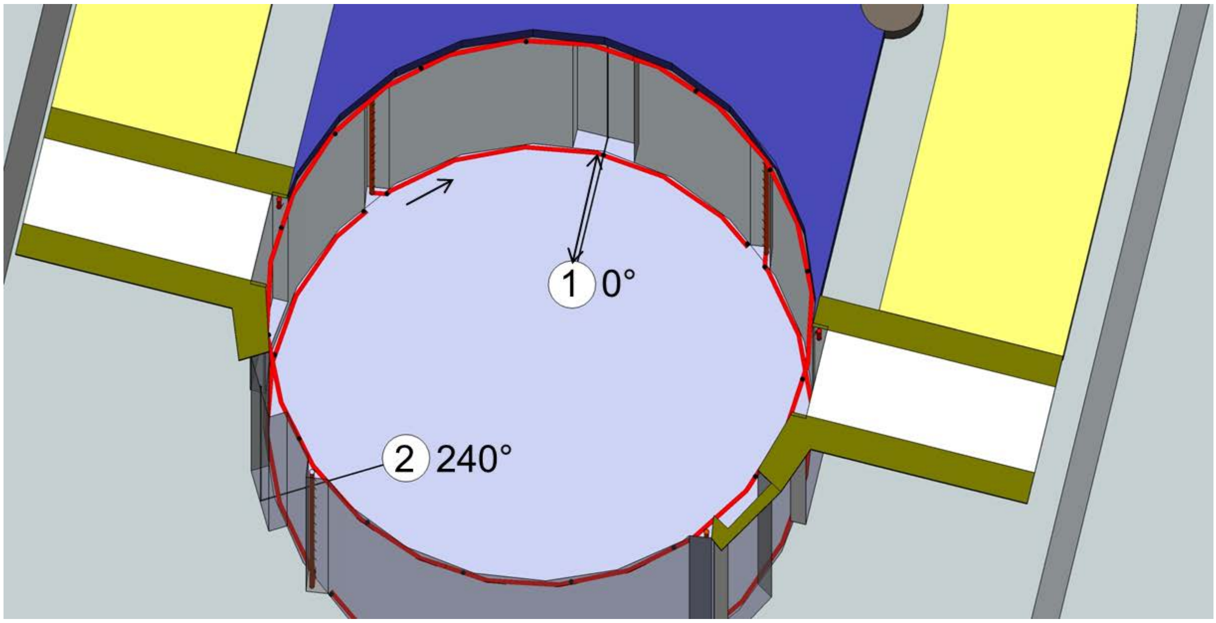


Figure 5.7. Total pressure sensors in the bottom of the experimental deposition hole.

Radial pressure is measured in the experimental deposition hole in three major sensing levels: 400 mm, 4000 mm and 7000 mm from the bottom of the experimental deposition hole (Figure 5.8). In each level three calibrated total pressure sensors are mounted to acid-proof steel plates which have machined individual recesses or slots for each sensor and its cabling (Figure 5.9).

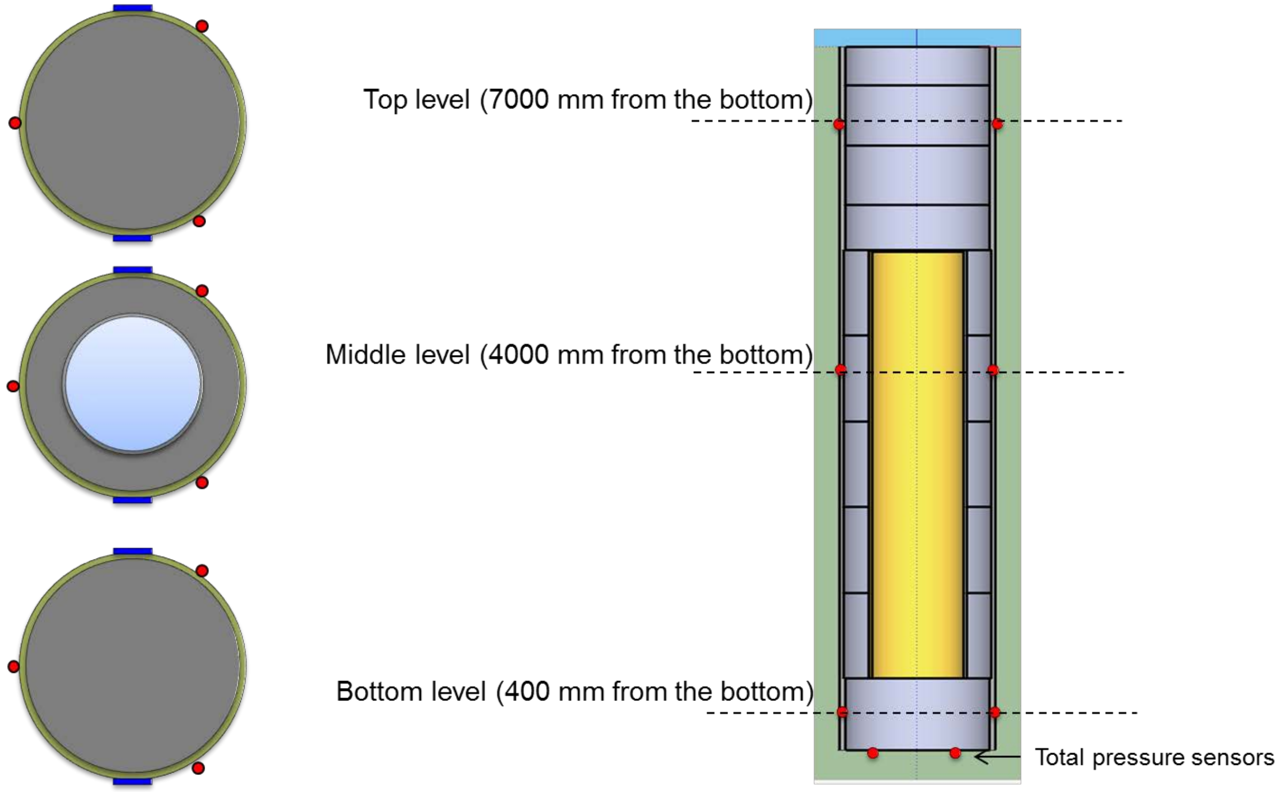


Figure 5.8. Radial pressure measurements in three major sensing levels: 400 mm, 4000 mm and 7000 mm.

Total pressure is measured on the backfill tunnel wall and vault in several locations (Figure 5.9).

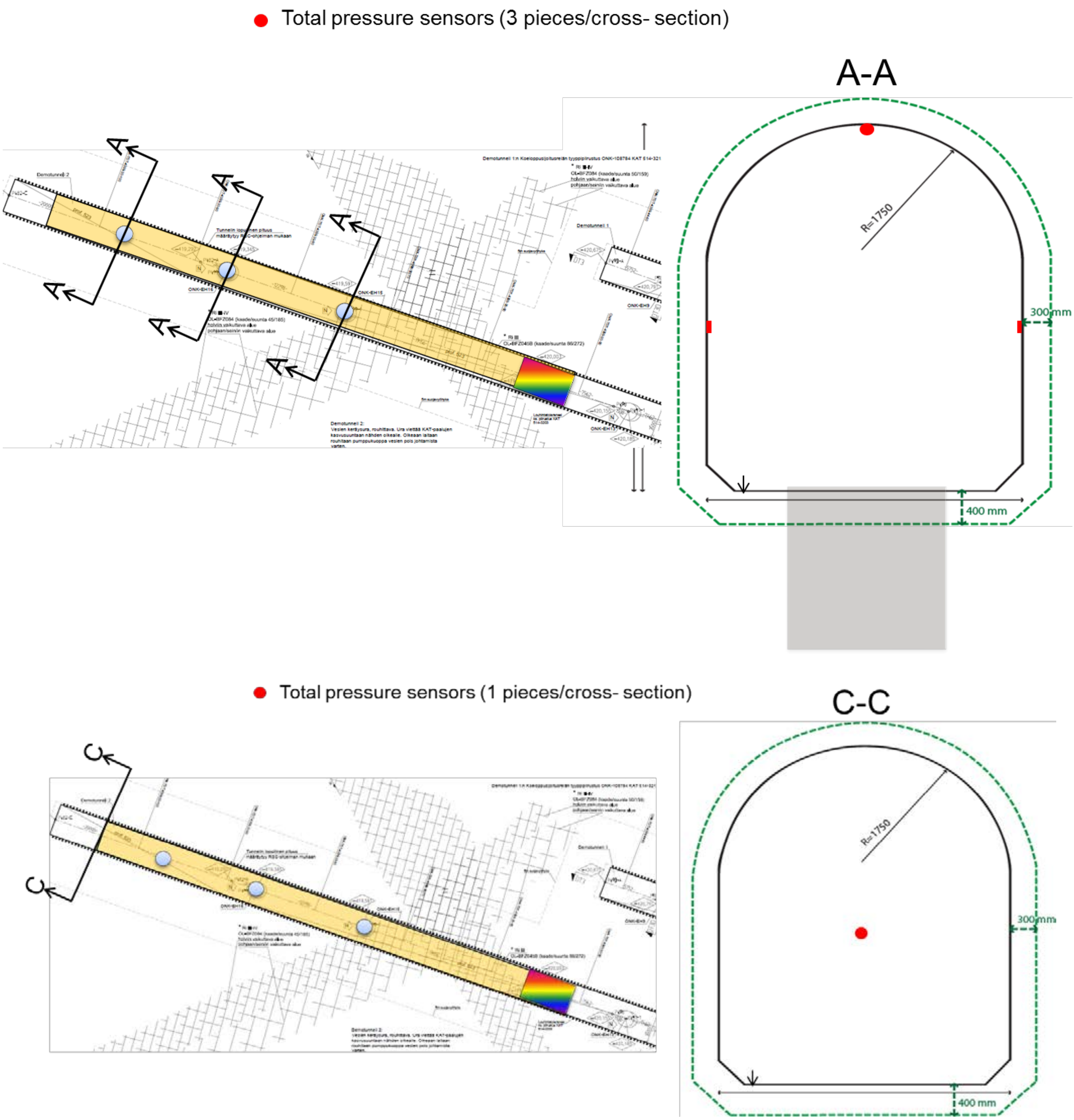


Figure 5.9. Total pressure measurements in the backfill tunnel.

Total pressure sensors are attached to the rock by anchoring adhesive.

5.4 Pore pressure measurements

Pore pressure is measured in several locations in experimental deposition holes (Figure 5.10). Pore pressure sensors are installed in three major sensing levels: 400 mm, 4000 mm and 7000 mm from the bottom of the experimental deposition hole.

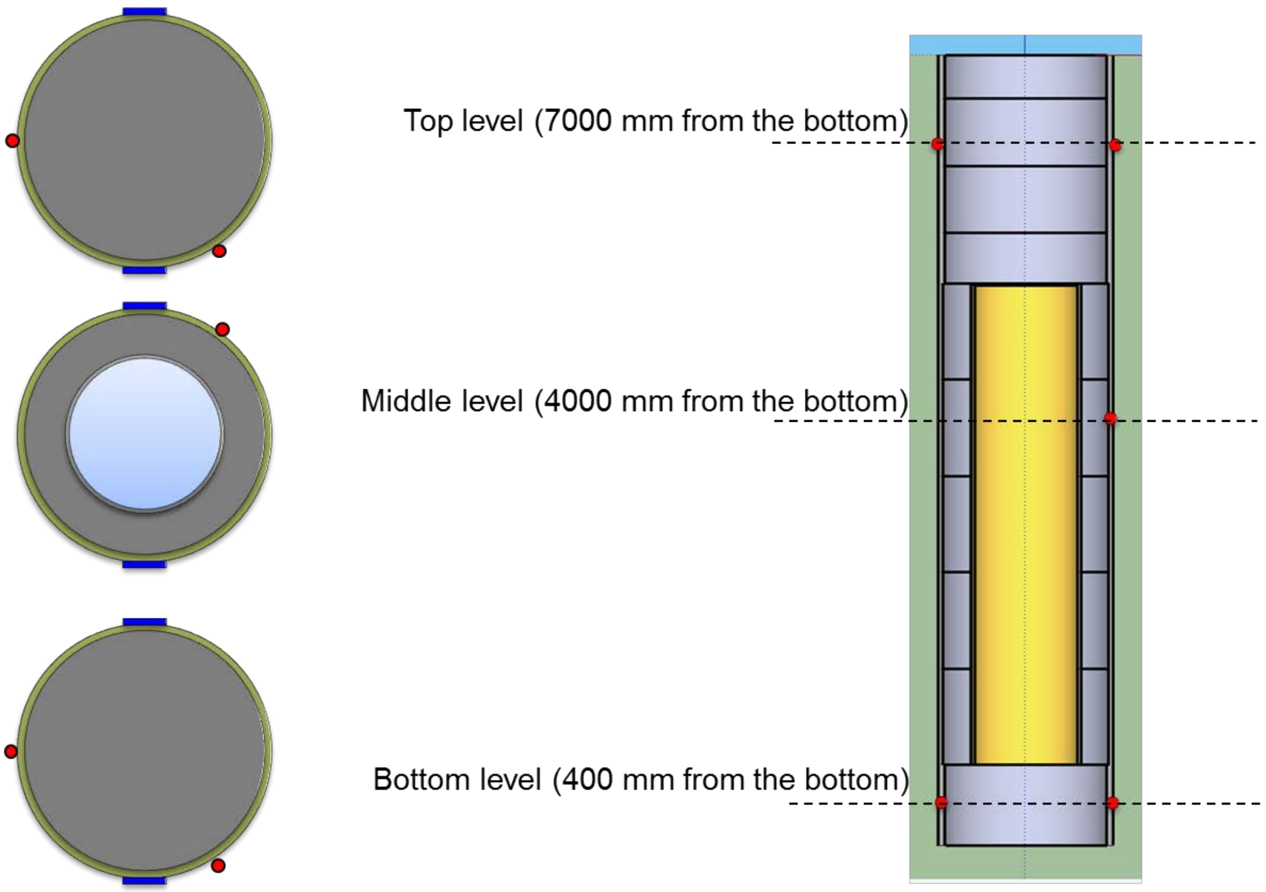


Figure 5.10. Pore pressure measurements in three major sensing levels: 400 mm, 4000 mm and 7000 mm.

Pore pressure is also determined at the backfill tunnel wall in several locations (Figure 5.11).

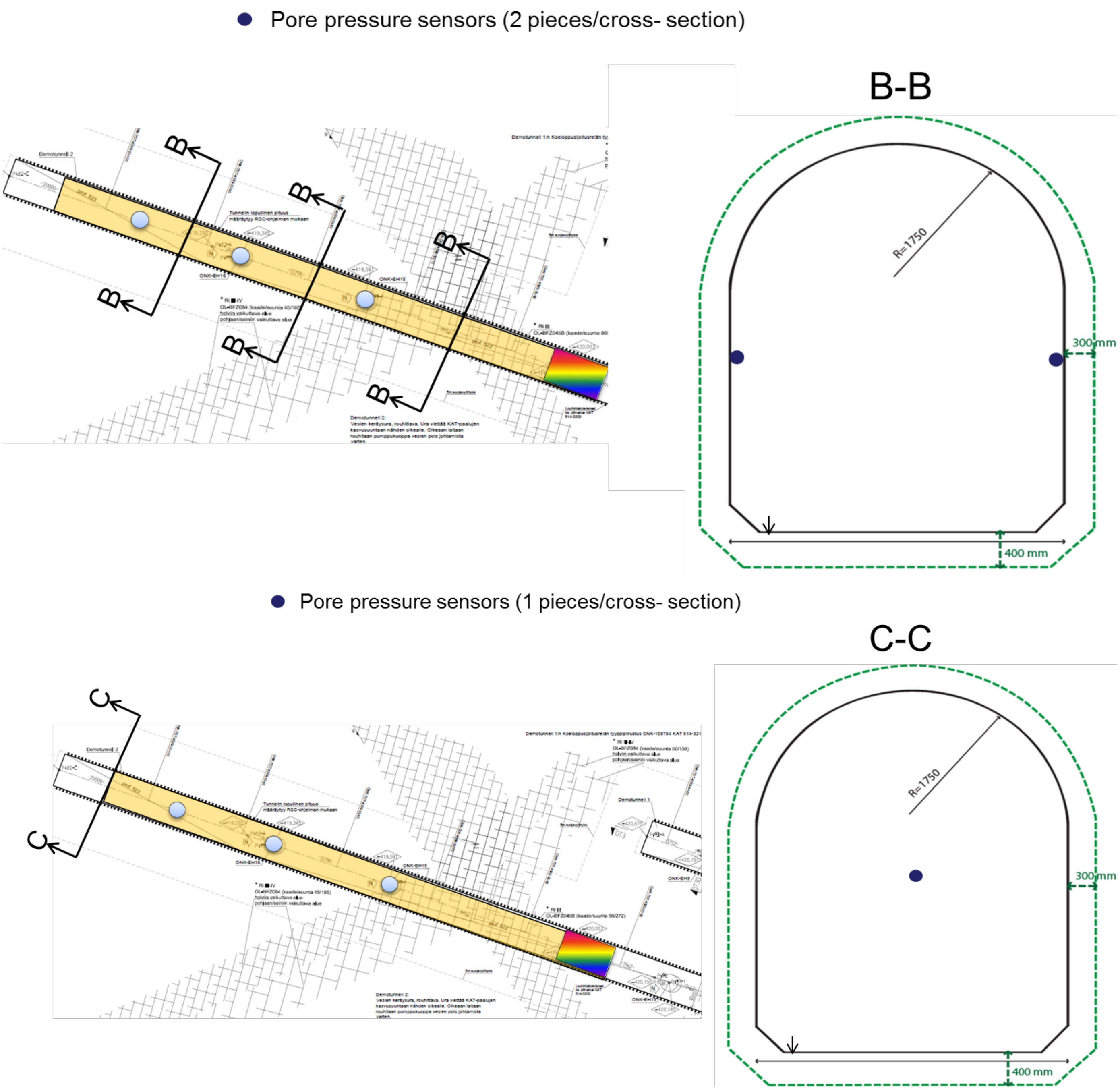


Figure 5.11. Pore pressure measurements in the backfill tunnel.

5.5 Water saturation measurements

The water saturation in the buffer and backfill is recorded by measuring the relative humidity in the pore system and by measuring electric potential difference (voltage) between a large number of metal electrode pairs. The following techniques and sensors are used:

- Capacitive humidity and temperature transducer

- Psychrometer including thermocouples
- ERT (Electric Resistance Tomography) electrode chains

Relative humidity measurements

Capacitive humidity transducers and psychrometers are installed side by side to the rock wall of the experimental deposition holes (Figure 5.12). Some sensors of both types are installed into the bentonite blocks in experimental deposition holes.

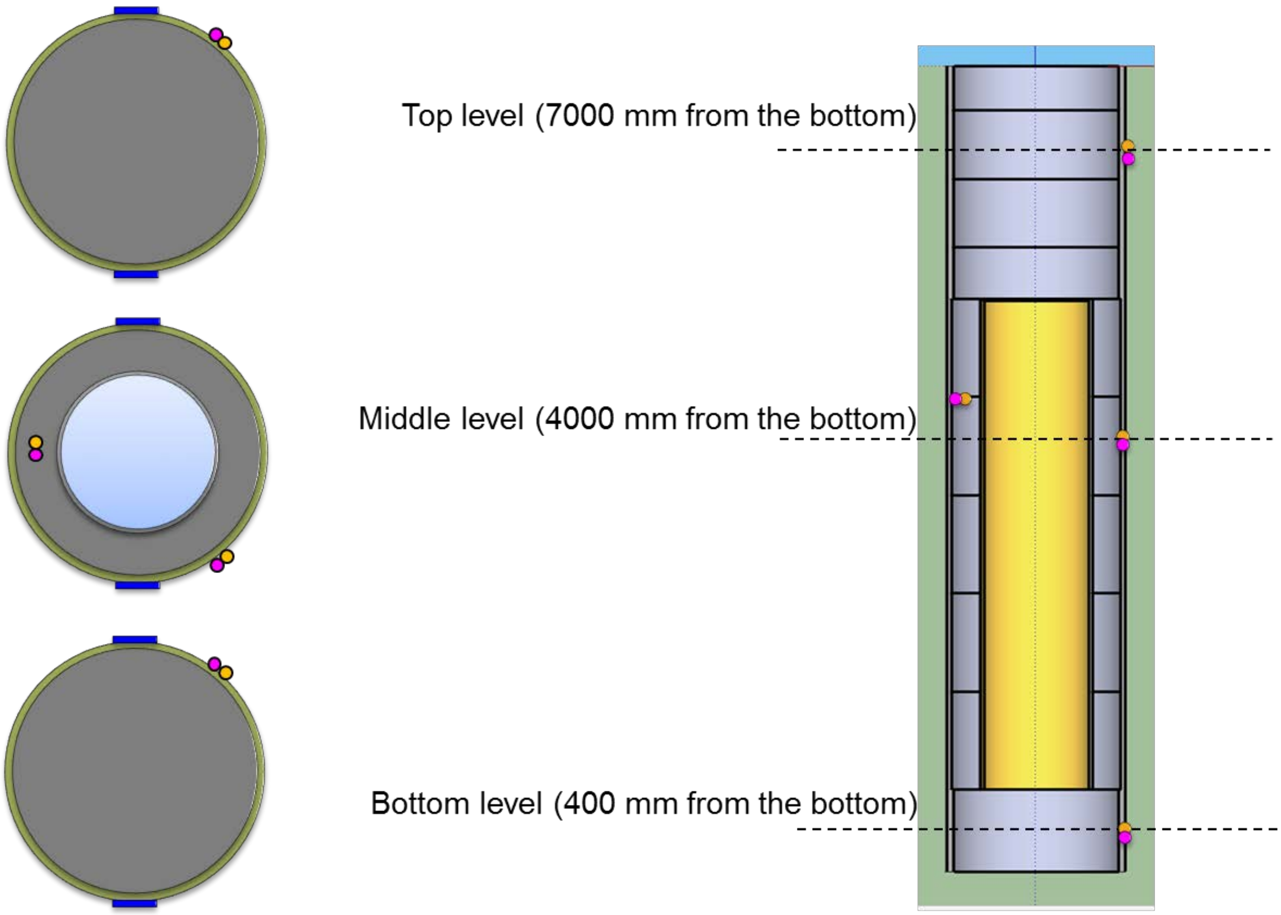


Figure 5.12. Relative humidity measurements (capacitive humidity transducers and psychrometers) in three major sensing levels: 400 mm, 4000 mm and 7000 mm.

ERT (Electric Resistance Tomography) electrode chains

The ERT-electrode chains in the experimental deposition hole include 16 electrodes in each chain.

There are four vertical electrode chains and one horizontal electrode chain (installed to the upper part of the experimental deposition hole) per experimental deposition hole. Therefore, the total number of electrodes is 80 mounted on each deposition hole rock wall and on the bottom of each hole (Figure 5.13).

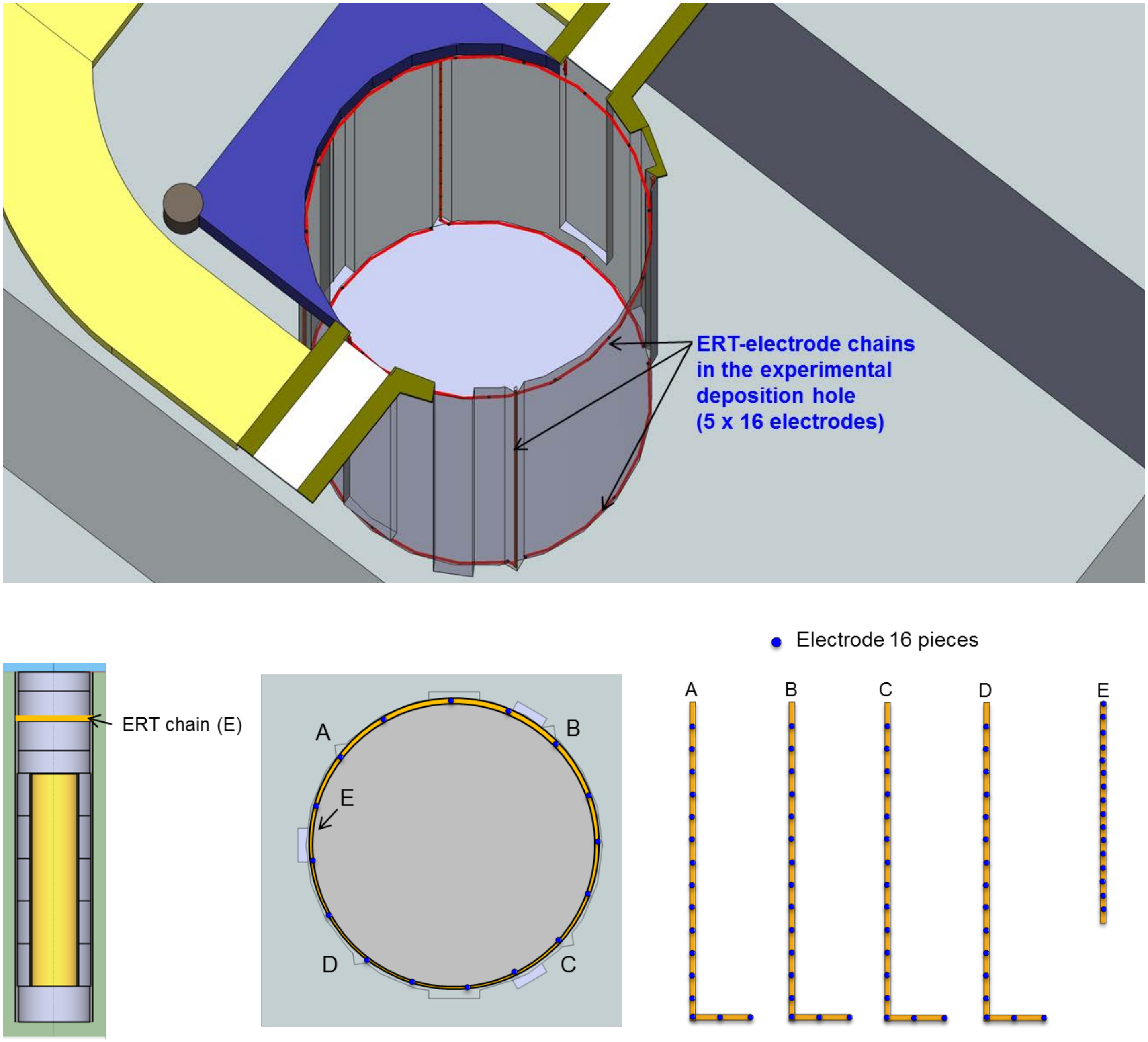


Figure 5.13. ERT - electrode chains in the experimental deposition hole.

ERT - electrode chains are also installed to the walls and vault of the backfill tunnel. Each electrode chain includes 16 electrodes (Figure 5.14 and Figure 5.15).

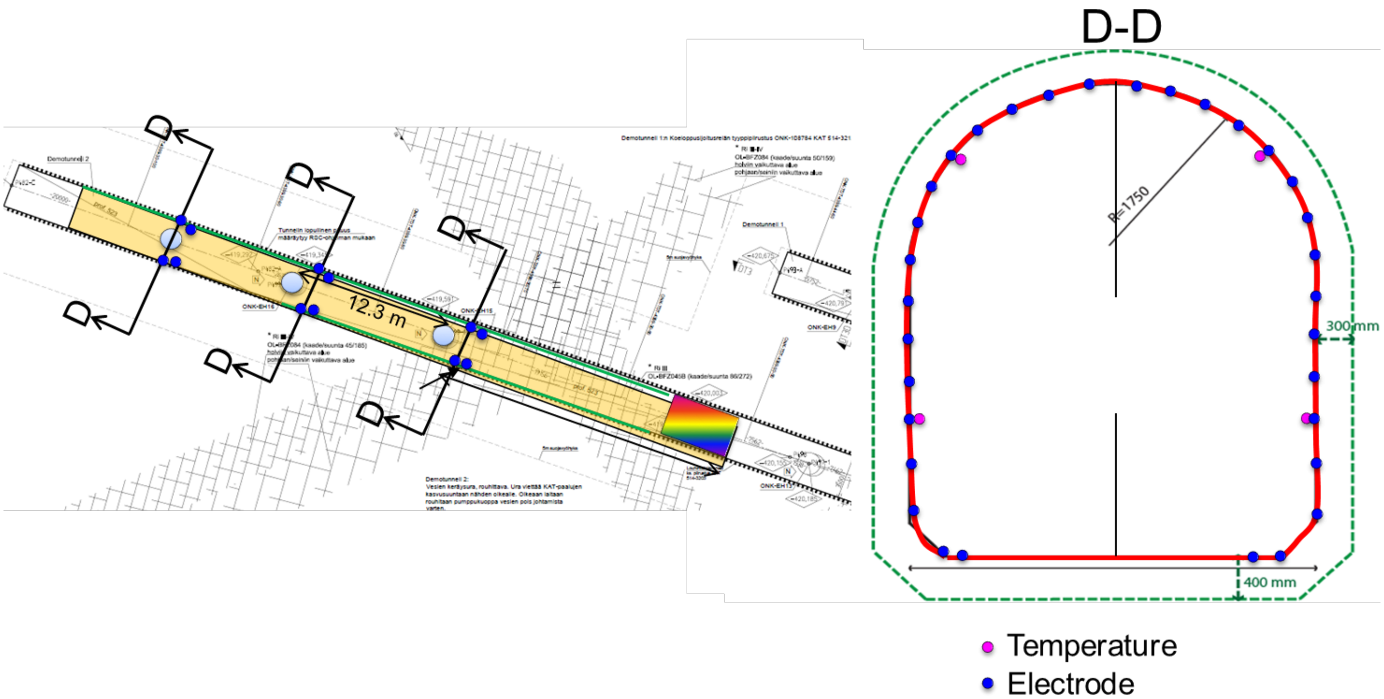


Figure 5.14. ERT - electrode chains in three cross sections of the backfill tunnel.

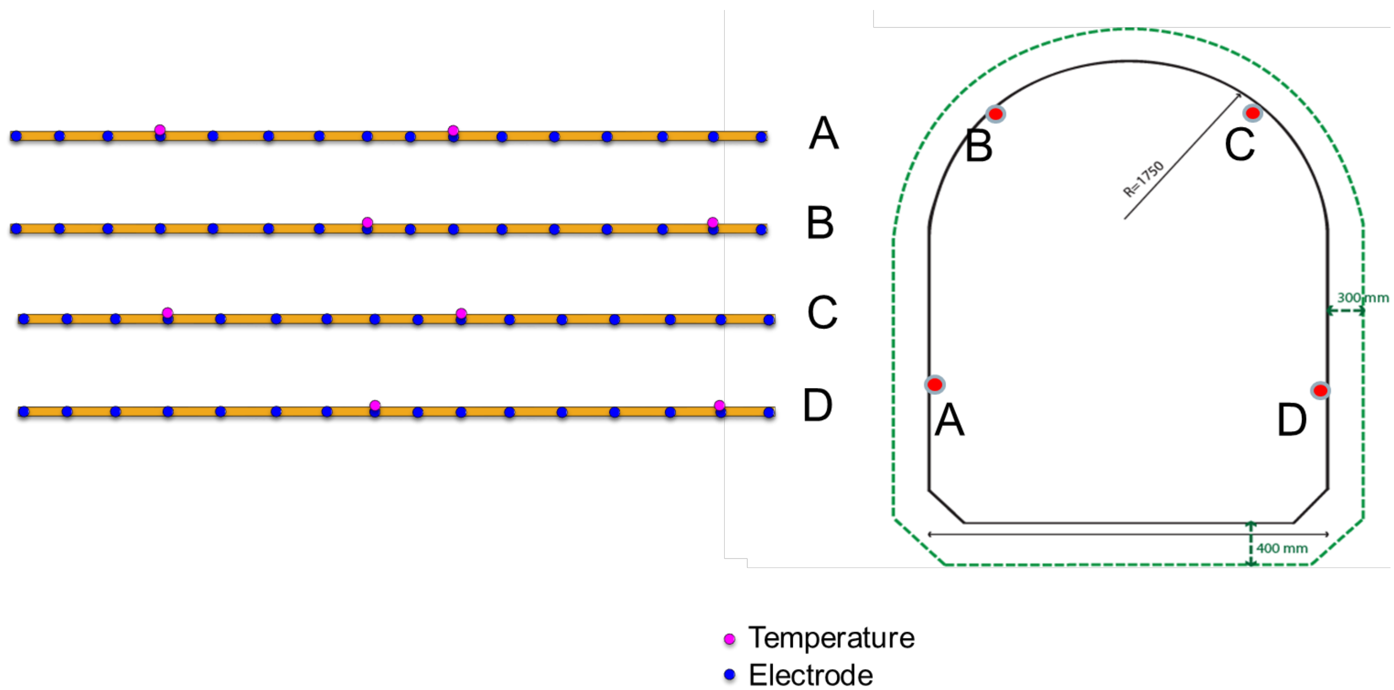


Figure 5.15. ERT - electrode chains in longitudinal lines of the backfill tunnel.

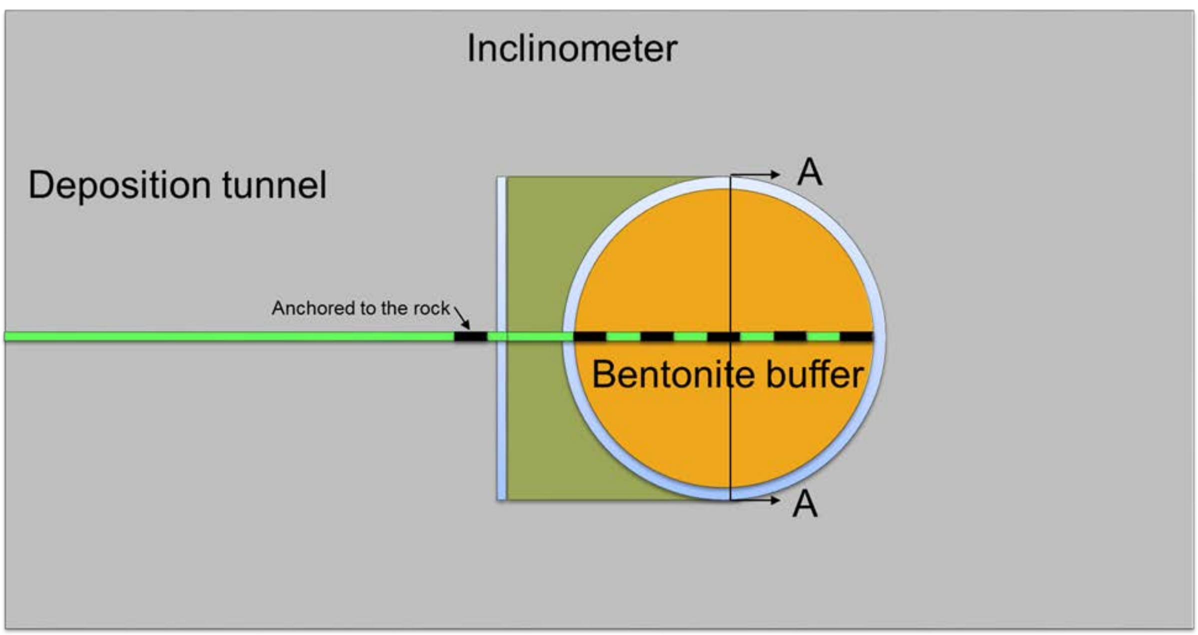
The electrical conductivity of clay blocks and bentonite pellets is influenced by the porosity, dry unit weight, pore water (gravimetric water content, degree of saturation and volumetric water content), as well as pore water salinity.

The idea of the time-lapse (4D) surveys is to conduct repeated measurements over the same fixed network of electrodes and using exactly the same measurement protocol at different times. Data acquisition with electrodes is principally the same as for conventional resistivity methods: two grounded metal electrodes are supplied with a known electric current which causes an electric potential field in the sub-surface. The potential field depends on the yet unknown resistivity distribution. This potential distribution is characterised for each current dipole by measuring the electric potential difference (voltage) between a large number of metal electrode pairs, i.e., each ERT data point requires just a simple current and potential measurement.

5.6 Displacement measurements

The possible upheave of the bentonite buffer is measured with an inclinometer chain (Figure 5.16). The inclinometer chain includes biaxial inclination sensors, which are installed into a tube and filled with casting resin. The space between inclination sensors are filled with elastic mass.

The inclinometer chain is installed on the surface of the upper most bentonite block in the buffer. One inclination sensor is anchored to the rock.



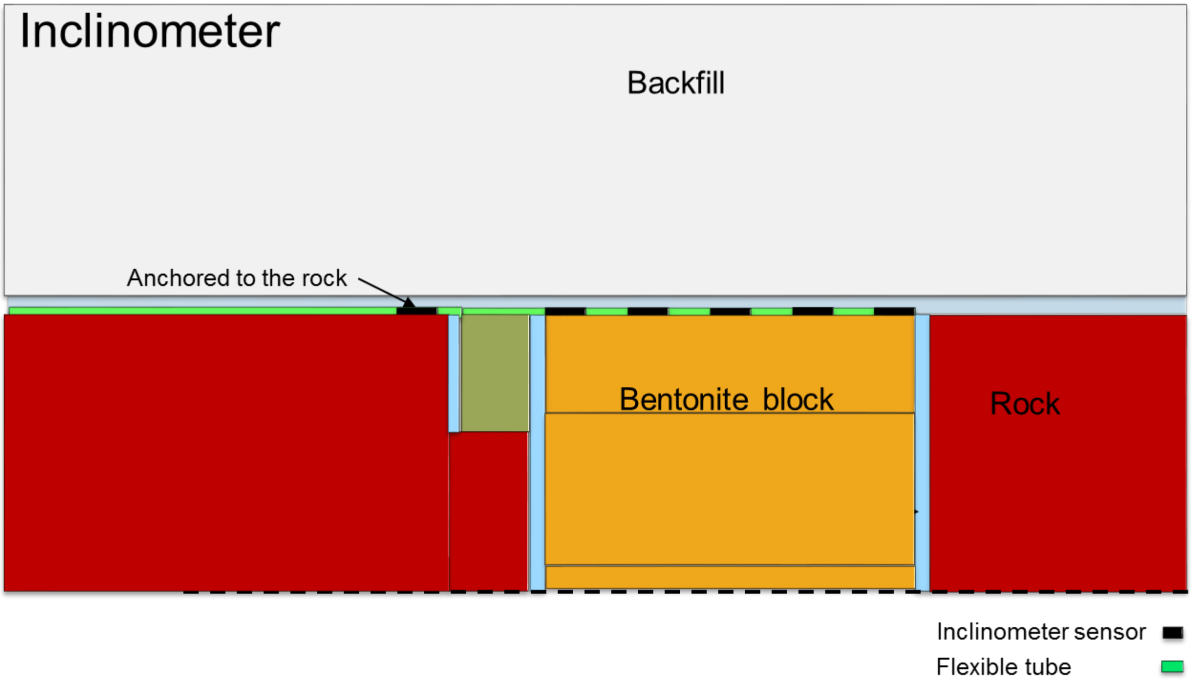


Figure 5.16. The location of the inclinometer in the upper part of the experimental deposition hole.

6 Execution of the monitoring plan

The monitoring process will be simultaneously a learning process to the interaction between the different components and a test to verify the modelling results. Still a careful consideration and different scenarios with reasoning and conceptual model behind might increase the understanding. Different EBS components might behave in different way. The general strategy is to store measurement data with a relatively high frequency in the beginning of the test and then to decrease the frequency. There are several factors behind this consideration. Too frequent measurements will increase the amount of data and although nowadays the databases are able to store almost unlimited amount of data it will influence to the data handling and interpretation. When setting up full scale measurements it is not well known how fast the processes are and therefore frequent measurements in the beginning is reducing the risk to miss some information. The reasoning behind this is that the THM processes might be relatively quick in the beginning of the test and most probably slow down as the saturation of the bentonite progresses. Some sensors are quite flexible for measurement frequency and it is good to adjust according to the evolution of the experiment.

6.1 Temperature, water pressure and total pressure in canister, buffer and backfill

In this EBS monitoring plan the measurement frequency is similar for all components in the beginning. The instrumentation will be installed prior the EBS components and in that way the baseline can be measured prior monitoring of the EBS component behaviour is initiated. The basic frequency for measurements might be adjusted and in beginning it is suggested to be one measurement per minute, or per five minutes at the latest. During the first three months all of this data is saved and reported. Month 4 to 12 one measurement every 10 minutes is stored and reported. For the rest of the duration of the tests one measurement per hour is recorded. As mentioned before the all measurements for month is saved temporarily in case something unexpected happens in which case more data is stored and reported.

6.2 Temperature and water pressure in borehole sections in crystalline bedrock

The interpretation of engineered barriers early evolution do need the surrounding site information to be able to understand the possible changes. The most relevant site properties to support the monitoring of EBS components are hydrogeological and hydrogeochemical properties as well some mechanical properties. With this EBS monitoring plan the temperature and pressure conditions in surrounding rock are the supporting elements which will be followed simultaneously. Some of the measurements need to be established separately to support the EBS monitoring plan, but in many cases in planned repositories this information might be received as part of the site monitoring programme. It is still important to remember in beginning the boundaries and needs toward site monitoring from the EBS monitoring point of view. In this current EBS monitoring plan these supporting measurements are collected by the existing

ONKALO™ general monitoring system with some additional measuring points, which are added to the existing monitoring programme.

6.3 Moisture in buffer and backfill with Electric Resistivity Tomography (ERT)

Since the measuring of all locations are not very practical a novel method is planned to be used to monitor the moisture distribution in buffer and backfill. This measurement system differs from the rest since it is an active process to apply current and measure the resistivity over buffer and backfill. This is done in campaigns that take approximately a couple of days for measurements and weeks for interpretation. The attained data is then analysed and a variation in resistivity over backfill and buffer is presented. This can be converted to water ratio of saturation rate. Ideally in the beginning of the test (approximately the first two months) the measurement are run more frequently, as one campaign has ended and the results been presented and analysed the next campaign will start. It is estimated that this corresponds to one measurement campaign per week. In month three two measurement campaigns are made and for the rest of the first year one campaign per month is made.

If the saturation has slowed down according to predictions the one campaign in every other month is made during year 2. For the rest of the duration of the test one campaign is made every other month or more seldom. There should be some triggers in other values (possible rapid changes in pressure, relative humidity, temperature) which cause a measurement campaign. The ERT measurements do require also other type of moisture sensors to support the interpretation of the results. Those more conventional moisture sensors are installed in the vicinity of ERT sensors and their measurement frequency will be similar to the pressure sensors.

6.4 Moisture and pressure in deposition tunnel plug

Basically the deposition tunnel plug with filter and seal layer is part of the backfill. The plug construction will take place months after the buffer and first part of the backfill and therefore an independent monitoring system is needed. A separate approach to monitor a plug system is tested as part of the DOMPLU (Grahm et al, 2015) and POPLU (Holt & Koho, 2016) projects as part of the DOPAS project (Euratom 7th framework programme).

7 Expected evolution of the measuring systems

All measuring systems and sensors will be exposed to very harsh conditions. The presence of saline ground water bears a high risk for corrosion. The groundwater intrusion and the resulting swelling of the buffer and backfill exposes the sensors and cables to high hydraulic and mechanical pressures. All sensors close to the canister undergo moderate to high temperatures.

These conditions need to be taken into account when selecting the sensor materials and sheltering systems for sensors, wires and cables. The expected evolution of the measuring system can only be estimated based on the exposures and inherent properties of sensors and cables.

Still it needs to be remembered that the inflows to the repository like environment are limited and processes are slow. The installation of the sensors to study the EBS behaviour happens mostly in beforehand in different type of test set ups and therefore the sensors are in open tunnel conditions were they can be damaged already prior or during the EBS component installation and that period also gives possibility for water access. Therefore, special care needs to be taken when storing and handling the sensors before and during installation.

Prior to the installation at the site, a qualification and calibration of the sensors is necessary. Since the available commercial sensors and components (e.g. cables, wires, connectors) are usually developed for their use in other environments, a special qualification process has to be developed and applied. The selection of components potentially useful in the repository monitoring system represents the first stage of the qualification process. The selected components should next undergo a series of laboratory and on-site tests to be considered qualified. The second stage of the qualification process considers the testing of the selected components. Testing should be performed at the laboratory and on-site when possible as laboratory and field tests are essential and complementary. Special testing procedures were developed within the Modern2020 project in Task 3.6 (Modern2020, WP 3, Deliverable D3.6, 2019).

A particular testing procedure is a robustness test to simulate long-term conditions in EBS environment. It is planned to be done in cycles so that it will give provisional results already during the test program. The test plan consists of selected sensors and dummy sensors manufactured form different materials. The idea is to test sensor enclosure and sensor cable armouring/sheltering pipe with the dummy sensors. A test would consist of 20 iterative steps:

- Selected specimens will be exposed 1 month to salinity in neutral salt spray chamber that is expected to simulate 5 years exposure.

- Specimens will be exposed to 15-20MPa pressure that is consider to be hydrostatic pressure 500m below sea-level (5MPa) + swelling pressure of saturated bentonite (10-20MPa). The pressure is applied in a pressure chamber being equipped with heating elements and heated to a temperature of 85°C that simulates temperature close to canister.

Further information on the qualification of components and different recommended tests can be found in Modern2020, WP 3, Deliverable D3.6, 2019.

7.1 Thermocouples

K-type thermocouples will be installed to the inner surface of the copper canister, to the surface of the BWR insert, to the electrode chains and to the 9 m cores drilled to the host rock. The thermocouples in the canister will be protected with alloy inconel 600. The temperatures inside the canister are expected to be less than 150 °C close to the heaters and in the copper canister less than 100 °C. The life expectancy of the thermocouples is high. The installation of the thermocouples and pulling of the sensor cables through the protection tubes are the main risk points of the temperature measuring system.

K-type thermocouples installed to the electrode chains in the backfill tunnel will be protected with 15/11 polyamide tubes. Temperature of the rock is measured with K-type thermocouples installed into polyamide tubes. The 18/15 polyamide tubes will be installed into a 60 mm core hole which length is 9 meters and after installation the hole will be filled with low pH concrete.

7.2 PT100 RTDs

Pt100 resistance temperature detectors (RTDs) will be installed into the heaters. The maximum temperature of the heater is expected to be less than 150 °C. The main risk for damaging the Pt100 sensors is when the sensors are pulled through the protection tubes.

7.3 Total and pore pressure sensors

Total pressure vibrating wire sensors and pore pressure vibrating wire piezometers are selected on the basis of the experiences in the Canister Retrieval Test, Temperature Buffer Test and Prototype Repository test carried out by SKB (Sanden et al. 2005). The risk of corrosion is reduced by selecting titanium for the sensor material.

7.4 Capacitive RH transducers

Total pressure vibrating wire sensors and pore pressure vibrating wire piezometers are selected on the basis of the experiences in the Canister Retrieval Test, Temperature Buffer Test and Prototype Repository test carried out by SKB (Sanden et al. 2005). The risk of corrosion is reduced by selecting titanium for the sensor material.

7.5 Psychrometres

The effective measuring range with psychrometers is from 95 to 99.6% relative humidity. RH can be converted to a suction value, and indirectly to a water content and a degree of water saturation. RH corresponding to suction between -54 kPa to -6916 kPa at 20 ˚C. Since psychrometers can only measure reliable high RH they do not yield results until the pellet filling in the outer gap of the buffer is close to saturation. The risk of failure is high with psychrometers because the structure of the sensor is not designed for external pressures. Commercially available alternatives that can resist external pressure are lacking.

7.6 ERT electrode chains

Stainless steel tube fittings are used as electrodes in the ERT system. The cables of the ERT chain are installed into polyamide tube. The swelling pressure of bentonite blocks in the buffer is expected to be high (> 5 MPa) after 5 to 10 years from the beginning of the test. When the swelling pressure has reached such high values the ERT system is not necessarily needed anymore because the buffer is close to full saturation. There is a risk that the connection between the polyamide tubes and the stainless steel electrodes cannot withstand the swelling pressure. Additionally there is a corrosion risk for the stainless steel electrodes in the saline ground water.

7.7 Inclinometers

The possible upheave of the bentonite buffer will be measured with an inclinometer chain. This type of inclinometer is typically used for monitoring ground movements. The measuring device is an automatic inclinometer consisting of a flexible tube, which includes biaxial inclination sensors.

Six inclination sensors will be installed inside the flexible tube horizontally on the surface of the uppermost bentonite block so that it moves and bends according to the movement of the bentonite blocks and pellet filling. The first inclination sensor of the chain will be anchored to the rock. The displacement profile is calculated from the information provided by the inclination sensors and the distance between sensors. There is a risk that the protection tube does not withstand high external pressures, both hydrostatic and swelling pressure.

7.8 Finishing the test and retrieval

The lifetime of the sensors might define the length of the test, but there are several other facts as well influencing the years to follow up an installed test setup. The model will give the estimated behaviour for a certain time span and it can be used as a guideline when evaluating the test length. The decision to follow up the test is simple when the early evolution follows the modelled behaviour and the sensors do produce reliable readings and simultaneous site information supports that as well. If the evolution is not confirmed by the measurements or the data gives contradicting readings then the test plan needs to be re-evaluated when the setup needs to be dismantled. Dismantling will verify the achieved results or inform about processes, which cannot be seen by instrumentation. Therefore a plan, which handles different scenarios, is needed at the time of the commissioning of the test.

8 A mock up case study to use ERT method for moisture distribution studies

ERT (Electrical Resistivity Tomography) is a widely proven and robust method of characterizing subsurface structure and monitoring subsurface processes for geological, geotechnical, hydrological and environmental applications. Recent advancements in data collection hardware and imaging software have enabled ERT to become practical for variable scale 3D characterization and high-resolution 4D time lapse monitoring applications. The sensitivity of subsurface electrical conductivity to a number of important hydrological and geotechnical parameters enables ERT efficiently to provide non-destructive and often non-intrusive information. Over the past 10-15 years, ERT survey instrumentation has advanced rapidly, enabling large amounts of data to be collected quickly and autonomously, and providing the opportunity to characterize the subsurface and monitor subsurface properties at high resolution in space and time. ERT has developed from a slow procedure of manually measuring point by point to rapid multi-channel data acquisition using automatic multi-electrode systems. These multi-electrode scanning implementations are best known as electrical resistivity/resistance tomography (ERT). The development in computational power has allowed for more efficient processing and imaging-inversion of data, which has been encouraging for investigations with large amounts of data, such as three-dimensional investigations and repeated measurements.

Recently ERT monitoring has been applied in the tunnel floor pellet fill experiments built by Posiva (Korkealaakso et al. 2016). Regularly and automatically repeated measurements have been used to map in 3D the progress of infiltration fronts and water content (moisture) changes caused by injected water in the pellet-concrete-rock system.

The use of electrical resistivity/resistance tomography (ERT) in site investigation studies has been increasing all over the world. It is a convenient method for evaluating spatial and temporal variations of moisture and heterogeneity of geological structures. Recently quantification of geotechnical properties has become an important issue for rigorous use of ERT in engineering applications. The correlations of different geotechnical and/or geochemical properties with ERT are closing the gap that exists between geophysical volume imaging and geotechnical and/or geochemical point (i.e. only at key locations) sampling, testing and drilling.

ERT monitoring has been tested in the mock up test for the bentonite buffer–canister environment. For this mock-up, the experimental 40%-scale laboratory arrangement to imitate the deposition hole-bentonite buffer system that was built by Posiva and equipped by VTT. The main target of the ERT monitoring of small 40%-scale experiment was to evaluate the applicability of the method in moisture monitoring of the bentonite buffer in the deposition hole-type environments. Bentonite blocks surround infinitely conductive canister (electrical conductor). The results and experiences from this study will be used further to examine the feasibility of ERT in general and to develop further the monitoring capabilities of 4D ERT for the similar kind of future monitoring tasks in the bentonite /pellet /rock /concrete /canister systems. The electrical conductivity of clay blocks and bentonite pellets is influenced by the porosity, dry unit weight, pore water (gravimetric water content, degree of saturation and volumetric water content), as well as pore water salinity. It is found that for high water salinities, the electrical conductivity is most significantly related to the volumetric water content.

In the experimental 40%-scale bentonite buffer - canister structure (Figure 8.1) bentonite blocks are surrounded by an infinitely conductive canister (electrical conductor). The canister rested directly on the bentonite block, but there were thin air gaps between the upper (~ 5 cm) and vertical (~ 2 cm) block-canister contacts. The whole cylindrical structure was surrounded by reinforced concrete elements. The empty spaces above and under the canister and bentonite blocks as well as between the concrete elements and the bentonite blocks were filled with bentonite pellets. The test set up is equipped with inflow points and to the bentonite the inflow rate with simulated ONKALO™ groundwater was 1 ml/min.

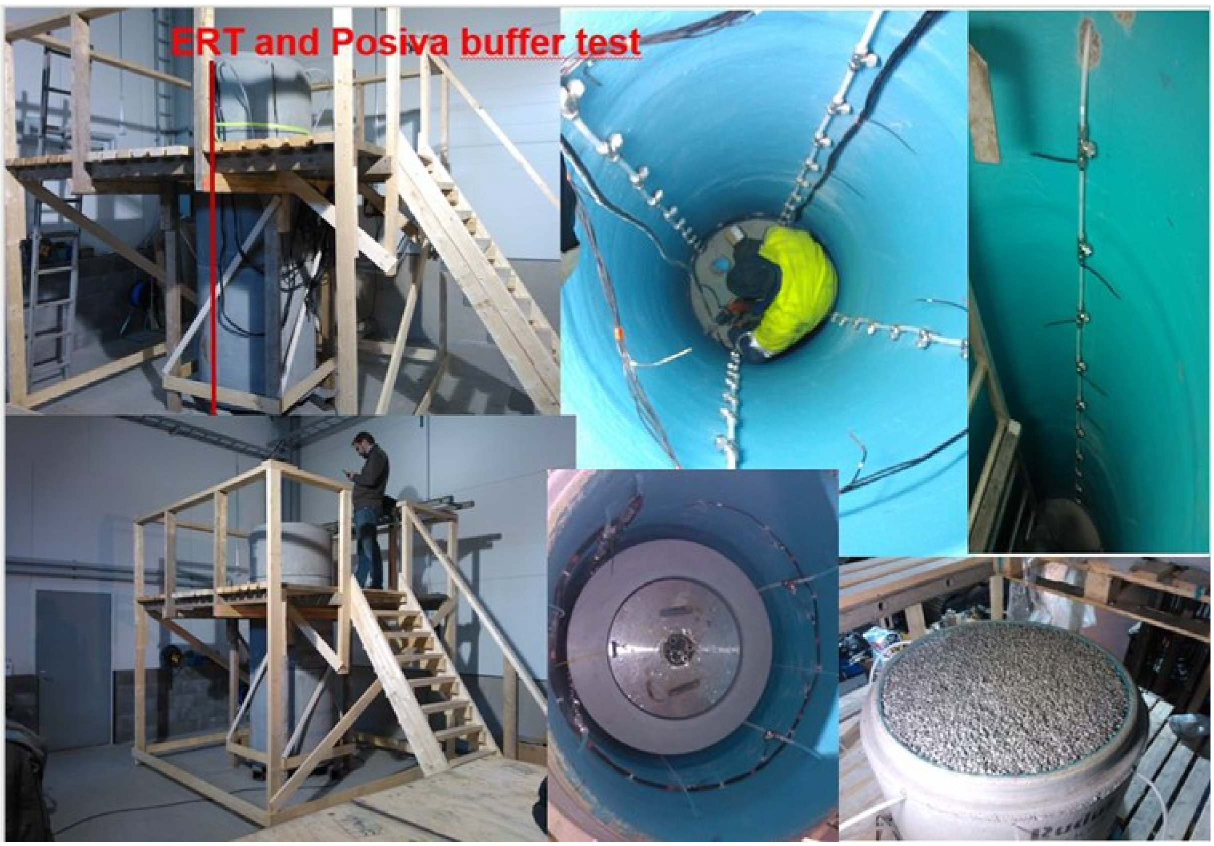


Figure 8.1. The ERT mock up test set up for the experimental 40%-scale bentonite buffer - canister structure

In Figure 8.2 the positioning of the ERT electrodes on the inner concrete surface and in the pellet layer between the concrete wall and the bentonite buffer volume is shown. The electrode layout consists of four sets of vertical electrode chains and two sets of horizontal ring chains. Vertical electrode spacing was ~220 mm and horizontal ~250 mm. There were also three additional electrodes in the middle of the structure between vertical electrode line pairs T1-T2, T2-T3 and T3-T4. The ERT monitoring that covered the whole water injection period was carried out in 3D using all 63 electrodes. Swagelokconnectors were used as electrodes in the vertical lines and 5 cm long copper rods in all horizontal chains. The possible disturbing effects of iron bars of the surrounding concrete frame were decreased using water insulating paint on the inner concrete element surfaces. The electrode surroundings were not wetted in the beginning of the test.

The horizontal chains have been built to surround both the upper blocks and the lower blocks above and under the canister. In this way the monitoring volume consists of four closed, rectangular subvolumes where each subvolume consists of two adjacent vertical electrode chains with over- and underlying horizontal, curved electrode chains that complete the loop between vertical chains (see Figure 8.2). In the middle of the system there were still three additional electrodes located in the middle three of the vertical electrode lines. Sensitivity studies have shown that using these horizontal chains together with four vertical electrode chains it is possible to monitor rather evenly the pellet and buffer volume. With the support of horizontal loops it is possible to monitor also moistening processes in the bentonite volumes above and under the canister. In the implementation of these horizontal lines the copper electrodes were applied. This kind of electrode arrangement minimizes also the possible shunting and scaling effects of the perfectly conductive canister to the current lines. The current vectors can be directed between adjacent vertical electrode chains and thus along the outer block and pellet volumes of the cylinder and of course not across and through the canister.

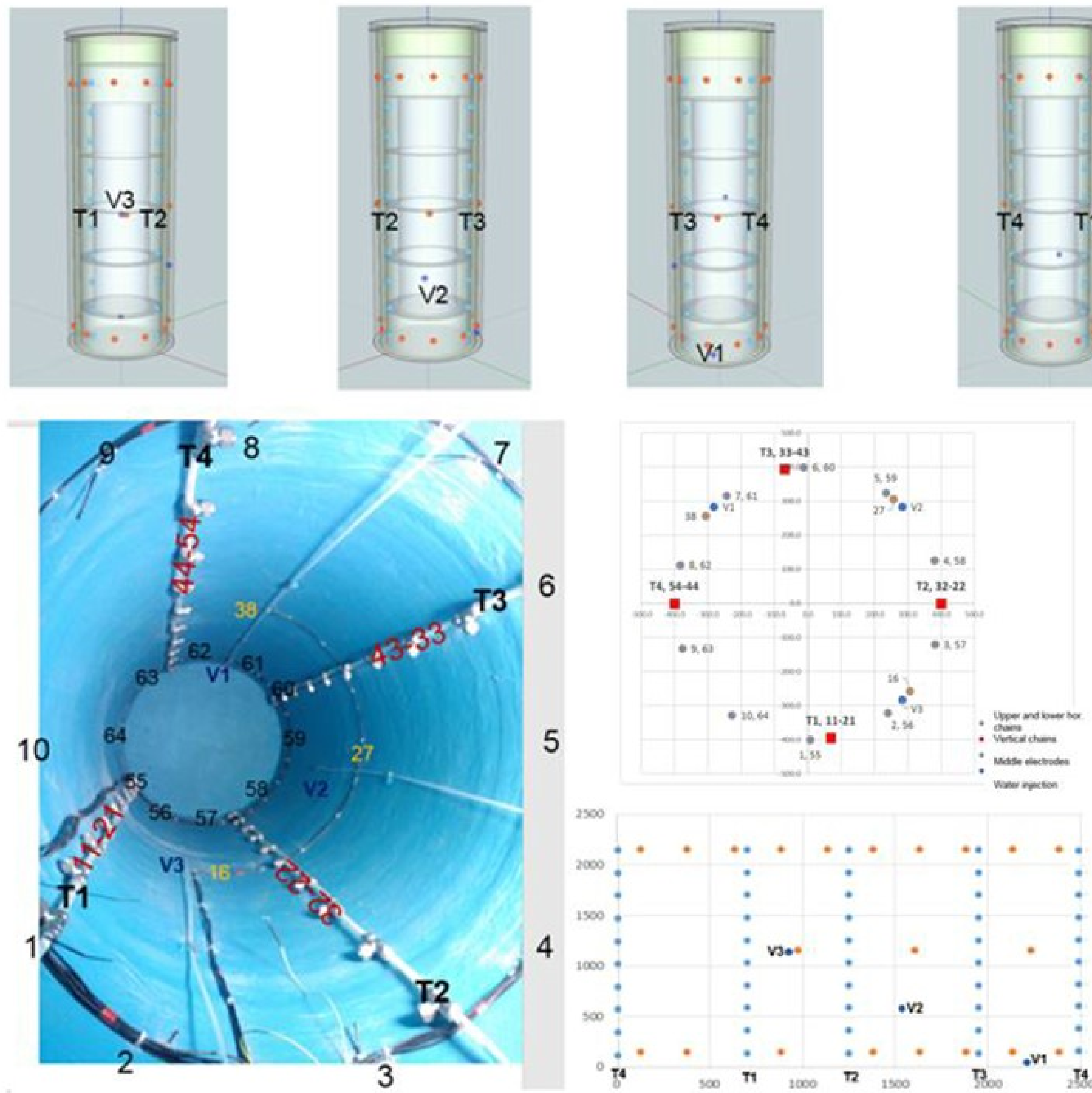


Figure 8.2. The locations of 63 electrodes and alternative water injection points V1, V2 and V3 as well as the numbering of electrodes in the 3D model, in the 2D rectangular electrode surface of the 3D cylinder model and in the actual ERT test arrangement.

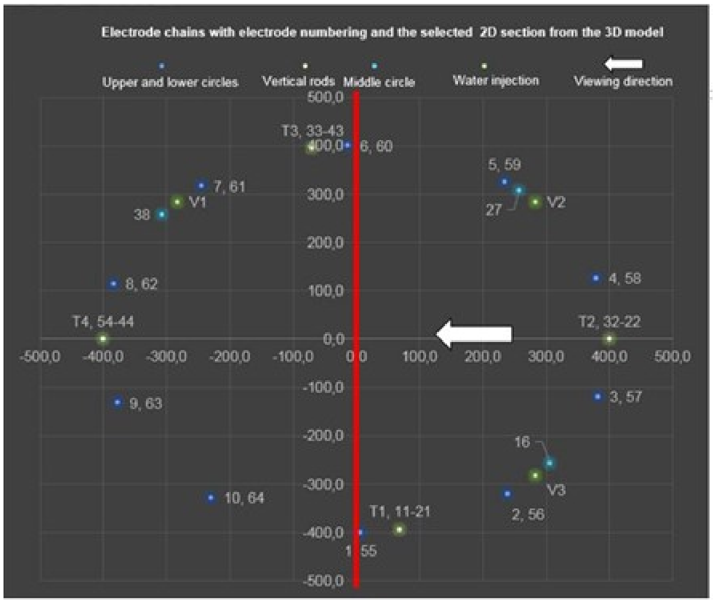
The locations of 63 electrodes and alternative water injection points V1, V2 and V3 as well as the numbering of electrodes in the 3D model, in the 2D rectangular electrode surface of the 3D cylinder model and in the actual ERT test arrangement.

The idea of the time-lapse (4D) surveys is to conduct repeated measurements over the same fixed network of electrodes and using exactly the same measurement protocol at different times. ERT data acquisition is simple and fast. Data acquisition with electrodes is principally the same as for conventional resistivity methods: two grounded metal electrodes are supplied with a known electric current which causes an electric potential field in the sub-surface. The potential field depends on the yet unknown resistivity distribution. This potential distribution is characterized for each current dipole by measuring the electric potential difference (voltage) between a large number of metal electrode pairs, i.e., each ERT data point requires just a simple current and potential measurement.

The automatic monitoring protocol was programmed to repeat the measurements in the interval of 8 hours. The first monitoring was timed to start daily at the midnight, the second at 8 am and the third at 4 pm. Each single monitoring cycle consisted of 2634 four electrode potential- current measurements and took about four hours. Thus, each successive monitoring result reflects the moisture changes that have happened during last 8 hours (the interval between identical four electrode resistance measurements is exactly 8 hours). The first measurement was made on 18.10.2016 at 4 p.m. and the monitoring ended at midnight on 23.1.2017.

The ABEM Terrameter LS (where LS stands for Lund Imaging System) was used for the measurements. The system integrates receiver, transmitter, electrode selector and computer units (http://www.abem.se/). The system can be programmed for automatic measuring at pre-selected intervals and includes also remote control possibility and support via Ethernet. Built in relay-switch and built in processors allow programming of own monitoring protocols. The instrument has a built- in relay switch that handles 64 electrodes, but it can be expanded with a number of Electrode Selector ES10-64C relay switches to allow for more electrodes. The electrode layouts are defined in so called spread files that define the type of measurement setup (e.g. 2D surface layouts, 3D grids, borehole cables, etc). The measurement sequences are specified in protocol files that can be designed for arbitrary measurement arrays.

The primary results of the ERT test are the 3D resistivity distributions that are calculated for each single monitoring. These results are typically studied as 2D vertical and horizontal slices that are cut from the 3D models or in 3D as selected colour contours. The other alternative is to present results as 2D rectangular surfaces as a function of distance from the centre of the bentonite-canister cylinder structure. Slices are here presented as absolute resistivities. In Figure 8.4 and Figure 8.6 the 3D inversion results from the first days of monitoring are presented as the 2D vertical cross-sections. These considerations were selected to investigate the wetting front indications from the contact resistances in more detailed. In the 2D snapshots of the Figure 8.4 the vertical presentation plane goes through the centre line as well as vertical through T1 and T3 electrode chains (see Figure 8.3) and in the snapshots of the Figure 8.6 the presentation plane goes through the center line as well as V1 and V3 injections points (see Figure 8.5). The results reveal the same wetting front development with the wetting of volumes below the canister and the spreading of the front upwards along the volumes around the T1 vertical electrode chain.



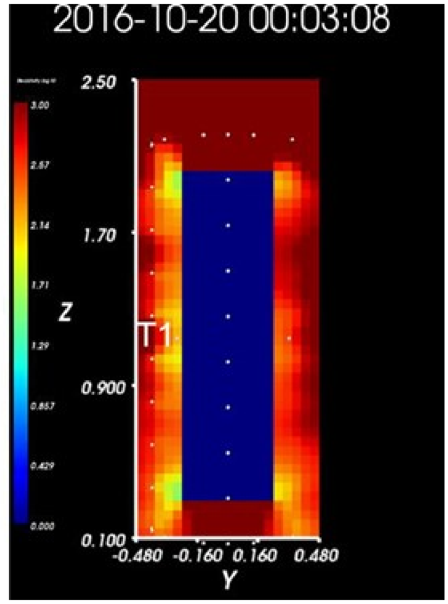


Figure 8.3. The location of the selected vertical cross-section to present the 3D monitoring results in Figure 8.6.

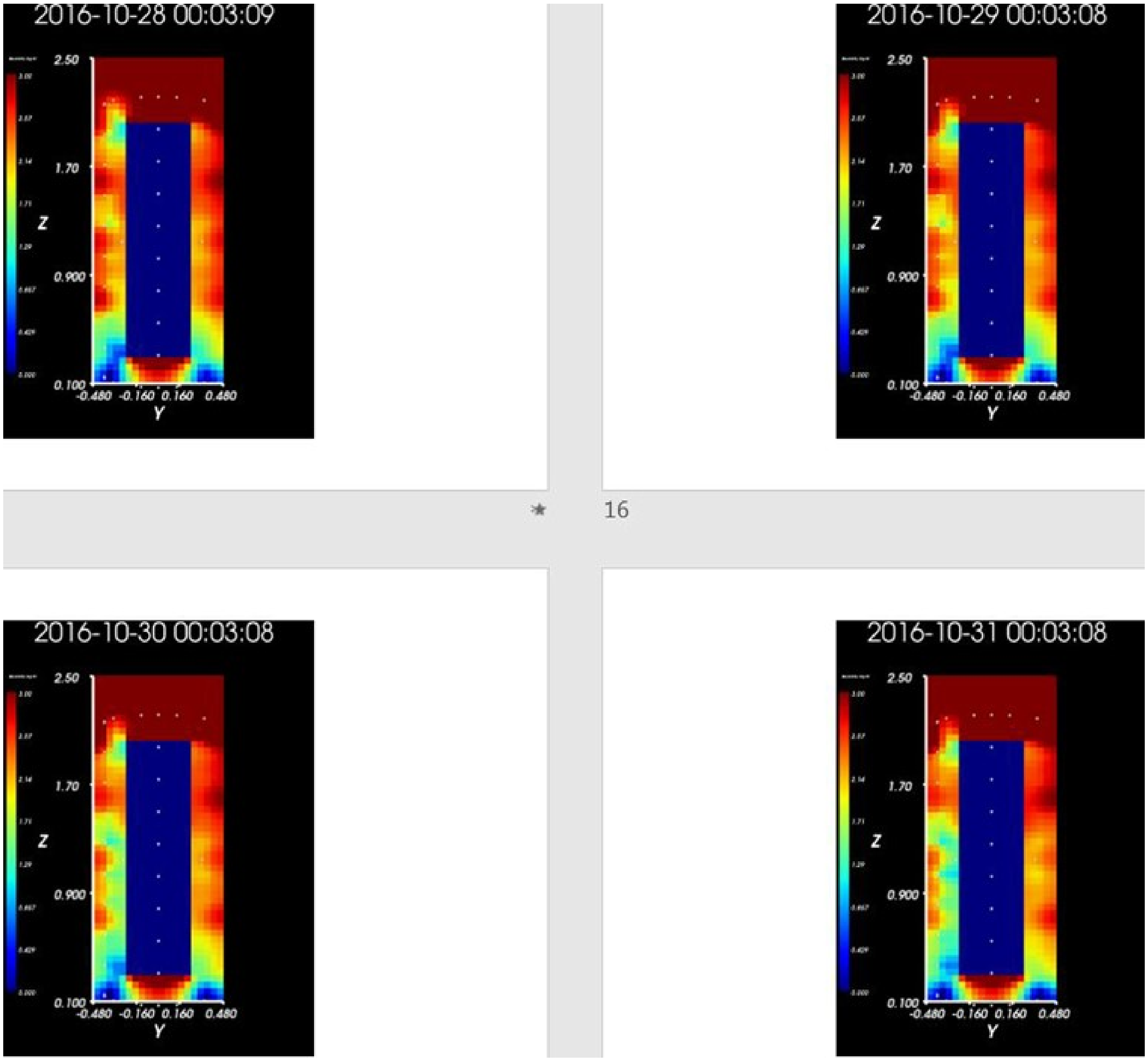


Figure 8.4. The 3D inversion results from the first days of monitoring presented as the selected 2D vertical cross-section. The wetted areas can be traced as the dark blue volumes of under 10 Ohm-m (in the logarithmic scale: under log10 = 1) resistivities.

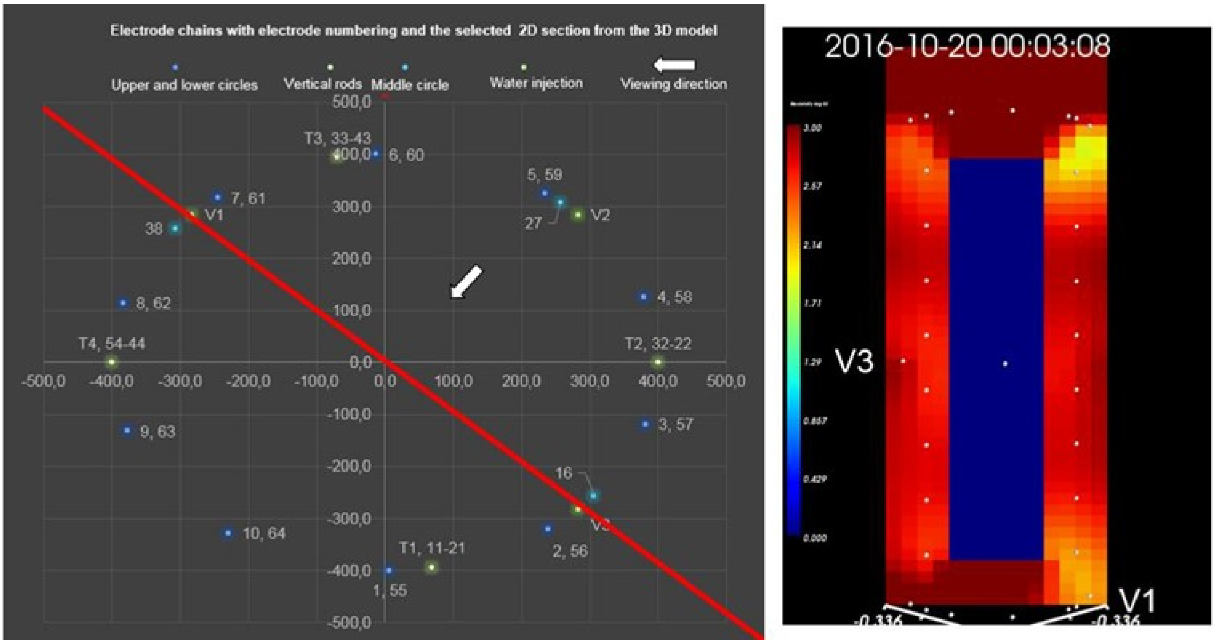


Figure 8.5. The location of the selected vertical cross-section to present the 3D monitoring results in Figure 8.6.

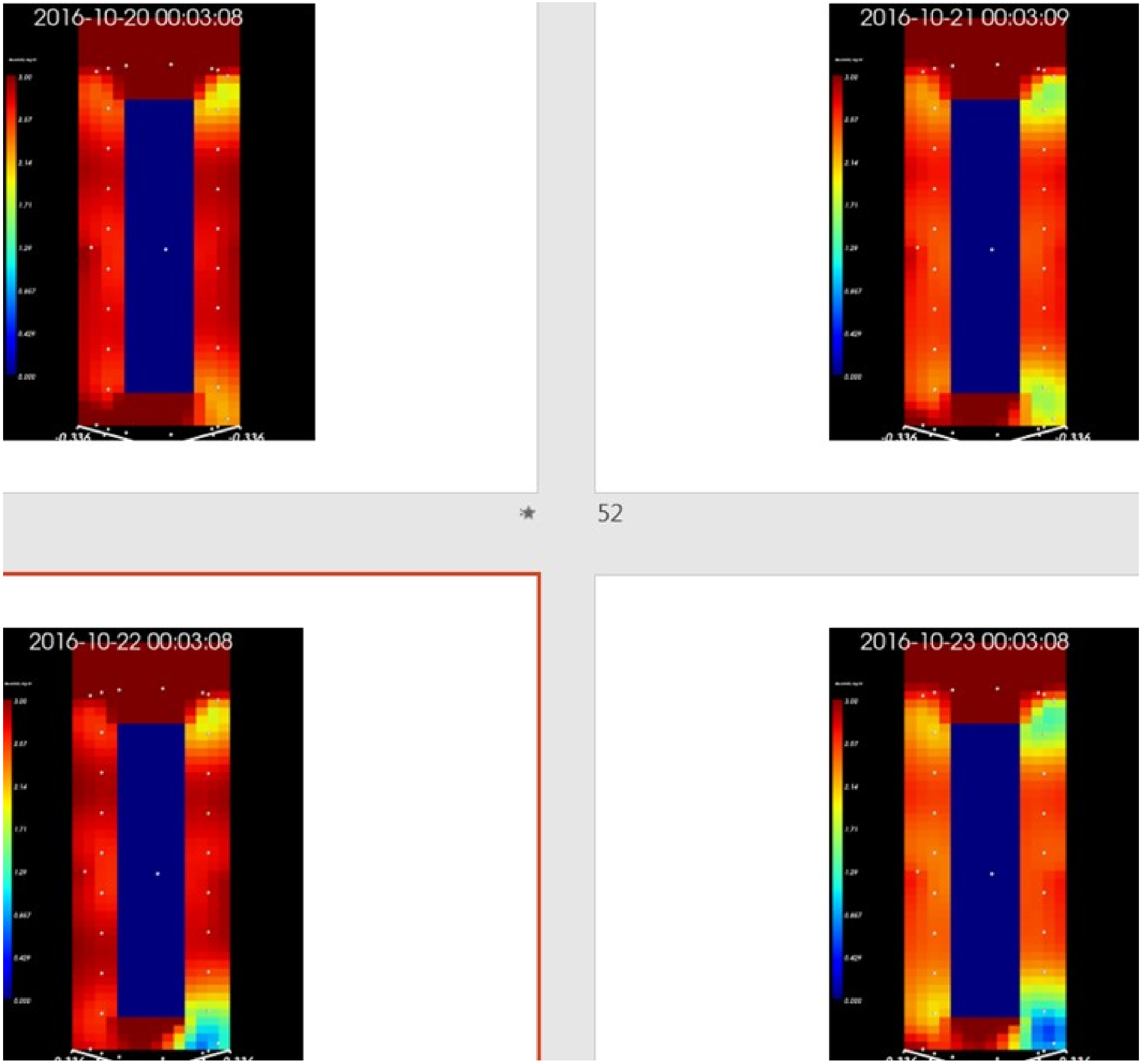
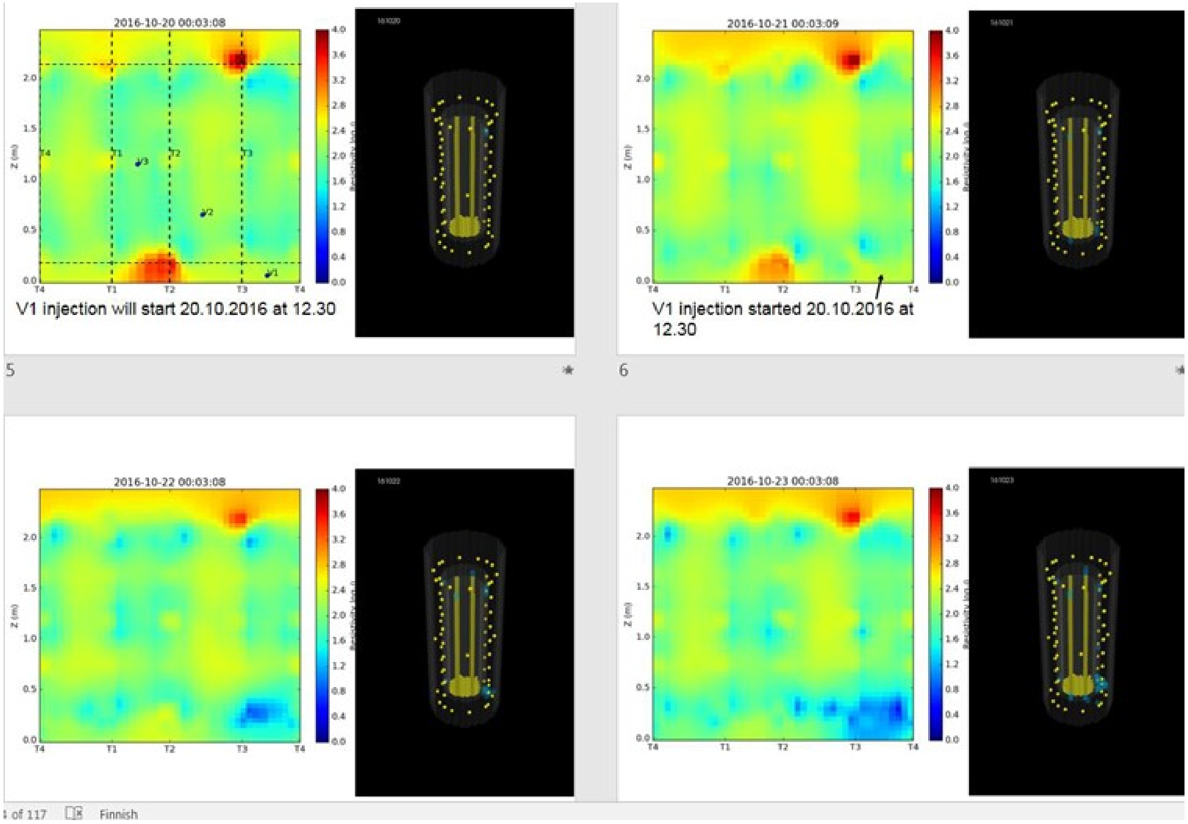


Figure 8.6. The 3D inversion results from the first days of monitoring presented as the selected 2D vertical cross-section.

The 3D results for the whole test monitoring period are presented in Figure 8.*7*. The inverted snapshots are presented as the opened 2D surface of the cylinder model together with the 3D colour contour (transparency) presentation.


2016-10-20 00:03:08
V1 injection will start 20.10.2016 at 12.30
2016-10-21 00:03:09
V1 injection started 20.10.2016 at 12.30
5
6
2016-10-22 00:03:08
2016-10-23 00:03:08
Z (m)
T4
T1
T2
T3
V1
V2
V3
Finnish

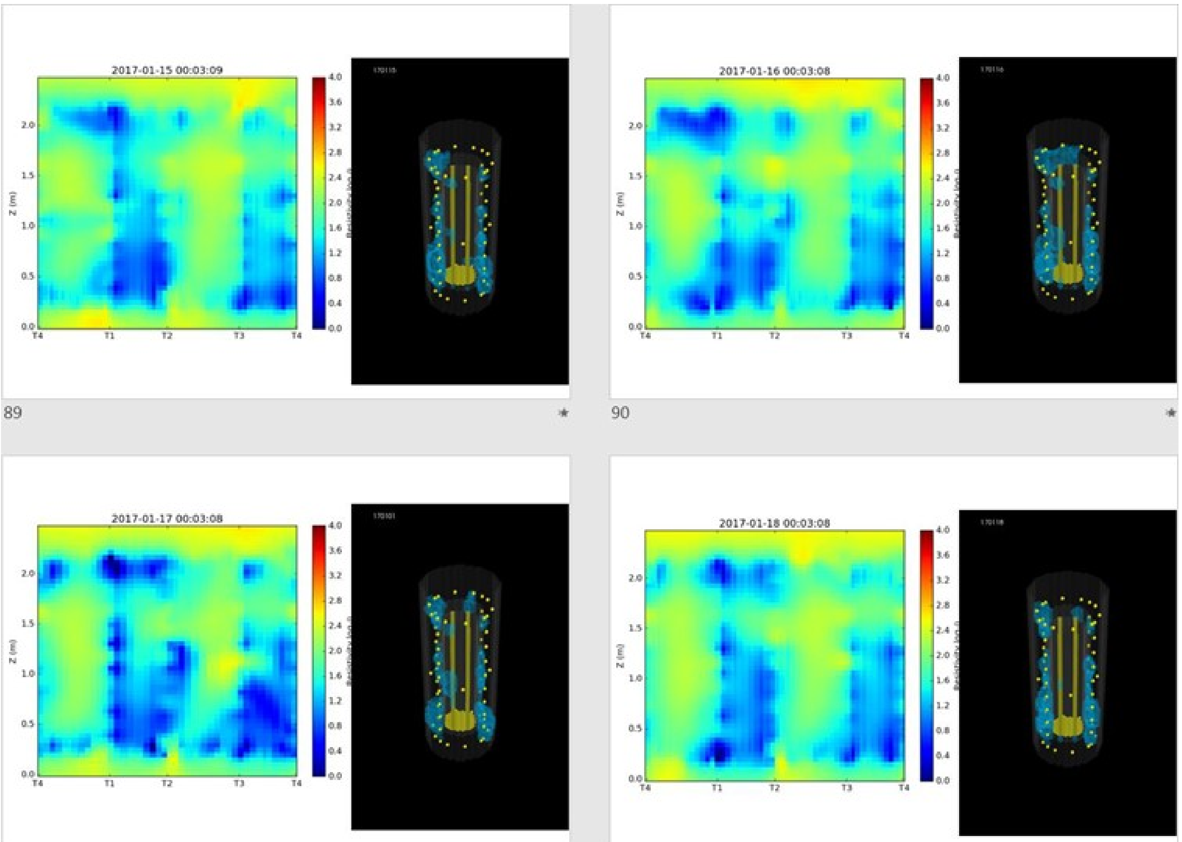


Figure 8.7. The 3D results for the whole test for selected dates are presented as daily snapshots during the first and last monitoring days.

These time-lapse tomograms provide valuable insights into field-scale saltwater/tracer migration behaviour and hydraulic heterogeneities in the floor and block stack, tomographic inversion for the single pixel volumes results in underestimation of tracer mass. Such underestimation is attributed to reduced measurement sensitivity to electrical conductivity values with distance from the electrodes and spatial smoothing (regularization) from tomographic inversion.

9 Conclusions

This EBS monitoring plan does describe the processes to be monitored, proposes an instrumentation to be used for monitoring and proposes an example for the experimental deposition tunnel, which can be used as basis for making design for full scale experiments where monitoring aspects are included as part of the test. In practice, the main part of the objectives set for an EBS monitoring plan can be applied for different type of test setups and experiments and just one example is presented in this report.

The objectives set for a monitoring plan will be verified by comparing monitoring results to predictions and discuss disagreements in the perspective of the safety case. In most cases differences between predictions and monitoring results will have no implication for the safety case and this needs to be analysed. In this monitoring plan the verification is not planned to be done within Modern 2020.

The results from monitoring data in combination with results from the dismantling and parallel development work will be used for improving the understanding of THM processes during the course of the test. This understanding can in turn be used for the adjusting the detailed design of EBS components like canister, buffer and backfill.

The scope of the report is to present predictions for an artificial location in crystalline host rock to be monitored and propose a monitoring set up based on the Modern2020 work in WP2 and WP3. An assessment of monitoring methods is included as well as the mock up for moisture distribution monitoring inside an artificial deposition hole.

10 References

Aggarwal S, Addepalli V, Smart N, 2015. Further metallographic analysis of MiniCan SCC test specimens. SKB R-15-11, Svensk Kärnbränslehantering AB.

Benmokrane, M., Chekired, H., Xu (1995). Monitoring behavior of grouted anchors using vibrating-wire gauges. Journal of Geotechnical Engineering-ASCE Vol. 121 (1995), pp. 466–475.

Coutts, D., Wang, J., Cai, J. (2001). Monitoring and analysis of results for two strutted deep excavations using vibrating wire strain gauges, Tunnelling and Underground Space Technology 16 (2001), pp. 87–92.

Dunmore, F. (1938). An Electric Hygrometer and Its Application to Radio Meteorography; J. Res. Natl. Bur. Stand. Vol 20, 1938, pp. 723–744.

ENRESA, 2006. Full-scale Engineered Barriers Experiment. Updated Final Report 1994–2004. Publicación Técnica ENRESA 05-0/2006, Madrid, 590pp

Farahani, A., Wagiran, R., Hamidon, M. N. Humidity Sensors Principle, Mechanism, and Fabrication Technologies: A Comprehensive Review; URL http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4063076/ (06.02.2015).

Fenner, R., Zdankiewicz, E. (2001). Micromachined Water Vapor Sensors: A Review of Sensing Technologies; Ralph Fenner and Edward Zdankiewicz, IEEE Sensors Journal, Vol. 1, No. 4, Dec. 2001; http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=983470&tag=1 (06.02.2015).

Globalspec: URL http://www.globalspec.com/learnmore/sensors_transducers_detectors/weather_sensing/weather_instruments (06.02.2015).

Goudarzi R., Prototype Repository – Sensor data report, (Period 010917–180101), Report No 29, SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

Grahm, P.; Malm, R.; Eriksson, D. (2015). DOPAS Work Package 4, Deliverable D4.3: DOMPLU Summary Report, Version 1, December 2015 (content identical to SKB publication SKB TR-14-23).

Hakola, I., Kivikoski, H., Löija, M., Marjavaara, P., 2015. Designing, Commissioning and Monitoring of 40% Scale Bentonite Buffer Test. Working Report 2015-08. Posiva Oy.

Holt, E. and Koho. P. (2016). DOPAS Work Package 4, Deliverable D4.5. POPLU Experiment Summary Report

Instruction manual, Model 4500 series vibrating wire piezometers (2014). Geokon, Inc. URL http://www.geokon.com/content/manuals/4500_Piezometer.pdf (6.2.2015).

Kang, U., Wise, K. D. A High-Speed Capacitive Humidity Sensor with On-Chip Thermal Reset; Fellow, IEEE; URL http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=830983 (06.02.2015).

Kivikoski H., Marjavaara P. and Rantamäki, P. (2014). Designing, Commissioning and Monitoring of 40% Scale Bentonite Buffer Test. In: Final Proceedings of the 40th Waste Management Conference (WM2014), March 2–6, 2014, Phoenix, Arizona, USA, CD-ROM, Paper No. 14260.

Korkealaakso, J. & Saarenpää, J. (1998). Sähköinen tomografiakuvaus pohjaveden suojausrakenteiden valmistuksessa. Kunnalliselämä, 7/1998, pp. 22–27.

Korkealaakso, J. (1998). Underground imaging (GRP and ERT) in infrastructure studies. In Urban underground water and waste-water infra-structure: Identifying needs and problems. European Commission, 123 p.

Korkealaakso, J. (2013). The development of repeated DC/IP monitorings and interpretation. Sovelletun geofysiikan XIX neuvottelupäivät 25.–25.9.2013. Sarja B, Nro 96, Eurajoki, 2 p.

Korkealaakso, J., Marjavaara, P. (2014). Electrical Resistance Tomography. The Full Scale Buffer Test: Work packet Deliverable, WP 5.0 Instrumentation design Version 1.1, Posiva.

Korkealaakso et al. (2016). Published in Schatz, T., Hassan, Md. M. & Marjavaara, P., 2017. Assessment and Optimization of Foundation Layer Design at Large-Scale. Posiva Oy, Olkiluoto, Finland, WR 2017-38

Kristensson, O. 2015. Description of Code_Bright models incorporating surface fracture representations. Internal Posiva Memorandum

Matsuguchi, M., Shinmotol, M., Sadaok Y., Kuroiwa, T., Sakai, Y. Effect of cross-linking degree of PVCA film on the characteristics of capacitive-type humidity sensor; URL http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=721966 (06.02.2015).

MoDeRn Project (2013). WP2 State of Art Report on Monitoring Technology. Deliverable D-N: 2.2.2. EU FP7 Euratom Research and Training Programme on Nuclear Energy, Grant Agreement no. 232598, 16.05.2013, 217 p.

Modern2020. Work Package 3. Deliverable D3.6 Reliability and qualification of components. 2019, p. 59

Posiva 2012a. Safety case for the disposal of spent nuclear fuel at Olkiluoto – Synthesis 2012. Eurajoki, Finland: Posiva Oy. POSIVA 2012-12. 277 p. ISBN 978-951-652-193-3

Posiva 2012b. Monitoring at Olkiluoto – a Programme for the Period Before Repository Operation. Posiva-report 2012-01. Posiva Oy, Eurajoki, Finland.

Posiva 2012c. Safety case for the disposal of spent nuclear fuel at Olkiluoto - Description of the Disposal System 2012. Eurajoki, Finland: Posiva Oy. POSIVA 2012-05. ISBN 978-951-652-186-5.

Pusch R, Börgesson L, Svemar C (eds), 2004. Äspö Hard Rock Laboratory. Prototype Repository. Final report (Deliverable D36). SKB IPR-04-27, Svensk Kärnbränslehantering AB.

Sanden T., Goudarzi R., Börgesson L. 2005, Transducers and cable connections for measuring THM-processes in engineering barriers - design and experiences. Advances in Understanding Engineered Clay Barriers - Alonso & Ledesma 2005.

Sánchez, M., Gens, A., 2006. FEBEX Project final report. Final report on thermo- hydro-mechanical modelling. Publicación Técnica ENRESA 05-2/2006, Madrid, 163pp.

Saksa, P., Korkealaakso, J., Pirhonen, V. & Kaila, J. (1986). Neste Oy Muovitehtaan alueen EDC-kulkeutumistutkimus. Valtion teknillinen tutkimuskeskus, Geotekniikan laboratorio, 44 p.

Skierucha, W. (2004). Design and performance of psychrometric soil water potential meter, Institute of Agrophysics of Polish Academy of Sciences, Soil Physics, Doswiadczaina 4, 20-290 Lublin, Poland, online 25 September 2004

Teague, K. A., Gallicchio, N. (2017). The Evolution of Meteorology. A Look into the Past, Present, and Future of Weather Forecasting , Wiley Online Library, 2017

Tyler, R. G. (1976). Vibrating wire pressure gauge. Tunnels Tunnelling, 11/1976, Volume 8, Issue 7.

United States Department of Defense (2011). Technology Readiness Assessment (TRA) Guidance. URL: http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf

User’s manual, Vibrating-wire piezometers (2008). Applied Geomechanics, San Francisco. URL http://www.ampere.com.mx/pdf/Manual_Usuario_Bigboy_VWP.pdf.

Vaisala: URL http://www.vaisala.fi/Vaisala%20Documents/Technology%20Descriptions/HUMICAP-Technology-description-B210781EN-C.pdf (06.02.2015).

Water Potential System Users Manual, Wescor, Logan, UT, 2004.

Wu, J. (2018). A Basic Guide to RTD Measurements, Texas Instruments, Application Report, SBAA275–June 2018

Yu, F., Gupta, N. (2005). An efficient model for improving performance of vibrating-wire instruments. Measurement, Volume 37, Issue 3, April 2005, pp. 278–283.

Appendix A.1 Table of relevant measurement technologies (1/2)

EBS component	Process/property to be monitored	Parameter	Technology	Range	Accuracy	Durability, Reliability	Durability, Reliability	Applicability for wireless sensing	Technology Readiness Level (TRL)	References	Notes	Evaluation - decicion making process 1 = low/poor/negative 2 = moderate/unknown 3 = high/good/positive							
					e.g. % of measuring rage	Service Life 1 to 10 years	Service Life 10 to 100 years		1-3: basic/ conceptual 4-6: proof of concept in lab or relevant environment 7-9: prototype demonstration to succesful operation			A effect of cable length on signal	B dimension of sensor and ease of instal-lation	C accuracy of measure ment	D dura-bility, relia-bility	E Applica-bility for wireless sensing	F TRL and referen-ces	G Specialty, singularity, novelty, uniqueness	R evaluation result, rating
											weighting factor f_i:	5 %	10 %	5 %	30 %	5 %	25 %	20 %	100 %
Canister (copper)	Radiogenic heat production	Surface temperature	Thermocouple	-270 to +2300 °C, usually used > 100 C	+/- 0.75 %; max 1.5 K	high	medium	high	9	BAST Heft B105, Modern Deliverable 2.2.2	OK long term stability, fast response, reliable, applicable for very high temperature, easy to wire	3	3	3	3	3	3	2	2,80
	Radiogenic heat production	Surface temperature	Resistance temperature detector (RTD)	-200 to +800 °C	+/- 0.5 %; 0.5 to 1.5 K	high	high	high	9	BAST Heft B105, Modern Deliverable 2.2.2	Best long term stability	3	3	3	3	3	3	2	2,80
	Radiogenic heat production	Surface temperature	Thermistor	-100 to +500 °C, usually < 100 C	high accuracy	high	medium	high	9	BAST Heft B105, Modern Deliverable 2.2.2	moderate long term stability, risk for drift, nonlinear behaviour, fast response, small, simple electronic circuitry	2	3	3	3	3	2	2	2,50
	Radiogenic heat production	Surface temperature	Direct Write Thermal Spray (DWTS) thermocouple	high range (0-800C)	good	high	medium-low	high	4-6	VTT BA2111	High wear resistance and durability, high temperature tolerant	3	1	2	3	3	1	3	2,25
Buffer & backfill	Heat transfer	Temperature	Thermocouple	-270 to +2300 °C, usually used > 100 C	+/- 0.75 %; max 1.5 K	high	medium	high	9	BAST Heft B105, Modern Deliverable 2.2.2	OK long term stability, fast response, reliable, applicable for very high temperature, easy to wire	3	3	3	3	3	3	2	2,80
	Heat transfer	Temperature	Resistance temperature detector (RTD)	-200 to +800 °C	+/- 0.5 %; 0.5 to 1.5 K	high	high	high	9	BAST Heft B105, Modern Deliverable 2.2.2	Best long term stability	3	3	3	3	3	3	2	2,80
	Heat transfer	Temperature	Thermistor	-100 to +500 °C, usually < 100 C	high accuracy	high	medium	high	9	BAST Heft B105, Modern Deliverable 2.2.2	moderate long term stability, risk for drift, nonlinear behaviour, fast response, small, simple electronic circuitry	2	3	3	3	3	2	2	2,50
	Heat transfer	Thermal conductivity	Heat flow meter	high range	medium	medium	low	medium	6-8	VTT BA2112	system based on heat source and temperature field measured by thermocouples	3	2	2	1	2	2	2	1,75
	Water uptake	Moisture - water content	Neutron moderation	0-60%	+/- 0.5%	medium	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	large sensing volume, robust, not affected by salinity, manual readings, requires radiation source (safety hazard, strict regulations)	1	1	3	2	1	3	1	1,90
	Water uptake	Moisture - water content	Time domain reflectometry (TDR)	5-50%	+/- 1%	low	low	low	7-9	Munoz-Carpena et al._SR-IWM-2	moderate sensitivity to salinity, affected by attenuation of e.g. heavy clays, specific calibration required, small sensing volume, large sensors, requires complex electronics and software	1	2	2	2	1	3	1	1,95
	Water uptake	Moisture - water content	Freq domain capacitance (FD) / Freq domain reflectometry (FDR)	0-100%	+/- 1%	low	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	low sensitivity to salinity, affected by attenuation of e.g. heavy clays, good contact with medium is required (risk in swelling/shrinking medium), no data processing - direct connection to loggers possible, specific calibration required, small sensing volume, sensitive to temperature, density, clay content and air gaps	2	2	2	1	2	3	1	1,75
	Water uptake	Moisture - water content	Amplitude domain reflectometry - impedance (ADR)	0-100%	+/- 1%	medium	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	little affected by salinity, small - minimal disturbance, no data processing - direct connection to data loggers, not affected by temperature, specific calibration needed, small sensing volume, non-linear behaviour	2	3	2	1	2	3	2	2,05
	Water uptake	Moisture - water content	Phase transmission	5-50%	+/- 1%	low	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	sensitive to salinity, large sensing volume, large - considerable disturbance, no data processing - direct connection to data loggers, requires specific calibration, non-contact measurement	2	1	2	1	2	3	1	1,65
	Water uptake	Moisture - water content	Time domain transmission (TDT)	0-70%	+/- 5%	low	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	large sensing volume, large - considerable disturbance, no data processing - direct connection to data loggers, requires specific calibration	2	1	1	1	2	3	2	1,80
	Water uptake	Moisture - water content	ERT/IPT	high range	medium	high	high	low	7-9	VTT BA2112	non-destructive/3D overall distributions of moisture changes, large sensing volume, affected by temperature and salinity, requires processing and interpretation of data	3	3	1	3	1	3	3	2,80
	Water uptake	Moisture - water suction	Tensiometer	80 kPa (max 1500 kPa)	+/- 1 kPa	low	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	moderate sensing volume, not affected by salinity, limited suction range, slow response time, good contact with medium required (problems in swelling and coarse soil), not used near saturation, requires frequent maintenance (refilling of water inside sensor)	2	2	2	1	1	3	1	1,70
	Water uptake	Moisture - water suction	Gypsum resistance block	50-1500 kPa	+/- 1 kPa	low	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	moderate sensing volume, simple system, affected only by high salinity, low resolution, very slow response time, affected by aging/degradation (service life < 2 to 5 years), good contact with medium required (not suitable for swelling materials), not used near saturation, requires minimal maintenance, nonlinear behaviour (hysteresis), temperature dependent	3	1	2	1	2	3	1	1,70

Appendix A.2 Table of relevant measurement technologies (2/2)

	Water uptake	Moisture - water suction	Granularmatrix sensor (GMS)	10-200 kPa	+/- 1 kPa	low	low	medium	7-9	Munoz-Carpena et al._SR-IWM-2	moderate sensing volume, simple system, minimal maintenance needed, affected only by high salinity, low resolution, very slow response time, good contact with medium required (not suitable for swelling and coarse materials), can be used closed to saturation, problems with re-wetting after drying	3	2	2	1	2	3	1	1,80
	Water uptake	Moisture - water suction	Heat dissipation	10-3000 kPa	+/- 7%	low	medium	low	8	Munoz-Carpena et al._SR-IWM-2	moderate sensing volume, continuous reading possible, no maintenance required, not affected by salinity, slow response time, fairly large power consumption, very fragile, corrections/specific calibrations needed, operation is demanding	3	2	1	2	1	3	1	2,00
	Water uptake	Moisture - relative humidity	Soil psychrometer	95-100%	low	low	low	medium	8	Munoz-Carpena et al._SR-IWM-2	high sensitivity, demands very accurate temperature measurement, not suitable if there is a thermal gradient, small sensing volume, very slow response time, special equipment needed for sensor excitation and reading, high failure rate in long-term use	3	2	1	1	2	3	2	1,95
	Water uptake	Moisture - relative humidity	Electronic capacitive hygrometer	0-100%	+/- 3%	medium	low	high	8	e.g. www.wmo.int	suitable for high temperatures, small sensor, small sensing volume, low accuracy in wet range, non recovery after saturation, high failure rate in long-term use	2	3	1	1	3	3	2	2,05
	Water uptake	Moisture - relative humidity	temperature compensated resistance meter	64-100%	medium	high	medium	medium	8-9	e.g. www.enercorp.com	moderate sensing volume, unique working principle involving a piece of wood over which a conductance is measured, inbuilt thermocouple, slow response time, not suitable for dry conditions, special equipment needed for data acquisition, recoverable after saturation, not feasible for high surrounding pressure	3	3	2	1	2	3	1	1,90
	Swelling	Pressure, mechanical	Piezoresistive sensor	0-200 MPa	+/- 0.1%	med	low	high	9	Modern Deliverable 2.2.2	high working temperature, small sensitivity to temperature, high linearity, not recommended for applications with static pressure, direct data conversion, fast response	2	3	3	1	3	3	1	1,95
	Swelling	Pressure, mechanical	Vibrating wire sensor	-0.1-150 MPa	+/- 0.1%	high	medium	medium	9	Modern Deliverable 2.2.2	sensitive to vibrations & shocks, otherwise robust, nonlinear behaviour, large in size, reliable and good long-term performance, complex signal conversion needed, operation at high tempertures >200C possible	3	2	3	3	2	3	3	2,85
	Swelling	Pressure, mechanical	Foil Strain gauge	0-100 MPa	+/- 0.1%	high	medium	high	9	Modern Deliverable 2.2.2	fairly robust, internal temperature compensation, likely to show hysteresis due to thermoelastic strain	3	3	3	3	3	3	2	2,80
	Swelling	Pressure, mechanical	Capacitive sensor	Wide range	+/- 0.5%	medium	low	high	9	Modern Deliverable 2.2.2	high failure rate, poor long-term stability, direct data conversion, fast response	2	3	3	1	3	3	1	1,95
	Swelling	Pressure, mechanical	Optical sensor	up to 35 Mpa	+/- 0.1%	medium	low	low	7-9	Modern Deliverable 2.2.2	internal temperature compensation, signal conversion needed	3	2	3	1	1	3	2	2,00
	Swelling	Pressure, mechanical	Fibre optic sensor	0-40 MPa	< 1%	medium	low	medium	7-9	FOS&S	Immunity to electromagnetic interference, no generation of electromagnetic disturbance, reliable data transfer, high data rates, protection against water intrusion must still be improved	3	3	3	1	2	3	2	2,15
	Swelling	Pressure, areal	Tactile pressure film	0.05-100 MPa	+/- 5%	low	low	medium	8-9		large sensor, must be sealed against water contact, limited cable length, complex electronics near sensor	2	1	1	1	2	3	3	2,00
	Swelling	Displacement profile	**Inclinometer chain**	± 90°	+/- 0.5%	high	medium	high	7	Liikennevirasto	Sensitive to reference point stability, lot of electronics	3	2	3	2	3	2	3	**2,35**
	Swelling	Pore water pressure	Piezoresistive transducer	0-140 MPa	+/- 0.1%	high	low	high	9	Modern Deliverable 2.2.2	high working temperature, small sensitivity to temperature, high linearity, direct data conversion, sensitive to low and underpressure situations (non-saturated condition), risk of filter clogging and sensor corrosion, sensitiv to pressure drops along cabling	3	3	3	2	2	2	1	2,00
	Swelling	Pore water pressure	Vibrating wire transducer	-0.1-150 MPa	+/- 0.5%	high	low	medium	9	Modern Deliverable 2.2.2	sensitive to vibrations & shocks, otherwise robust, nonlinear behaviour, large in size, reliable , complex signal conversion needed, operation at high tempertures < 200C possible, sensitive to low and underpressure situations (non-saturated condition), risk of filter clogging and sensor corrosion, sensitiv to pressure drops along cabling	3	2	3	3	2	3	3	2,85
	Swelling	Pore water pressure	Strain gauge	0.2-2.0 MPa	+/- 2%	high	low	high	9	Modern Deliverable 2.2.2	fairly robust, internal temperature compensation, likely to show hysteresis due to thermoelastic strain, sensitive to low and underpressure situations (non-saturated condition), risk of filter clogging and sensor corrosion, sensitiv to pressure drops along cabling	3	3	1	3	3	3	2	2,70
	Swelling	Pore water pressure	Linear variable differential transformer (LVDT)	0-1.0 MPa	+/- 0.5%	high	low	high	9	Modern Deliverable 2.2.2	linear behaviour, usually analogue output, in need of frequent re-calibration, sensitive to low and underpressure situations (non-saturated condition), risk of filter clogging and sensor corrosion, sensitiv to pressure drops along cabling	3	2	3	1	3	3	1	1,90
	Swelling	Pore water pressure	Fibre optic sensors	0-5.0 MPa	+/- 1%	medium	low	medium	7-9	FOS&S	Immunity to electromagnetic interference, no generation of electromagnetic disturbance, reliable data transfer, high data rates, sensitive to low and underpressure situations (non-saturated condition), risk of filter clogging and sensor corrosion, protection against water instrusion must still be improved	3	3	3	1	2	3	2	2,15