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Synthesis on monitoring demonstrators and additional cases

Work Package 4

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Approved by

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- Johan Bertrand, the Modern2020 Project Co-ordinator (on behalf of the Modern2020 Project Executive Board), *06/09/2019*

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Executive Summary

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project aims to provide the means for developing and implementing an effective and efficient repository operational monitoring programme. The main focus of the Project is monitoring of the repository near field during the operational period to support decision-making and to build further confidence in the post-closure safety case.

This deliverable reports the work performed within Task 4.5 of Work Package 4 (WP4) of the Modern2020 Project. As WP4 is dedicated to “Demonstration of monitoring implementation in repository-like conditions”, the objectives of this synthesis Task 4.5 are:

- To make an overall assessment of the four demonstrators that have been developed in Work Package 4 (WP4) under their respective subtasks 4.1 to 4.4.
- To perform a similar assessment of existing cases that are considered relevant to the Modern2020 project. The inclusion of other cases in addition to the demonstrators was proposed, as they bring longer experiences with them.
- To synthesize the findings from this assessment into conclusions and, where relevant, recommendations for (1) long-term monitoring system optimisation, and (2) implementation of a monitoring strategy, by addressing the most common issues and how they could be dealt with.

In short, by assessing the field implementations (both Modern2020 demonstrators and additional cases), we try to find out if, and how far, these reflect the Modern2020 methodology or findings as reported in the other Work Packages. More specifically, we check if the strategic (monitoring program design), technological and societal aspects of monitoring, as investigated in the respective Work Packages 2, 3 and 5 can be identified in the actual implementations. In particular, the safety cases that have been worked out in task 2.2 (WP2), with the development of respective monitoring plans, could give detailed input to this assessment.

The original intention of developing recommendations formulated as “good practices” has been not possible within the limited timeframe and resources allocated. The collection and synthesis of information was more complex than expected and not all suitable elements are inside reports. Nevertheless, the assessment of existing test setups has given us some consideration about monitoring technologies and implementation procedures.

Several Modern2020 demonstrators and other cases are based on work that was initiated prior to the Modern2020 (and even its predecessor MoDeRn) project. Nevertheless, the experience gained through these demonstrators gives reliable input on the Modern2020 results, e.g. by confirming statements or recommendations stated in the other Work Packages.

The results reported here are based on

- the results of the four demonstrators;
- the discussions held during the three workshops;
- a review of the selected existing cases.

The four demonstrators that have been developed within WP4 are (task leader between brackets):

- EBS Monitoring Plan (POSIVA);

- (A)HA Demonstrator (ANDRA);
- Long-Term Rock Buffer Monitoring - LTRBM (IRSN);
- Full-Scale Emplacement (FE) and Testing and Evaluation of Monitoring Technologies (TEM) – (NAGRA).

The four additional, existing cases that have been selected are (location and country between brackets):

- PRACLAY (HADES, Belgium);
- ILW-LL container monitoring programme (Bure URL, France);
- FEBEX (GTS, Switzerland);
- Prototype Repository (Äspö HRL, Sweden).

Through the Modern2020 project, three WP4 workshops have been held, at which the progress of the demonstrators, the interactions with the other Work Packages, and this assessment were discussed:

- 23-24 May 2016 in Turku, Finland;
- 22-23 May 2017 in Mont Terri, Switzerland;
- 2-4 October 2018 in Saint-Dizier/Bure, France.

The assessment has allowed confirming many points put forward by other tasks. The selection procedure of each test case has been analysed in correlation with the screening methodology developed in WP2. Application of the screening methodology has been performed to few cases. The work was done also in way to identify the role of monitoring data on the decision-making process on the different step of the experiments/test cases. They therefore confirm the usefulness or value of the recommendations made in the other Work Packages. The only weak point found through the different cases, was the involvement of citizen stakeholders. The use of demonstrators or other field implementations for (citizen) stakeholder interaction will therefore require more attention in the future.

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Glossary

(A)HA	(Auscultation of) High Activity Waste Industrial Pilot Experiment (France)
Cigéo	French industrial underground radioactive waste disposal
CMHM	Centre de Meuse/Haute-Marne (ANDRA's site at Bure, with the URL)
COx	Callovo-Oxfordian claystone
DTS	(Raman) Distributed Temperature Sensing
EBS	Engineered Barrier System
ERT	Electrical Resistance Tomography
FE	Full-scale Emplacement Experiment (Mont Terri, CH)
GCR	Rigid Gallery Concept at the URL of the CMHM
GER	Liner Test Gallery at the URL of the CMHM
GTS	Grimsel Test Site (HRL at Grimsel, Switzerland)
HADES	High Activity Disposal Experimental Site (URL in Mol, Belgium)
HLW	High-Level (radioactive) Waste
HLW-LL	High-Level Waste - Long Lived
HRL	Hard Rock Laboratory
ILW-LL	Intermediate Level Waste – Long Lived
IPT	Induced Polarization Tomography
KBS-3V	Swedish disposal concept and safety case ("3": three barriers, "V": vertical configuration)
LTRBM	Long-term Rock Buffer Monitoring Experiment (Tournemire, France)
MEMS	Micro-Electro-Mechanical Systems
MI	Magneto-Inductive
OFS (or FOS)	Optical Fibre Sensor (or Fibre Optic Sensor)
OTDA	Optical Time Domain Analyzer
PWP	Pore Water Pressure
RH	Relative Humidity (sensor)
SF	Spent Fuel
TDR	Time Domain Reflectometry
TEM	Testing and Evaluation of Monitoring Techniques/Systems (Grimsel Test Site, CH)
THM(CB)	Thermo-hydro-mechanical(-chemical-microbiological)
THG	Thermo-hydro-geochemical
TRL	Technology Readiness Level
URL	Underground Research Laboratory
VWE, VWS	Vibrating Wire Extensometer, Vibrating Wire Sensor
WMO	(Nuclear) Waste Management Organisation

1. Introduction

1.1 Background

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project is a European Commission (EC) project jointly funded by the Euratom research and training program 2014-2018 and European nuclear waste management organisations (WMOs). The Project is running over the period June 2015 to May 2019, and 28 WMOs and research and consultancy organisations from 12 countries are participating.

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 programs. The Project is divided into six Work Packages (WPs):

- WP1: Coordination and project management.
- WP2: Monitoring program design basis, monitoring strategies and decision-making. This WP aims to define the requirements on monitoring systems in terms of parameters to be monitored in repository monitoring programs with explicit links to the safety case and the wider scientific program.
- WP3: Research and development of relevant monitoring technologies, including wireless data transmission systems, new sensors, and geophysical methods. This WP will also assess the readiness levels of relevant technologies, and establish a common methodology for qualifying the elements of the monitoring system intended for repository use.
- WP4: Demonstration of monitoring implementation in repository-like conditions. The intended demonstrators, each addressing a range of monitoring-related objectives, are the EBS Monitoring Plan in Finland, the Highly-active (HA) Industrial Pilot Experiment in France, the Long-term Rock Buffer Monitoring (LTRBM) Experiment in France, and the Full-scale Emplacement (FE) Experiment, together with the Testing and Evaluation of Monitoring technologies TEM) in Switzerland. An assessment and synthesis of some selected other tests and demonstrators will also be undertaken, and this will include consideration of the reliability of monitoring results.
- WP5: Effectively engaging local citizen stakeholders in research and development (R&D) and research, development and demonstration (RD&D) on monitoring for geological disposal.
- WP6: Communication and dissemination, to include an international conference, a training school, and the Modern2020 Synthesis Report.

This report summarizes the work performed in WP4 by assessing the results of the four demonstrators, complemented with the results of other selected monitoring setups.

1.2 Objectives of this Report

The main objective of this report

- is to perform a general assessment of the different demonstrators developed in the Modern2020 project, extended with some existing cases (field setups) to enlarge the long-term experience base, and
- to synthesise the results of this assessment into conclusions and considerations

The assessment is based on the work of the others WP's of Modern2020. In this assessment, we try to correlate the operation and results of these cases to the work performed in the other WP's.

- General items related to WP2 were investigated, such as how parameters were selected, how the monitoring layout was performed, or how far decision-making based on monitoring data was developed. We try also to identify the feasibility of the measurement of some parameters found in the results of the WP2 base on the running test cases.
- Linked with WP3 (monitoring technology) are the experiences with mainstream and innovative monitoring technologies. One demonstrator (LTRBM) has a very clear link with the RD&D work on monitoring technology, as the objective of this demonstrator was explicitly to test new sensors (prototypes) that were developed in WP3. This part of the assessment does however not include a review or assessment of the sensor technologies involved, but it is rather an overall assessment of the experiences when implementing a monitoring strategy in the field. This involves both technical (e.g. common failure causes) as non-technical (e.g. long-term maintenance/follow-up) aspects.

This brings us to the lessons that the demonstrators and additional cases can teach us on how to implement successfully a monitoring plan into the operation of a radwaste repository.

Finally, we also look if there have been cases where citizen stakeholders have been interacted in a relevant way with the demonstrators (or other cases).

1.3 Report Structure

The report is set out as follows:

- Section 2 (Overview of the demonstrators and the additional cases) gives the main characteristics of the different Modern2020 demonstrators, and of the additional selected cases ;
- Section 3 (Assessment methodology) introduces the different criteria, according to which the demonstrators and cases will be assessed ;
- Section 4 (Assessment results) describes the results of the assessment exercise for each demonstrator/case, and further makes a first synthesis of the individual results ;
- Section 5 closes the report with conclusions and recommendations

The report concludes with the list of references.

2. Overview of the demonstrators and the additional cases

In this chapter, we introduce the demonstrators and field cases. Details are given as far as they are relevant for the assessment that is developed later on. First, the four demonstrators are summarized; a full description can be found in the respective task deliverables. In the next part, the additional cases are presented.

2.1 WP4 demonstrators

The four demonstrators in Modern2020 all differ quite a lot from each other. Some of the demonstrator work has been performed in the context of field setups that were already in operation several years before Modern2020. One demonstrator covered the design process, and intended to be an illustration of the parameter screening methodology and subsequent design work as developed in WP2; it was not planned to be realised yet in the field within the Modern2020 timing. Another demonstrator specifically served to test sensor prototypes that were developed in WP3. We can therefore expect that each demonstrator bring complementary info into this assessment.

2.1.1 T4.1: EBS Monitoring Plan (POSIVA)

The work performed in this demonstrator (Bohner et al., 2019) is considered as an example of applying the methodologies to identify EBS and host rock monitoring parameters (described in Modern2020 deliverable D2.1), starting from Posiva's safety case (based on the KBS-3V disposal concept), and with the results reported in deliverable D2.2 (in particular the test case study for Posiva). This demonstrator consists of two main parts: (1) an assessment of the monitoring technologies that are relevant for the EBS and host rock monitoring in the chosen concept, and (2) the development and design of a monitoring plan. This includes the design of a detailed instrumentation and test plan (sensor type, sensor location, wiring, etc.). The EBS Monitoring Plan demonstrator can be considered as the final step to arrive at a monitoring plan ready for implementation. It is used to support the development of the monitoring strategy for EBS components in the real repository for disposal of spent nuclear fuel. The EBS Monitoring Plan is a design, whose role it is to show the needs how the monitoring could look like in a full-scale test. Within Modern2020 – as specified in the Description of Work – it has not been realised in the field, but it can serve as input when a full-scale test is to be developed and operated.

The EBS Monitoring Plan considers a tunnel section of 50 m long (deposition tunnel), with three deposition holes. The selected tunnel is located in the ONKALO demonstration area, in a crystalline host rock environment at the depth of 420 m below the surface (Figure 1).

The monitoring strategy is based on considerations when and where to implement (as a full-scale demonstration, or as part of the actual repository). The degree of extent of the instrumentation has been investigated rather detailed – both options (minimal instrumentation or extensive – i.e. as complete as possible – have their advantages and disadvantages. Two main processes were retained to be subjected to monitor: (1) the heat transfer from the waste package into the host rock (through the buffer), and (2) the water uptake and swelling of buffer and backfill.

Next, the expected evolution of these processes have been calculated.

The available monitoring technologies were then assessed – in parallel with the work performed in Task 3.1 for planning reasons. The assessment was based on previous work and field experiences, and updated with the recent work within (but not limited to) Modern2020. The potentials for application in repository conditions (monitoring periods from 10 to 100 years, but also shorter phases from one to 10 years) of these technologies were then assessed. Financial aspects were explicitly not included in this assessment.

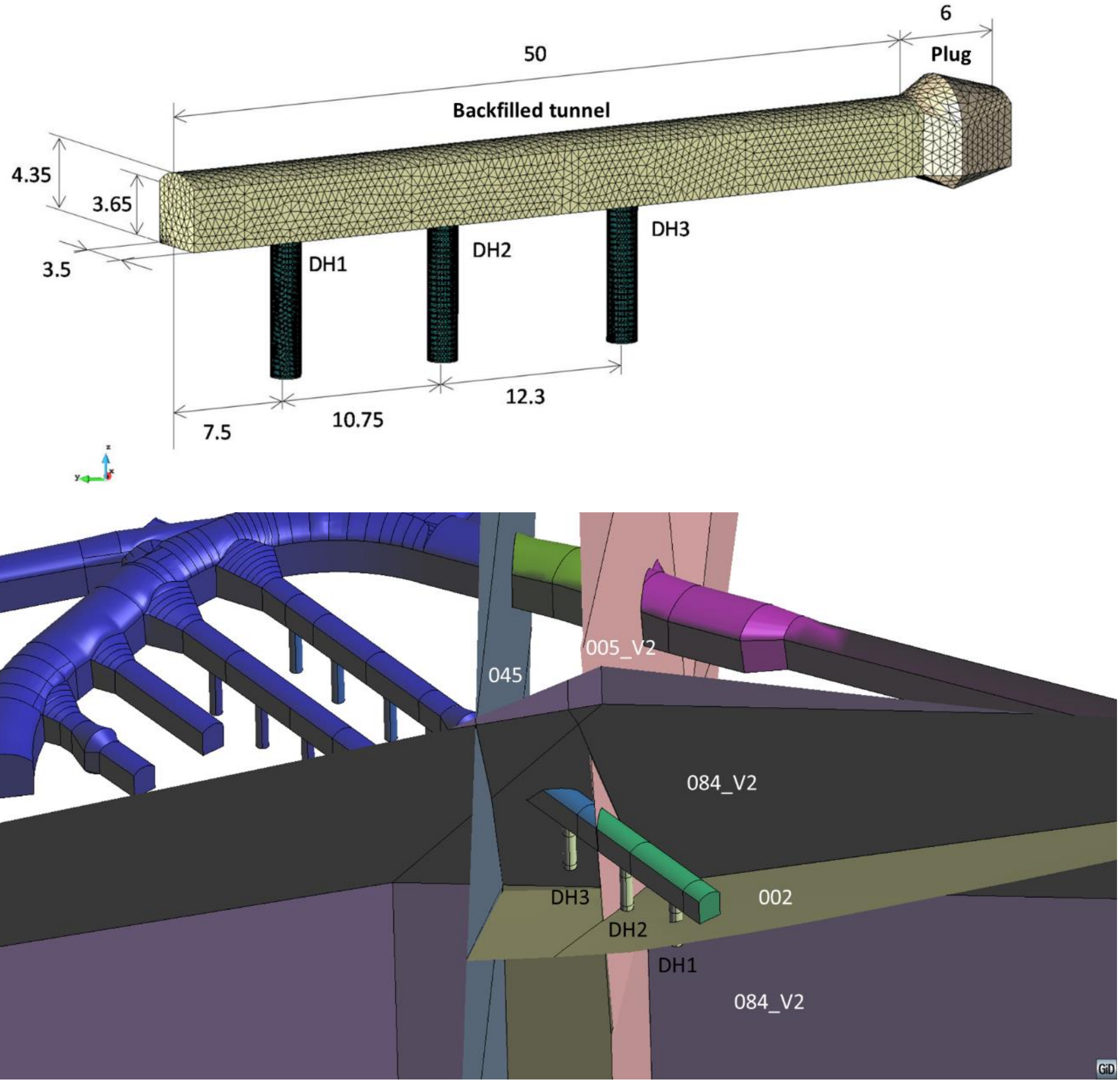


Figure 1 Top: geometry and dimensions for the EBS Monitoring Plan; each deposition hole (DH) contains a canister surrounded by a bentonite buffer. Bottom: fracture geometry with respect to the deposition holes; the fractures are only partially drawn for clarity reasons. (Bohner et al., 2019)

To select the most appropriate monitoring technologies – and the related sensors – a decision making process has been developed. Based on several (weighted) criteria, this process resulted in a list of technologies and sensors. The criteria list is quite illustrative and is reproduced from D4.1 (Bohner et al., 2019). Each monitoring technology gets a value between 1 and 3 (as each criterion is given such value). The resulting technologies (we refer to D4.1 for the full details) contain mainly established technologies such as thermocouples, RTD's, vibrating wire sensors and capacitive relative humidity sensors. Inclinometer chains are based on Micro-Electro-Mechanical Systems (MEMS) sensor technology. A special technology to monitor the buffer and backfill evolution spatially (3D) is the electrical resistance tomography (ERT)/Induced polarization tomography (IPT).

Table 1 List of criteria for technology selection; value 1 (poor) to 3 (good) for each criterion

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
	Σ 100

With this information, the instrumentation layout is proposed, along with the operational details (planning with respect to the – optional simulated - operation of the repository). In addition, the expected evolution (in terms of performance, e.g. risk of failure due to harsh conditions) of each sensor type is discussed. 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.

Some considerations for the final phase (including dismantling and retrieval if applicable) are also included.

A dedicated mock-up is further proposed for the ERT/IPT method, in which point sensors give additional data to calibrate the overall geophysical monitoring system.

The EBS Monitoring Plan has therefore been a good exercise to propose a monitoring set up based on the Modern2020 work in WP2 and WP3. It should be kept in mind, that the example developed in the frame of Modern2020 is just one example of the different types of test setups and experiments.

2.1.2 T4.2: (A)HA Demonstrator (ANDRA)

This demonstrator deals with the HA industrial pilot experiments in Bure (France). It consists of the design and development of a monitoring plan related to the construction and characterisation (both thermo-mechanical and chemical) of a disposal drift for high-level vitrified waste (Alveolus) according to the Cigéo concept (Figure 2)

The objective is to demonstrate Andra's ability to implement a monitoring system dedicated to its HLW concept based on mature technology (≥TRL 7) (see Modern2020 deliverable 3.1 for the TRL scale), i.e. ready for implementation in the industrial pilot phase This instrumentation applied has to cope with all environmental conditions and the related technical requirements (see Modern2020 deliverable D2.2).

Experiments at the URL at Bure are conducted to validate concepts and methods to monitor the proposed parameters (see screening methodology). The monitoring program is conducted in such a way to:

- Propose measurement methods/technics aimed at checking the conformity of the structure with the specifications and requirements (acceptance testing) in addition to the data and surveys carried out during the construction of the structure (example: digging speed, deflection of the structure);
- Test implementation methods of the permanent instrumentation system for the monitoring of the parameters of interest with regard to long-term safety and reversibility needs;
- Validate the layout and distribution (position, size, redundancy …) of the instrumentation dedicated to a heavily instrumented HLW cell also called "witness cell";

- Define and consolidate the procedure for implementing the selected monitoring systems:
    - Confirm the installation method for the selected sensors;
    - Arrange/organize the monitoring sections at the extrados of the liner;
    - Test different sensors configurations in function of the previous experiences.
- Compare and analyse the results of redundant sensors (i.e. different sensor technologies or types that monitor the same parameter, or the variability of the measurement results of several instances of the same sensor type);
- To achieve a TRL 7 on the monitoring system component dedicated to HA cells.

These tests would also make it possible to investigate the intrusiveness of the sensors.

Inside the AHA program, the evaluation of the monitoring system is realized through a stepwise approach. Demonstrators named AHA1604, ALC1605 and AHA1605 are dedicated to evaluate progressively the monitoring system for HL-LL radioactive waste alveoli. The experimental programme is conducted from a light (AHA1604) to a heavily instrumented (AHA1605) system.

The list of monitoring parameters has been developed, based on both Andra's internal work dedicated to monitoring strategy, and on the results obtained during the screening methodology exercise made within WP2. The plan has been detailed up to the level of measurement range and measurement performance (such as accuracy). The monitoring technologies to perform the monitoring of the envisaged parameters have, or are being, qualified through a series of laboratory and in situ tests.

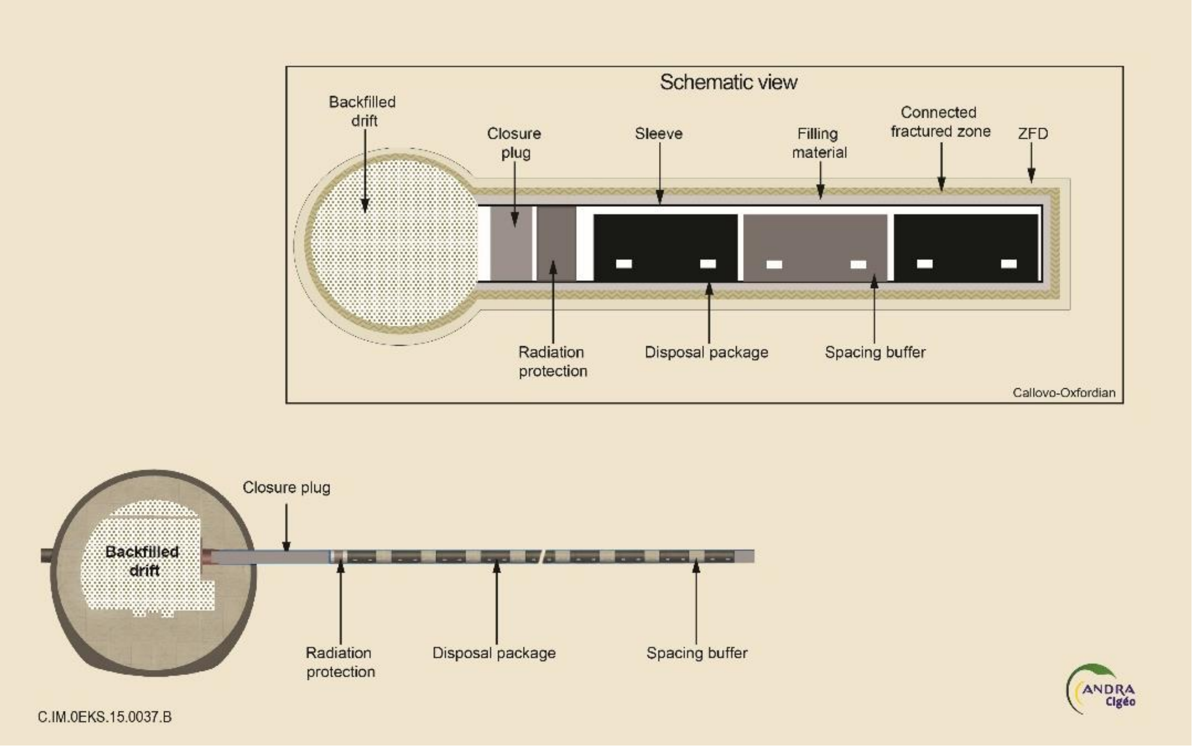


Figure 2 Schematic representation of the Cigéo HLW disposal cell design (Andra, 2019)

2.1.3 T4.3: LTRBM (IRSN)

The Long Term Rock Buffer Monitoring in situ test (LTRBM) is the field demonstrator that has been implemented completely within the Modern2020 project. Its main objective is to install and monitor the performance of sensor prototypes made in WP3, under conditions as close as possible to the expected ones in the repository.

The setup was installed in the Tournemire facility of IRSN in 2018 (IRSN, 2019). The experiment layout was based on the previous SEALEX experimental programme, while the actual sensors were delivered by the project partners that were involved in the R&D part within WP3. The proven SEALEX layout allowed developing the LTRBM design in a short time, so that all attention could be put to the installation and follow-up of the (prototype) sensors. Figure 3 to Figure 5 show the location and the layout of this demonstrator.

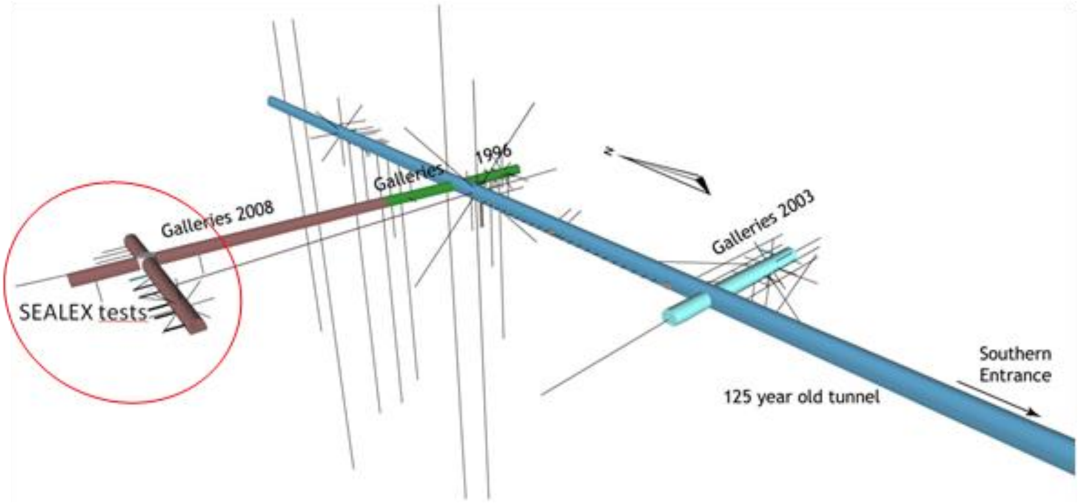


Figure 3 Overall location of the LTRBM test setup within the Tournemire facility (IRSN, 2019)

Many different sensor types were installed; the full details are given in the corresponding deliverable D4.3. They include wired prototype sensors – non-fibre optic – such as chemical sensors and psychrometers, fibre optic sensors (total pressure and deformation), wireless devices of different types, and many wired “conventional” sensors.

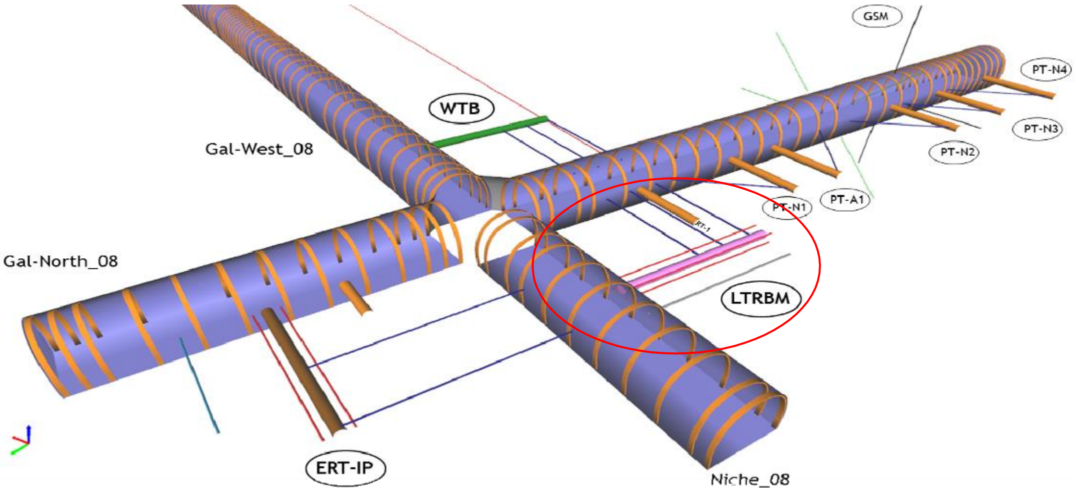
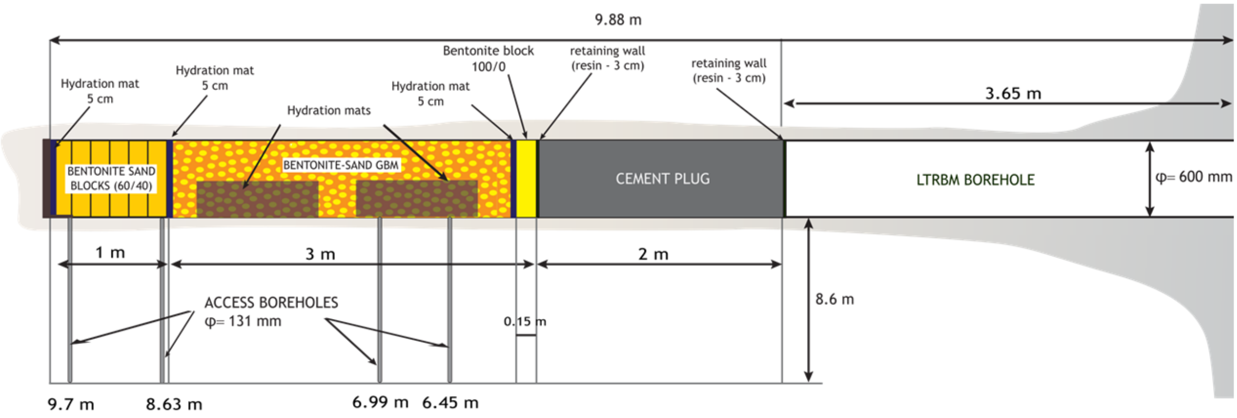


Figure 4 Detailed location of the LTRBM setup, together with related setups (IRSN, 2019)



Granular Based Bentonite-Sand Material (GBM)

- Length 3 m, composition: 75% bentonite (MX 80-Expangel SP7) pellets and 25% sand. Target dry density pellets + sand:1.4 g/cm^3

Cement plug

- 55% cement (Portland type IV) + 40% water + 5% bentonite (sodic)

Bentonite-Sand compacted blocks (moulds from SEALEX PT-N2)

- Diameter φ=560 mm, divided in 4 sections, length 1 meter
- Composition: 60% bentonite (MX 80) and 40% sand. Dry density 1.88
- 1 block 100% bentonite with a dry density of 1.5 g/cm3

Figure 5 General layout of the LTRBM demonstrator (IRSN, 2019)

In addition to the main borehole, additional holes were drilled for the ERT measurements (four parallel boreholes), one parallel borehole for the wireless units, and four hydration boreholes, perpendicular to the main borehole.

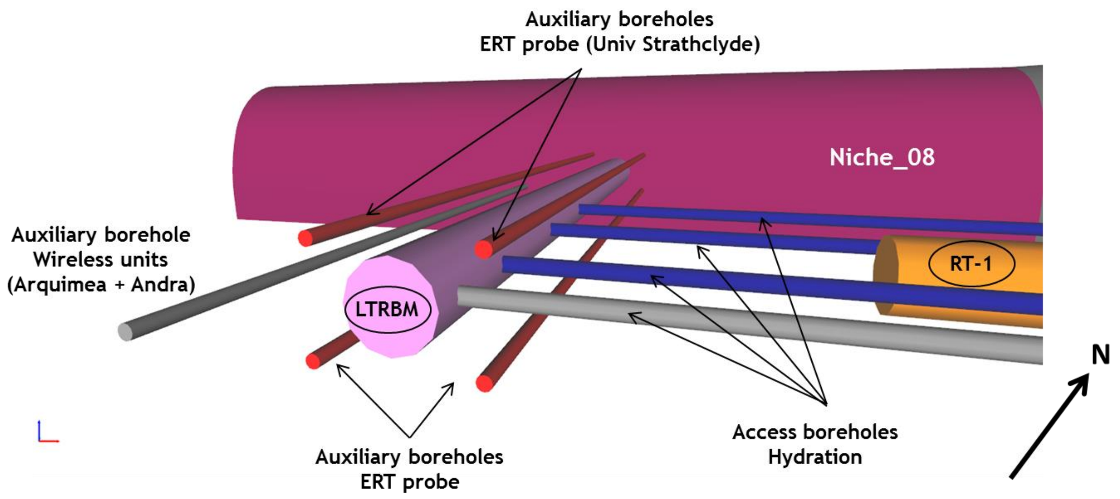


Figure 6 Overview of the auxiliary boreholes (IRSN, 2019)

2.1.4 T4.4: FE and TEM (NAGRA)

The FE (Full-scale Emplacement) experiment, located at the Mont Terri rock laboratory, and the TEM (Testing and Evaluation of Monitoring Systems) monitoring setup, located in the Grimsel Test Site, were selected to provide demonstration aspects under task T4.4. Both setups were already in operation before the start of Modern2020.

The FE setup is the most realistic simulation of the Swiss HLW disposal concept up to now. Its elaborate instrumentation programme, including up-to-date monitoring techniques, made it a good demonstrator case. The field part of the FE experiment started in 2010 (construction of the FE cavern) and therefore, the work performed under this task only covers a part of the overall work. Figure 7 shows the complete FE project history. For the assessment, we focus on the work performed in this task. It deals mainly with the application in repository-like conditions of distributed optical fibre sensing for temperature monitoring, and with the time domain reflectometry (TDR) for hydration/saturation monitoring of the buffer and the near field host clay rock. Related aspects, such as an adapted data management to handle the vast amount of monitoring data, are also included in this task.

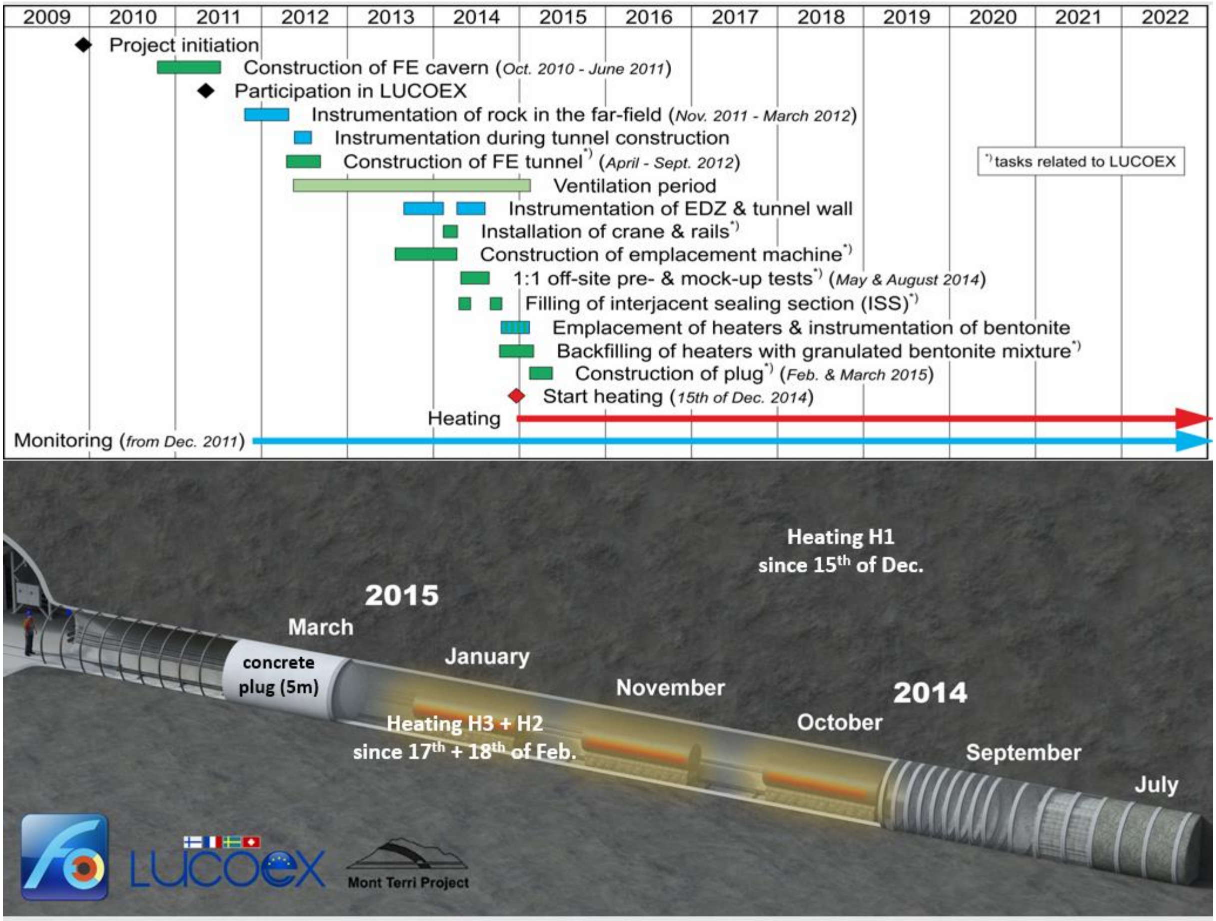


Figure 7 Project history of the FE setup (Fisch et al., 2019)

The TEM setup (Figure 8) was installed in 2007 in the frame of the ESDRED EC project (Tuñon Valladares et al., 2019). TEM is actually a full-scale, low-pH shotcrete plug demonstration test, and is located at the end of the former VE tunnel at the Grimsel Test Site (GTS). After the ESDRED project had finished, continuity of the follow-up of the TEM setup was assured by the different partners of this project, when relevant through other collaboration projects (including MoDeRn). As it includes both wired and wireless instrumentation, one of the relevant topics considered in the Modern2020 monitoring technology RD&D, and with an experimental duration of over a decade, this setup was included in the NAGRA demonstrator case for its relevant contribution to long-term monitoring. Specifically during the Modern2020 timeframe, artificial hydration of the bentonite buffer was included, allowing a more detailed assessment of the capability of the installed sensors (including wireless sensors) to monitor the resulting evolution in the environmental conditions.

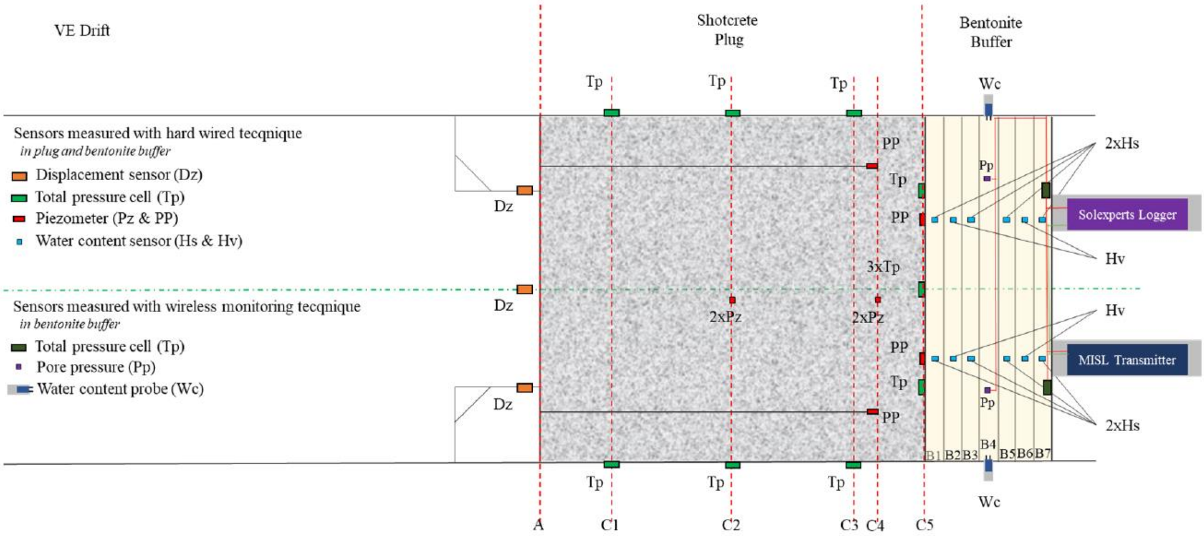


Figure 8 General layout of the TEM setup with hard-wired and wireless instrumentation (Tuñon Valladares et al., 2019)

2.2 Additional (existing) cases

From the wealth of monitoring setups that have been developed over the past decades, we selected a few of them that we considered relevant in the frame of Modern2020. In particular, to keep the link with the other Work Packages (in particular WP2 and WP3), we looked at the seven test cases considered in D2.2, the cases considered in D3.6, and on the available information that could be assembled readily. Four cases were selected to be further assessed according to the Modern2020 criteria: The PRACLAY Heater Test (HADES URL in Mol, Belgium), the monitoring programme for the IL-LLW concrete liner (Bure, France), the FEBEX field setup (GTS, Switzerland), and the Prototype Repository (at the Äspö HRL, Sweden).

2.2.1 PRACLAY (EURIDICE)

The PRACLAY demonstration test programme is a real-scale heating test performed in the HADES underground lab (Mol, Belgium), which is situated in the Boom Clay. The Boom Clay is also the host medium considered in the OPERA test case (one of the test cases in D2.2).

The current PRACLAY test setup is the result of various proposals that were made since the early 1990s, after the Boom Clay was assessed as a suitable formation for disposal of high and intermediate level – long lived radioactive waste (HIL-LLW). Since then, the Belgian WMO (NIRAS/ONDRAF) envisaged to perform a demonstration test at representative scale. However, the actual disposal architecture has seen since then several changes, in particular for the high-level waste part. Where the initial design consisted of micro-tunnels to house the HLW canisters, this changed into a disposal tube housed in a backfilled gallery, to arrive finally at the current “Supercontainer” concept. Because of these changes in disposal architecture, it was decided that the large-scale heating test would focus on the host rock heating. Because abstraction is made from the detailed design of the actual disposal gallery (as it still could change), PRACLAY is therefore also designated as a “generic” test, where the large scale and long-term (in an experimental context, i.e. at least 10 years) heating of the Boom Clay, and the investigation of its effects, is the main objective. The simulated (by heating) disposal gallery is mainly considered as the boundary condition, by imposing a fixed temperature at its interface with the host rock. In addition, the pore water pressure is a constant along this interface by backfilling the gallery with a permeable material.

One particular design item of the gallery has been considered however - the performance of the gallery lining – in the context of the retrievability.

In addition to the heating, two other separate tests are considered within the PRACLAY demonstration programme: the gallery crossing test, and the seal test. The gallery crossing test was defined to assess the construction of perpendicular galleries. The seal test deals with the performance of the gallery seal as a thermal and (mainly) hydraulic barrier, which closes the heated and pressurized gallery section from the open (accessible) part. It should be noted that the seal is not considered in the concept, although it is an essential part of the heating test.

Therefore, the core of this programme is a heating test at representative scale. A 30-m long gallery section (Figure 11) is heated for 10 years, and the resulting effects in the host medium (Boom Clay) are monitored. The first monitoring devices were installed in 2006 to include the initial (baseline) conditions prior to the excavation of the gallery (October 2007). Most of the monitoring devices consisted of instrumented boreholes drilled from the main gallery, the majority being multifilter piezometers (with up to 16 filters, up to a depth of 45 m, in one borehole). In 2009, additional monitoring boreholes were drilled from the new PRACLAY gallery. Because of its essential role in the experimental setup, particular attention has also been paid to the instrumentation of the seal (Figure 10). The seal separates the experimental part of the gallery from the accessible part, and therefore an important pressure (and temperature) gradient develops over this seal, in addition to the mechanical stresses. The conditions inside the experimental gallery section include a water pressure of almost 3 MPa, and a temperature up to 95 °C, while the accessible part carries environmental conditions (atmospheric pressure and temperatures around 25 °C). After installation (January 2010) of the seal structure, a lot of time went into the installation of the heater cables, and the wiring of all sensors installed in and from the PRACLAY Gallery, that had to be fed through dedicated "instrumentation" flanges in the Seal (Figure 9).

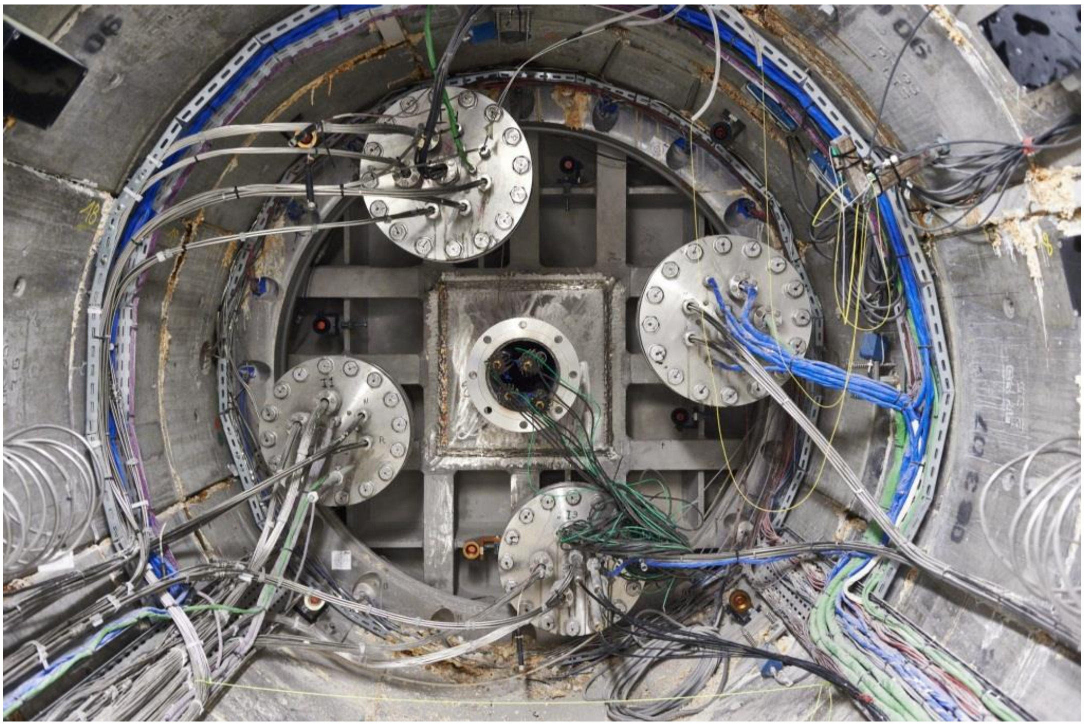


Figure 9 Four instrumentation flanges carried the major part of the sensor cables and piezometer tubes to the external sensors or directly to the data acquisition.

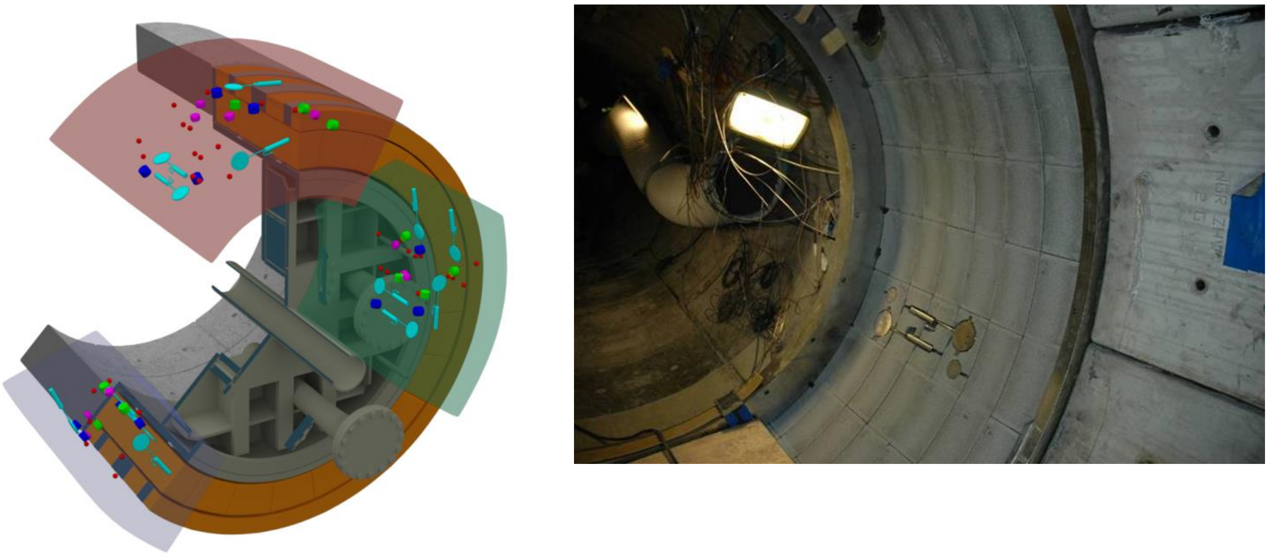


Figure 10 Instrumented Seal – left: cut-out view - right: pressure cells at inside of bentonite ring

Finally, the experimental section was backfilled with sand and filled with water in 2013. After thorough analysis of the Seal behaviour (in particular development of swelling and accompanying pressure in the bentonite sealing ring), the heating started in November 2014. The equilibrium temperature of 80 °C at the outside of the gallery lining was reached in August 2015, and since then, the setup is running at the so-called "equilibrium mode", i.e. the heater power is adjusted to maintain this temperature for the planned 10 years of heating.

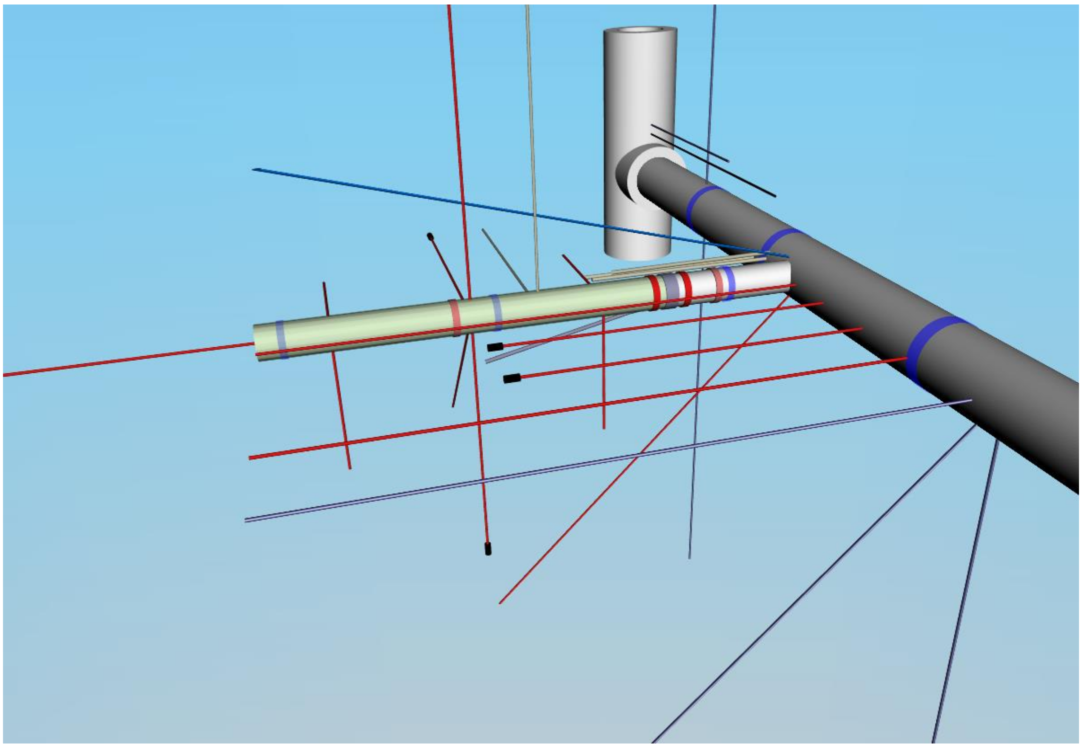


Figure 11 The PRACLAY test gallery located in the HADES URL, with the observation boreholes; the heated part is in green.

2.2.2 ILW-LL concrete liner monitoring program (Cigéo test case – ANDRA)

The French concept of disposal of intermediate level waste - long-lived (ILW-LL), consists of tunnels with concrete liners, with a diameter of about 8 m and 600 m long, as shown in Figure 12.

ILW-LL disposal cells:

- are tunnels oriented according to the direction of the principal major stress,
- are connected at one end to an access drift, which allows air into the cell, and
- at the other end to an air return drift for the air to exit, with a dedicated filtration room for each cell.
    - the HEPA filtration system and flow control damper of each cell are located in the air return drift,
    - a hot cell is located between the access drift and the usable part of the disposal cell,
    - the maximum usable part of the disposal cell is approximately 500 m. This length is compatible with the preservation of the undisturbed thickness of clay rock necessary for the justification of post-closure safety.

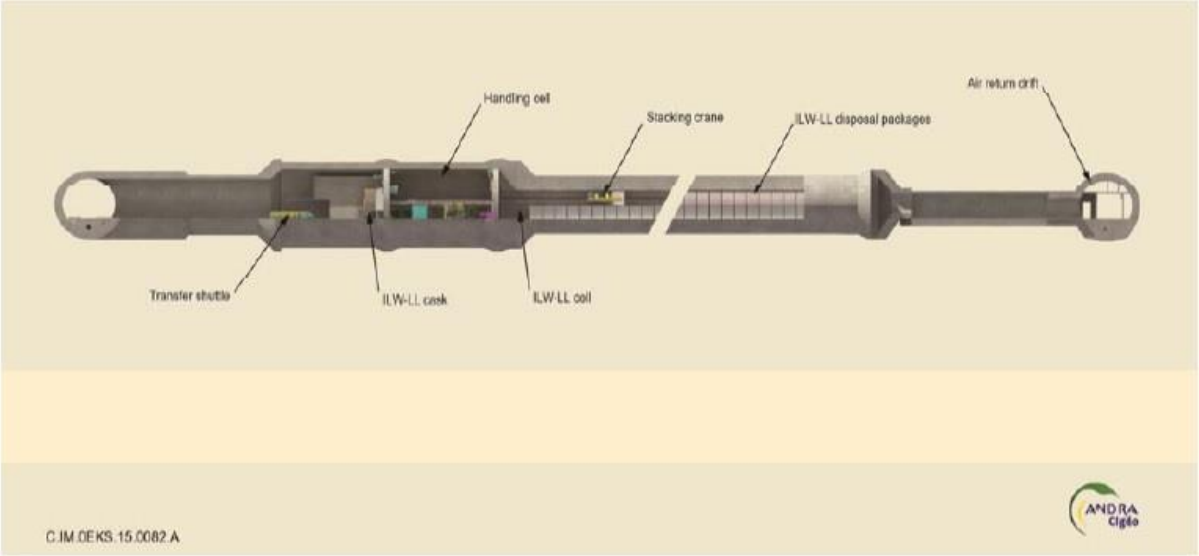


Figure 12 Design Principle ILW-LL cell

A specific experimental programme (called ORS - concrete support and liner observation) was set up to realize different parallel galleries with different construction methods, and to compare their effects on the hydromechanical behaviour of the rock, particularly the characteristics and the behaviour of the fractured zone and the evolution of the deformations or strains in the concrete support or liner.

The first galleries in the underground laboratory were made with "soft" supports allowing the clay host rock to converge. The GCR and GER galleries are galleries excavated by the Conventional Tunnelling Method, using a road header (point attack machine) or a hydraulic breaker, and imposing a time lag between the placement of the support and the pavement (7 to 8 months for the CGR and 8 to 12 months for the GER).

Four main variables were studied in these two galleries:

- The digging direction;
- the rigidity of the support (with and without the integration of compressible wedges);
- The time lag between the completion of the support and that of the coating;

- The rigidity of the final coating (two types of concrete in the coatings).

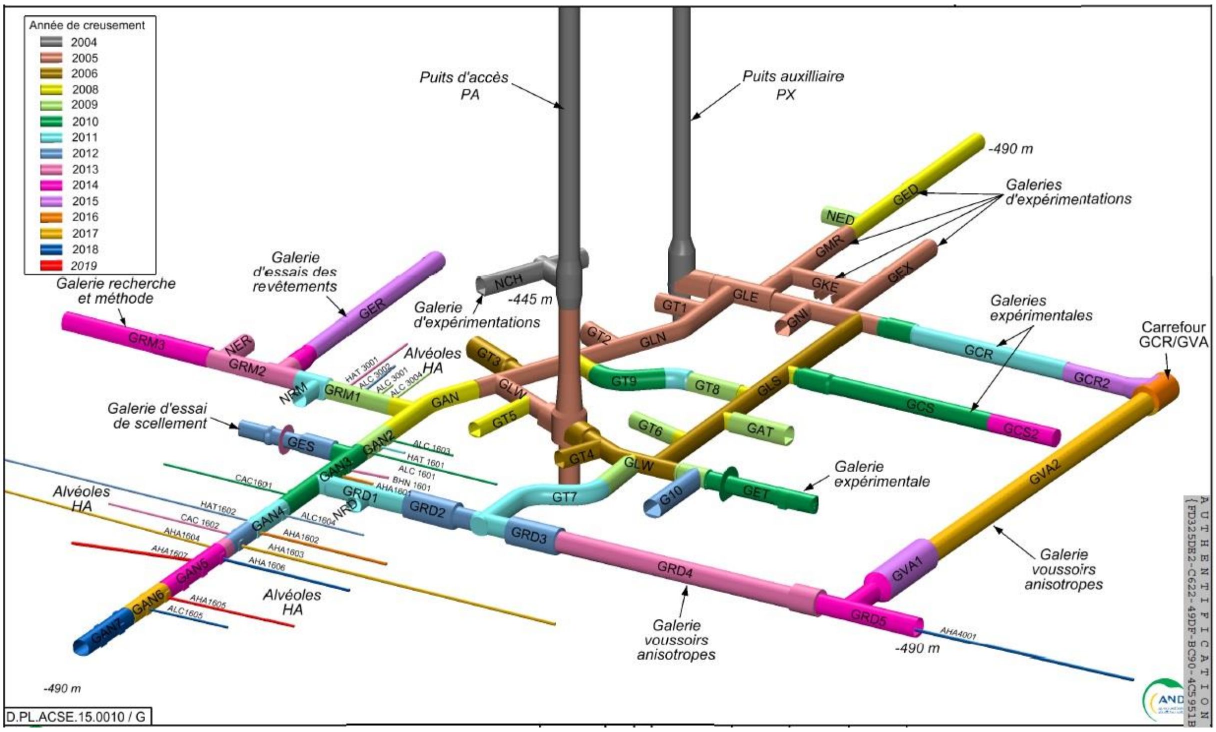


Figure 13 French URL with the realization of gallery in function of the year.

A monitoring program is attached to the ORS programme in order to test and qualify components of its monitoring strategy.

The qualification of the monitoring strategy is done gradually. Two galleries have been used to evaluate monitoring system:

1. Rigid gallery concept (GCR)
2. Liner test gallery (GER)

2.2.2.1 Rigid gallery concept (GCR)

In Andra’s URL at -490 m under the surface inside the clay host rock, the 65 m long GCR gallery was excavated from 2010 to 2011 along to the major horizontal stress field, using a tunnelling machine with a road header. This gallery has a large excavated diameter of about 5.40 m, and is covered by a 20 cm thick shotcrete liner immediately after excavation. This liner aims to retain the rock support elements in the medium and long term on THM behaviour and more particularly on the extension of the excavation-damaged zone. Six months later, a concrete lining ring was poured in situ; three types of lining support, each 30 cm thick, were constructed to see the loading impact on each type of support. The first support type was made with a stiff concrete type C60 (60 MPa at 28 days), and the second support type with a C40 type of concrete; both support types included compressible shims (cf. Figure 14); the third type of support was made with C60 concrete, without compressible shims however.

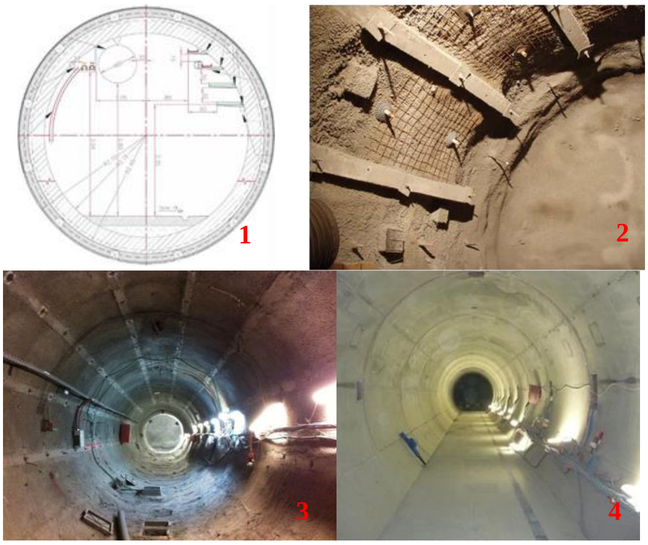


Figure 14 GCR gallery concept (1), beams & bolts (2), entire gallery after excavation and shotcreting (3), with concrete liner and slab (4)

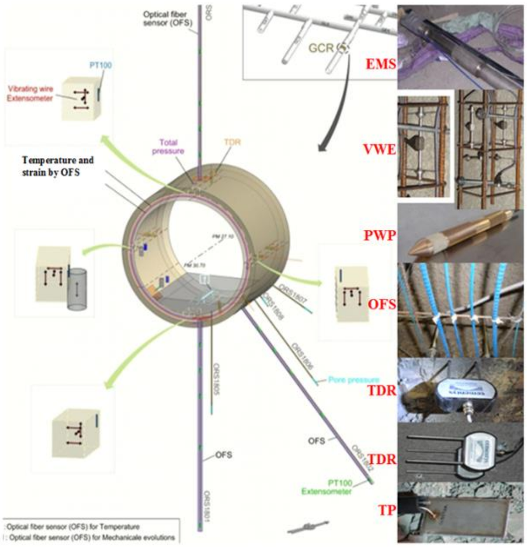


Figure 15 Sensors' location in the monitoring section test (demonstrator)

A specific section of the GCR gallery was dedicated as a monitoring demonstrator. This section contains 123 point sensors and 11 distributed optical fibres sensors (OFS), providing THM measurements every 30 minutes (5 or 10 minutes in the first months).

2.2.2.2 Liner test gallery (GER)

The gallery excavation lasted from Jan. 2015 to Sept. 2015, with shotcrete projection by patch of 1.2 m. Poured concrete layer, named Layer in the following, covers shotcrete by patch of 3.6 m, basement first then slab and finally vault. Construction finished in May 2016. Table 2 gives the details of the GER gallery.

Table 2 GER features

Gallery length	66 m
Completion date	17 Nov 2014 to 24 Sept 2015
Excavation diameter	5.2 and 5.4 m
Digging technique	MAP (road header, punctual attack)
Thickness of shotcrete	21 cm
Compressible elements	2 sections with / 1 section without
Waiting period before the liner construction	8 to 11 months
Thickness of concrete liner	30 cm
Description of the section	**Section 1:** only support with compressible element **Section 2:** support with compressible element + concrete liner C60-75 **Section 3:** support without compressible element + concrete liner C60-75

Figure 16 Installation of sensors in boreholes, shotcrete and poured concrete in GER gallery

The monitoring system in the GER gallery is composed of sensors placed in the Callovo-Oxfordian claystone (COx) inside boreholes, embedded into a shotcrete layer disposed over the COx, and into a poured concrete layer covering the shotcrete layer.

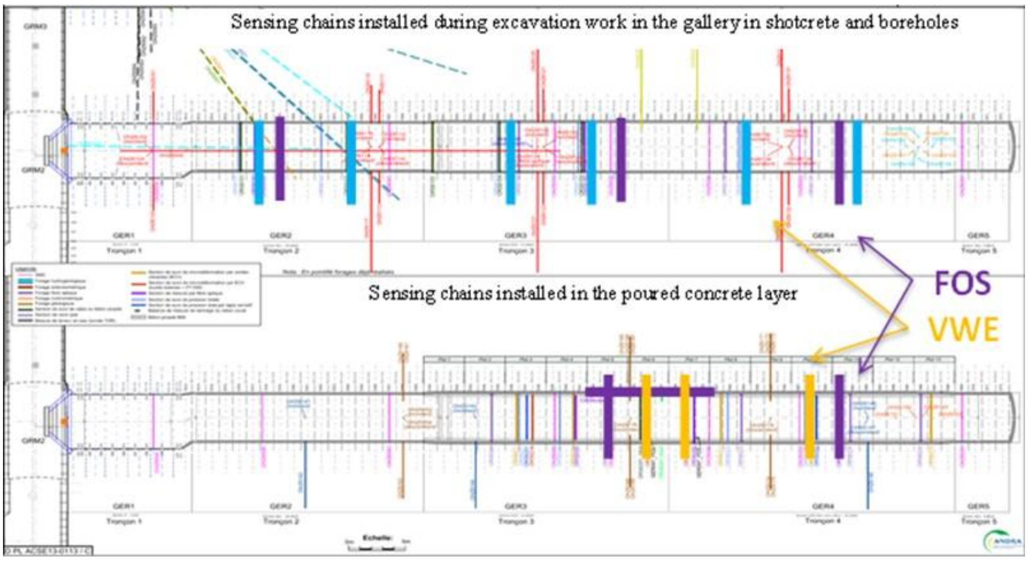


Figure 17 Layout of the full scale demonstrator (gallery) with sensors installed for monitoring system qualification for mechanical parameters, FOS in shotcrete and poured concrete layer (purple) and VWE in poured concrete layer (orange). VWE in shotcrete (blue)

The objectives of GER experiment are

(i) to understand the Thermal, Hydraulic and Mechanical (THM) behaviour of the COx and concrete layers,
(ii) to test innovative sensors,
(iii) to compare different technologies measuring the same parameter (like strain),
(iv) to improve installation procedures, based on feedback obtained from previous tests, and
(v) to provide input data for the development of decision making tools.

Boreholes (near field) were drilled in the four cardinal directions of some gallery sections, and equipped with inductive or resistive Displacement Sensors (DS), or/and distributed temperature and strain Fiber Optic Sensors (FOS). Pore Water Pressure sensors (PWP) with wireless transmission provide PWP profiles around the gallery.

Shotcrete and poured concrete layers are monitored for strain, temperature and water content using innovative monitoring devices, like fibre optic sensors (FOS) of various types, tactile pressure sensors and pulse sensors, or conventional ones, like Vibrating Wire Extensometers (VWE), Total Pressure Cells (TPC) and Time Domain Reflectometry probes (TDR). In addition, different designs of monitored concrete samples were embedded in the concrete layer to serve as TH references for strain measurements.

2.2.3 FEBEX (AMBERG)

The field demonstrator of FEBEX was installed more than 20 years ago at the Grimsel Test Site (GTS). It consisted of a test gallery excavated in the hard granitic rock, in which in the deepest 20 m a simulation was performed of the Spanish HLW disposal concept that was considered at that time (mid 1990s). The main components were the bentonite buffer (precompacted blocks), in which two heaters (simulating the waste packages) were embedded (Figure 18). After gallery excavation and construction (from end 1995 to early 1997), the heating, natural hydration and monitoring started in 1997; the temperature at the surface of the heaters was set at 100 °C. The setup has operated for more than 18 years. A first partial dismantling (with removal of heater #1 and extensive analysis of different experimental parts including retrieved sensors) was performed in 2002; the remaining part was refitted and continued to run until the summer of 2015, after which the final dismantling took place.

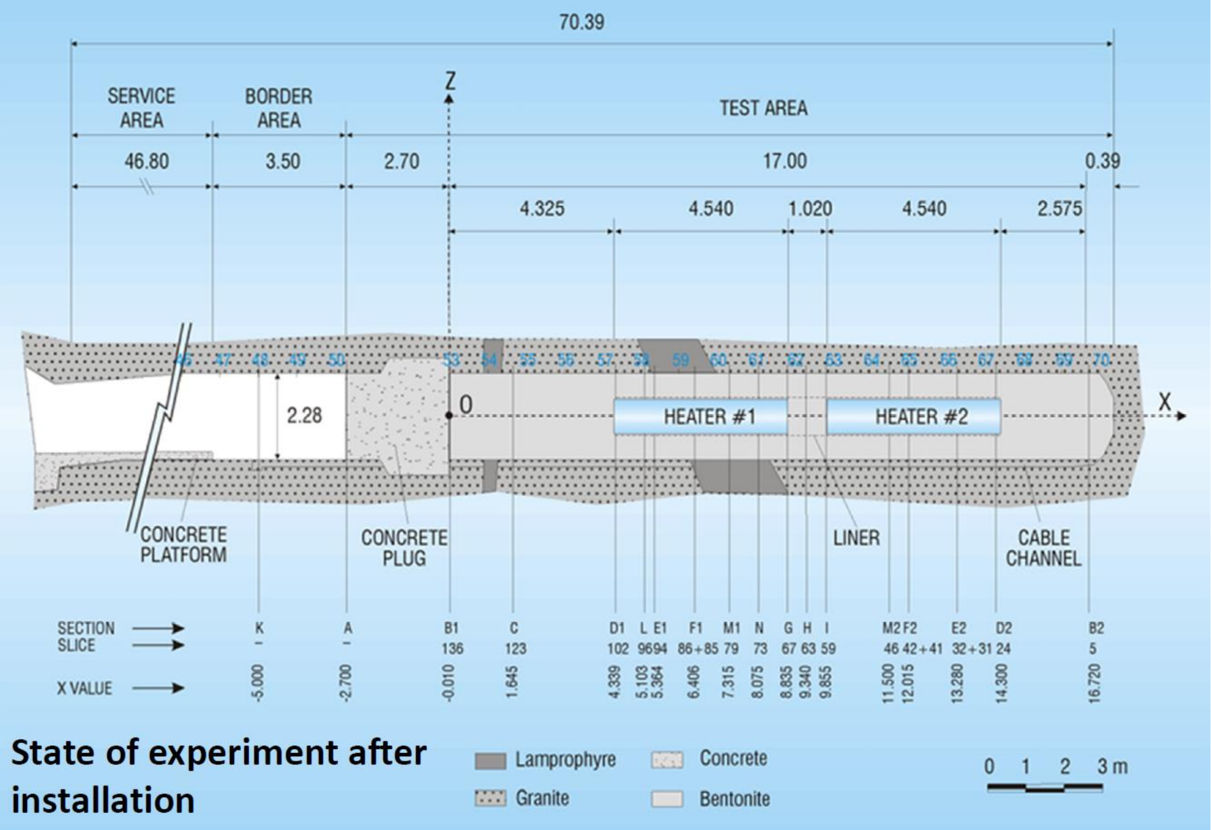


Figure 18 Layout of the FEBEX setup after installation in 1997 (Garcia-Siñeriz et al., 2017)

2.2.4 Prototype Repository (SKB)

The Prototype Repository project comprises a full-scale field test in the Äspö HRL and a number of supporting field and laboratory tests for getting basic data for thermohydro-mechanical-chemical-biological (THMCB) modelling. Here we focus on the full-scale demonstration experiment, which aims to simulate conditions that are largely relevant to the Swedish/Finnish KBS-3V disposal concept for spent nuclear fuel. This was achieved by testing canister deposition and retrieval techniques, by buffer, backfill and plug construction at full scale, as well as by long-term physical/chemical testing of buffer, backfills and plugs. When constructed, the setup was located at the very end of the main access ramp of the Äspö Hard Rock Laboratory (HRL), at 450 m depth below ground surface. The test programme included studies of individual engineered barriers as well as their combined engineered barrier system and their interaction with groundwater and surrounding rock.

Figure 19 shows an artist's view of the Prototype Repository. It covers 64 m of the main access ramp of the Äspö HRL and has two sections, one inner section with four deposition holes (at the deep end of the gallery) and one outer section with two deposition holes. The two sections are separated from each other by a stiff and watertight concrete plug, and the whole setup is separated from the rest of the Äspö HRL by a cast plug of the same design as the inner one (Figure 20).

The main objective of the Prototype Repository was to simulate a part of a future KBS-3 repository to extent possible with respect to geometry, design, materials, construction and rock environment, except that radioactive waste was to be simulated by electrical heaters. By that, a full-scale reference would be provided for predictive numerical modelling concerning individual components as well as the complete repository system, and for demonstration of sufficient understanding of the important processes that take place in the EBS and the host rock.

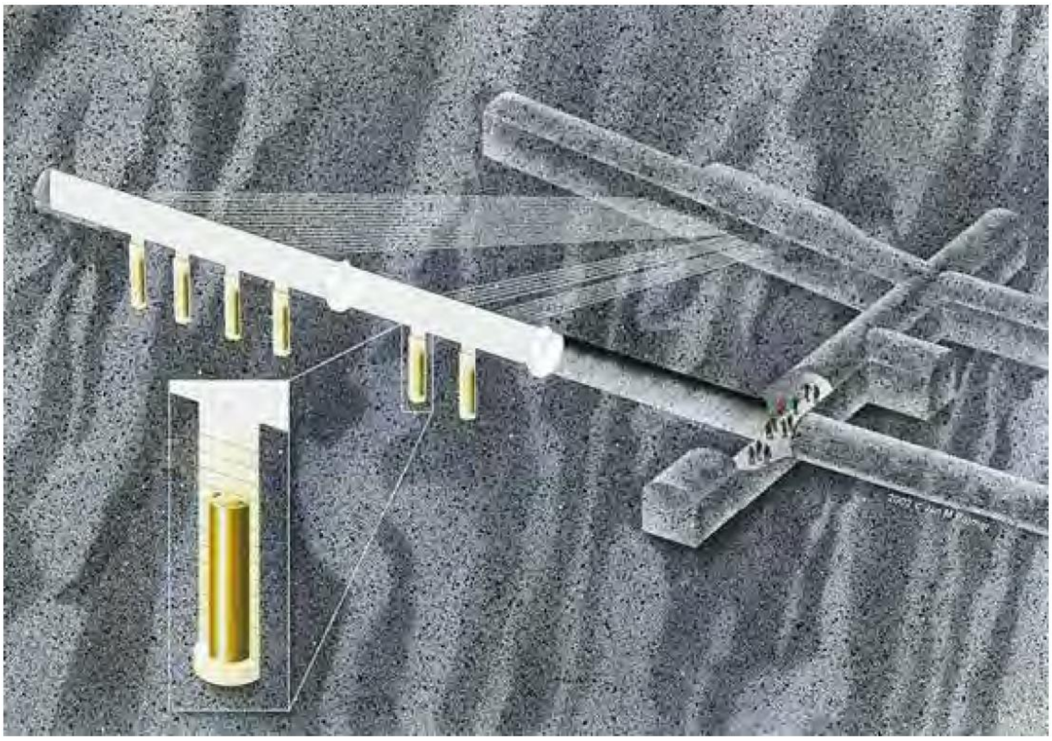


Figure 19 Artist's view of the Prototype Repository within the Äspö Hard Rock Laboratory (Svemar et al., 2016)

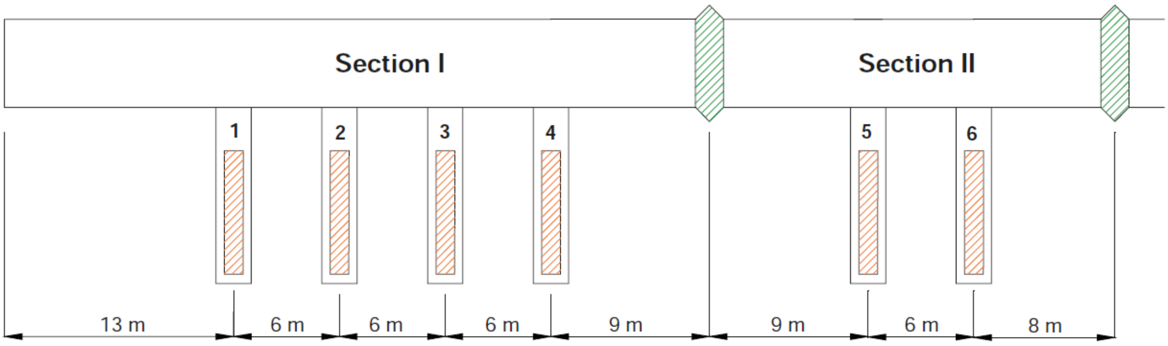


Figure 20 Schematic view of the layout of the Prototype repository and deposition holes (Svemar et al., 2016); Section I is also known as "inner section", and Section II as "outer section".

The planning of the project started in 1998, and it involved an extensive rock characterisation prior to the installation. Emplacement works started in September 2001. It involved placement of the MX-80 bentonite buffers with the embedded canisters (heaters), backfill of the tunnel with a mixture of crushed rock (70 % of weight) and bentonite (30 %), and installation of the plug. The installation was completed in June 2003. A heat flux regime was implemented based on the reducing heat flux likely from HLW and begun sequentially in each deposition hole – therefore, the inner section has operated since 2001, and the outer section since 2003. . The original intentions for the Prototype Repository were to operate the inner section for approximately 20 years in order to support the operational permit for the final repository for spent fuel with as accurate information and data as possible, and to operate the outer section for approximately five years in order to demonstrate the feasibility of the KBS-3V method in conjunction with the license application. Due to the different objectives the two sections were differently instrumented; the inner section more sparsely and the outer section more intensively.

In accordance to the intents, the outer plug was opened and the 23 m-long outer section was retrieved after about seven years of operation, with the overall objective to study the actual conditions of canister, buffer, backfill and the surrounding rock after being subjected to natural groundwater inflow and heating for a considerable time. The fieldwork commenced in 2010, and was completed in December 2011. In addition to sampling parts of the setup (mainly buffer), also the sensors retrieved were assessed.

3. Assessment methodology

In this chapter, we develop the assessment methodology for the cases presented in Chapter 2. We propose a systematic assessment of each case against a list of criteria. The list of criteria is based on the topics that have been studied in the other technical Work Packages of Modern2020, complemented with demonstrator specific criteria that are also of interest for future (more evolved, more advanced and/or larger-scale) setups that are envisaged to be applied in a final disposal context (e.g. pilot facilities). First, the different criteria are proposed and detailed. In the second part of this chapter, we explain in general which methods we will use to realise such assessment. The actual assessment is described in the next chapter (Chapter 4).

3.1 Assessment criteria

To draft our list of assessment criteria, we first check the main aspects of monitoring that have been dealt with in the other Work Packages. This should ensure us that the assessment scope covers all relevant aspects related to monitoring in a final disposal context, ranging from strategy, over technological implementation, to societal relevance of monitoring. In addition, our Work Package on demonstration has provided us with several criteria that will help in extracting the essential success factors for the implementation of a performant monitoring system in setups linked to final radwaste disposal operations.

We have not made a direct link between the results of the Work Packages – that have been obtained only recently – and the monitoring cases considered, which (for many cases) have been setup many years ago. As mentioned, these WP’s served mainly as a source of inspiration to make a more or less complete list that covers all relevant aspects.

3.1.1 Criteria linked to monitoring strategy (WP2)

This Work Package studies the requirements on monitoring systems in terms of parameters, the monitoring strategy, and decision-making based on monitoring results. In short, this covers the process from monitoring needs to (detailed) implementation plans.

In this context, the following criteria have been defined:

- Was there a formal process to define the monitoring objectives?
- Has there been an estimation of the expected behaviour? Is so, which one:
    - Overall modelling
    - Scoping calculations
    - …
- How monitoring results play a role in the decision on the experiment? Examples are
    - Change of experiment parameters (linked to e.g. duration, heating power, hydration,…)
- Have unexpected measurements or evolutions been encountered?
    - How have they been treated?
- Was it planned to use data for safety reasons
    - Follow-up of integrity of the structure
    - Operational safety (e.g. access to the site)

3.1.2 Criteria linked to monitoring technology (WP3)

This Work Package covered several monitoring technology developments, including wireless data transmission systems, new sensors, and geophysical methods. In addition, a methodology for the qualification of monitoring system elements has been established.

This puts forward the following criteria:

- How sensors and other monitoring components have been selected? Sub criteria include:
    - In-house development/production
    - Standard or custom-made sensors by (specialised) sensor manufacturer
    - Was there a (formal and/or systematic) qualification process for the monitoring components?
- What experience has been gained with novel sensor technologies
- Why (or why not) have they been installed
- Has sensor cabling caused specific issues?
- In the context (relevance) of the development of wireless techniques

The performance of particular monitoring technologies is not dealt with in this assessment, as this is covered in WP3.

3.1.3 Criteria linked to the engagement of local citizen stakeholders (WP5)

This Work Package investigated how monitoring could play a role to engage local citizen stakeholders in the final radwaste disposal (decision) process.

This has led to the following criteria, in which we have looked into a broader definition of “stakeholders”:

- Has the demonstrator or field set-up been used for interaction with citizen stakeholders?
- In an active or rather passive way
- Guided visits
- Presentation of monitoring data – possible discussed.
- Were performance issues kept “in-house”? (transparency)
- To which parties have monitoring data been communicated?
- Was there a review or analysis of monitoring data by independent organisations?

3.1.4 Criteria regarding the implementation and/or demonstration (WP4)

In addition the the previous sets of criteria, the actual performance of the demonstrator or other field setup is assessed through the following criteria:

- Did the monitoring equipment jeopardize safety functions, or other functions that could be linked to a safety function (e.g. functionality of a hydraulic barrier), e.g. leaking cables (also in WP3 – cabling issues);
- Have other artefacts been identified due to the monitoring equipment?
- Did the long-term nature of the field set-up give project management issues?
- How have the experimental data been followed-up?
- Can the demonstrator (or field set-up) give input on the cost of monitoring? (sensors, installation, follow-up,…)?
- Was the demonstrator dismantled (at the end) - if yes: was this experience relevant in a retrievability/reversibility context?

3.2 Assessment of the selected cases

The different cases will be subjected to the criteria listed, based on the following information:

- Deliverables of the four demonstrators;
- Literature review
    - Project descriptions
    - Data reports
    - Other papers discussing the results

Notwithstanding the fact that we try to do a systematic assessment of each case based on the criteria presented, some subjectiveness might still be present due to a lack of information on some specific topic, or due to some possible disagreement on the interpretation of some criteria. Some flexibility is needed because of the different nature of the different cases; a very strict definition of each criterion is therefore not always feasible.

4. Assessment results

4.1 Individual assessment results of the different cases

In this section, we screen the cases that have been introduced in Chapter 2, according to the criteria listed and detailed in Chapter 3.

4.1.1 T4.1: EBS Monitoring Plan (Posiva)

Design basis, monitoring strategy and decision-making

The EBS Monitoring Plan is based on the KBS-3V concept and its related safety case. EBS monitoring is only a part of the overall monitoring system that is envisaged. Other parts of the repository (operation) that are (will be) subject to monitoring include hydrogeochemistry, rock mechanics, the surface environment, and hydrology/hydrogeology. Further, Posiva also recognizes the need for operational monitoring (e.g. for workers safety), and for monitoring of radiation conditions. An important input for the monitoring is also specified by the regulator, although it does mainly specify what to monitor (e.g. EBS Performance), and not how it has to be achieved (not necessarily in the main repository). All these aspects (outside EBS monitoring) are however not included in Modern2020, and have therefore not developed within the Modern2020 project.

As part of the Modern 2020 WP2 Posiva made a study on how to apply methodologies identified in Task 2.1 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 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 performance will therefore mainly be assured through other means than repository monitoring, such as QA/QC procedures, lab experiments and an in situ full-scale test.

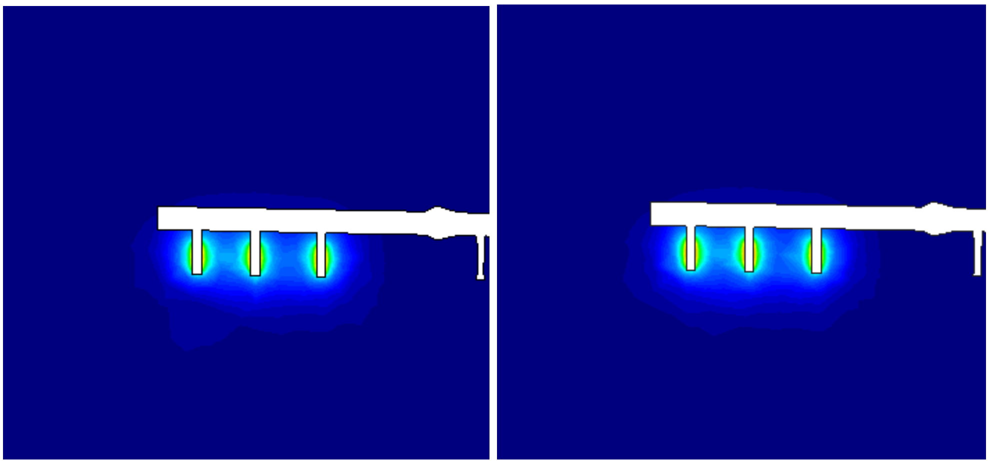
The methodology first considered the performance targets for the different EBS components (canister, buffer and backfill). These performance targets have been defined in such a way that, if they are met, the safety functions will be fulfilled. Once each performance target was screened, the resulting 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 (Bohner *et al.*, 2019). Finally, the monitoring strategy for the different parameters (e.g. parked, monitoring during operational phase, or investigation through full-scale demonstrator) is detailed.

As far as the EBS components, the related parameters will be investigated through alternative methods instead of monitoring during repository operation.

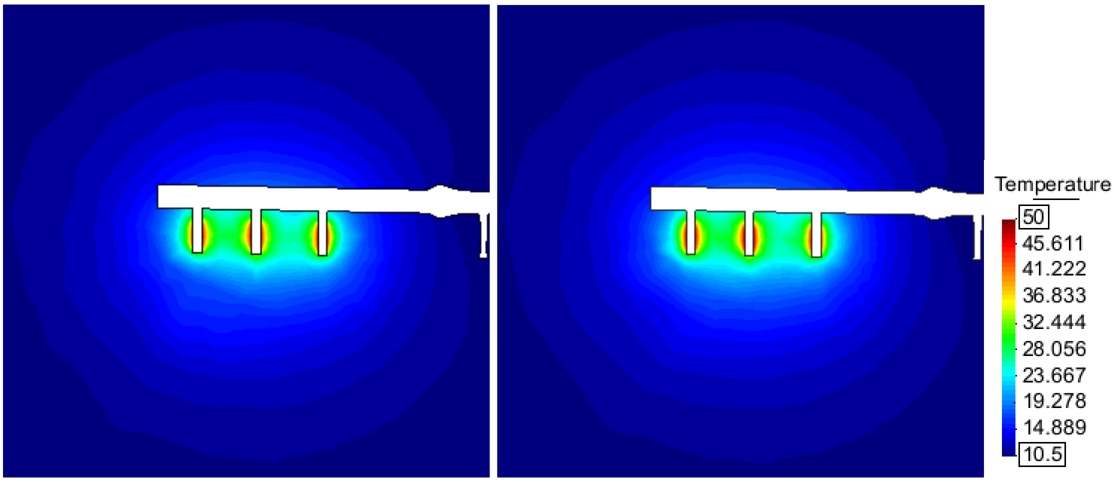
Modelling and scoping calculations

Modelling has been performed to predict the short- and medium term behaviour of the repository near field. The following four aspects have been developed:

- Pore water pressure evolution, including desaturation of the near field host rock (important boundary condition for buffer and backfill hydration);
- Temperature evolution in the host rock (near field) (see Figure 21);
- Saturation degree in the buffer and backfill;
- Temperature evolution in the buffer.



360 days (t = 560 d)



5400 days (t = 5600 d)

Figure 21 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) (Bohner *et al.*, 2019).

Monitoring technology

A screening of the monitoring technologies was an explicit part of the related task WP4.1. In particular, the latest EBS monitoring technologies were investigated to identify potentials, limitations and restraints of the different available techniques, equipment and procedures.

Particular attention went to wireless transmission (as one of the criteria in the selection procedure) and geophysical techniques (ERT/IPT) to limit the intrusiveness (cabling) of the monitoring set-up.

For the selection of the most appropriate monitoring technologies, a decision process has been worked out as mentioned in Chapter 2. Most selected technologies were therefore proven technologies, such as thermocouples and vibrating wire pressure cells.

Field realisation

Not applicable yet; to be implemented in the (near) future through the Finnish programme. It is stated that the EBS Monitoring Plan is a training exercise, so the actual implementation in a full-scale test might be different from the plan reported in D4.1.

4.1.2 T4.2: (A)HA Demonstrator (ANDRA)

Design basis, monitoring strategy and decision-making

As mentioned in chapter 2, the list of monitoring parameters has been developed, based on both Andra's internal work dedicated to monitoring strategy, and on the results obtained during the screening methodology exercise made within WP2. The plan has been detailed up to the level of measurement range and measurement performance.

An important aspect to be taken in the design of a monitoring programme is the retrievability requirement. This implies that the structural integrity of the borehole casing, in which the HLW canisters will be positioned, needs to be monitored. In particular, the ovalisation of the casing tubes needs to remain below a set limit.

Monitoring technology

The development and demonstration of a reliable monitoring technology for these aspects (structural integrity) is the main objective of the (A)HA Demonstrator programme, and was the logical link with the work performed in WP3. The monitoring technologies to perform the monitoring of the envisaged parameters have, or are being, qualified through a series of laboratory and in situ tests according to a well-planned methodology. Many efforts are performed to arrive at fibre optic systems, which allow an extensive monitoring with a limited number of (fibre optic) cables. Distributed optical fibre systems that monitor both strain and temperature are spiralled around the tube.

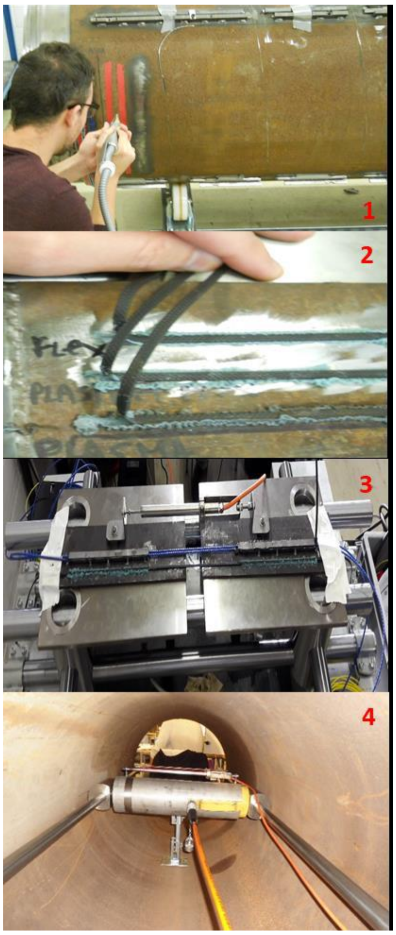
Field realisation

A stepwise implementation is being performed. Figure 22shows a typical instrumented installation of a sleeve (or section of a tube in which the waste canisters will be positioned). As mentioned, many aspects are tested, such as the surface preparation, how to obtain a good bond of the fibre on the tube by glueing, what strains can the fibre cable handle, and validation by application of a controlled deformation.

During the development of a "repository-proof" monitoring system, a close cooperation with instrumentation manufacturers is undertaken.

Two demonstrators that have been implemented yet are the AHA1604 demonstrator, which tested the installation method of the optical fibres in representative conditions on a real structure, and the ALC1605 demonstrator, which validated the installation by e.g. comparing the optical strain measurements with vibrating wire sensor data, and by operating at heated conditions (90 °C).

As detailed by Farhoud et al. (2019), both demonstrators showed a successful installation and operation of the distributed fibre optic cable monitoring systems.



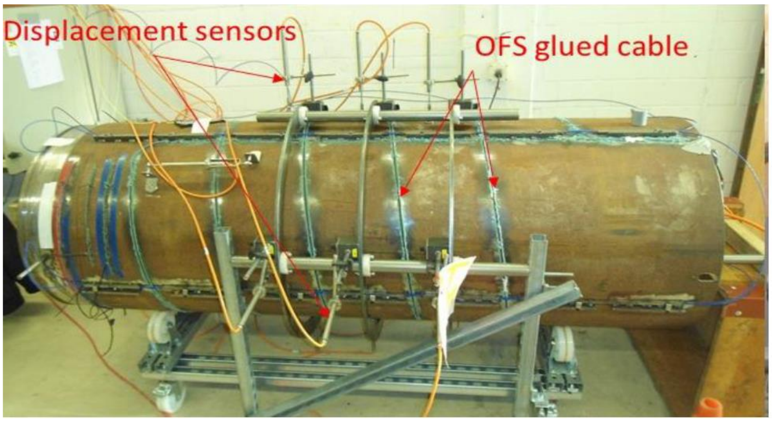


Figure 22 Top : instrumented in situ sleeve to validate sensing technologies

Left : (1) surface preparation (2) glue test (3) axial straining (until failure) (4) load test

(Farhoud et al., 2019)

Based on the success of the previous demonstrators, preparations for the field installation of the main demonstrator (AHA1605) is planned for mid-2019. This demonstrator will integrate all the tested monitoring techniques in order to provide a representative monitoring system of the HLW cells planned for the pilot phase in Cigéo. The expected monitoring system is planned to provide thermomechanical and chemical characterization of the cell (casing, cement material surrounding the casing and internal internal atmosphere).

4.1.3 T4.3: LTRBM (IRSN)

Design basis, monitoring strategy and decision-making

For this demonstrator, there was no direct link with a safety case; no extensive modelling or numerical predictions were performed neither. The main objective was to create a representative EBS environment into which the prototype sensors could be tested. This environment is based on the SEALEX experiments. The SEALEX experimental programme investigates the effectiveness of seal systems used to close up the engineering structures. These are made of a natural swelling clay-based material, which ensures continuity of the containment provided by the rock. IRSN's SEALEX research project is dedicated to assessing the effectiveness and robustness of such seals over time. This project involves examining the key factors that regulate the long-term hydraulic performance of the seals.

Tests are carried out over periods of several years.

Monitoring technology

Demonstration (installation and operation) of sensors based on innovative sensor technologies was the main objective of this task, and as such constitutes the logical link with the work performed in WP3. The sensor technologies implemented were briefly mentioned in chapter 2.

Field realisation

Given the number of different partners that provided the prototypes, the installation was rather successful. Some issues were discovered with the operation of the wireless devices, it is not clear yet at the time of writing of this report if these can be solved in a short term.

As it was realised at the end of Modern2020 project (which is rather logical, as it built upon the work performed in WP3), the task responsible has taken proactive steps to ensure a continued follow-up of this set-up in the near future. As such, also longer-term experience (several years, although the exact long-term planning will only become clear on a longer term) will become available for the partners of this task, which delivered the sensors.

4.1.4 T4.4: FE & TEM (NAGRA)

Design basis, monitoring strategy and decision-making

The Full-Scale Emplacement (FE) experiment is based on the Swiss concept and safety case. It is implemented on a 1:1 scale to a deep geological repository. As such, the FE experiment represents the different phases of construction, waste emplacement, backfilling and early post closure evolution of a spent fuel/vitrified HLW disposal tunnel as realistically as possible.

The main goal of the FE experiment is (1) to obtain a better understanding of the coupled effects of induced thermo-hydro-mechanical (THM) processes that may occur once the actual repository is in operation and (2) to validate existing coupled THM models. Furthermore, the FE experiment also aims to confirm the technical feasibility of constructing the disposal tunnels using standard equipment, to optimize the production of the bentonite buffer, and to investigate the procedures for the emplacement of canisters and the bentonite buffer under underground conditions. For some aspects (e.g. planning of deposition of waste packages in the disposal gallery), the remark is made the FE implementation cannot always be considered as fully representative due to e.g. the extensive instrumentation works related.

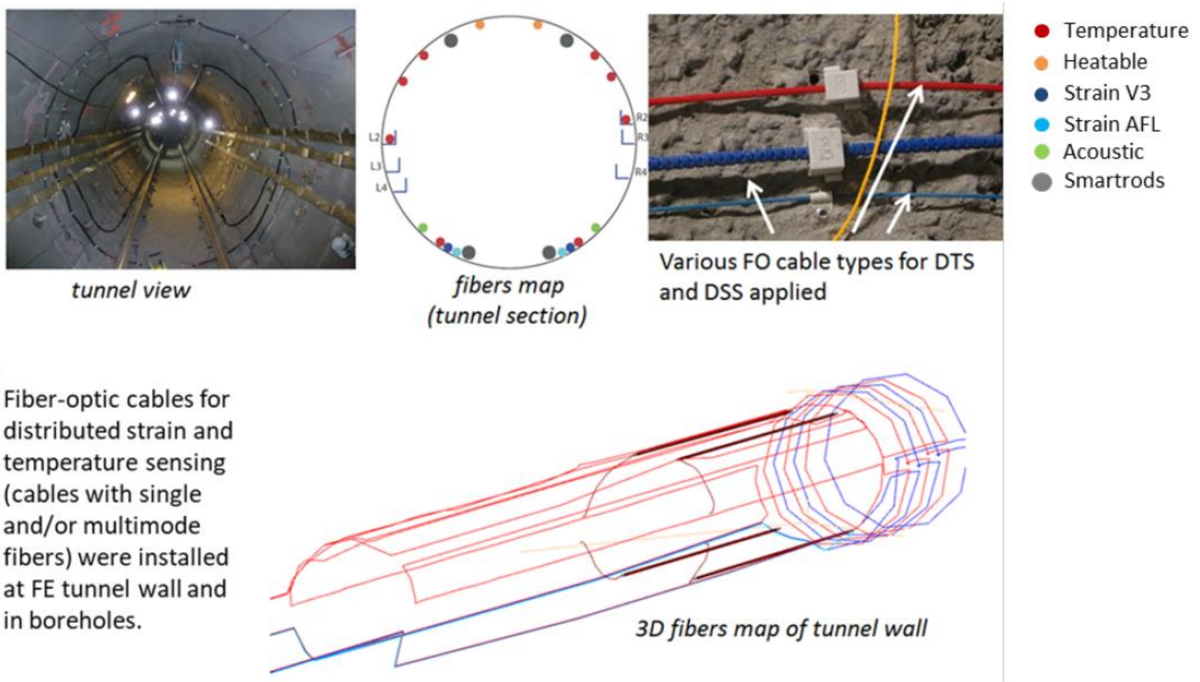
For the selection of the monitoring technologies and related sensors, the harsh conditions and the long-term aspect of the setup were considered (Müller et al., 2017). Due to these conditions, besides standard state-of-the-art sensors, fibre-optic sensors as well as modified and prototype measurement systems were installed. The prototype systems were designed to be more corrosion resistant. They were also constructed to be less heat-conductive, reducing the impact of the instrumentation on the experiment evolution.

In the TEM setup, the focus was the testing and monitoring of a seal plug through different monitoring technologies.

Monitoring technology (FE)

Two main monitoring technologies have been investigated within the Modern2020 project context: distributed sensing by fibre optic cables, and Time Domain Reflectometry (TDR).

Several fibre optic cables have been installed in the FE tunnel for distributed sensing of temperature and strain (also one acoustic type for seismicity monitoring).



tunnel view

fibers map (tunnel section)

Various FO cable types for DTS and DSS applied

Fiber-optic cables for distributed strain and temperature sensing (cables with single and/or multimode fibers) were installed at FE tunnel wall and in boreholes.

3D fibers map of tunnel wall

Figure 23 Fiber optic cables installed in the FE tunnel (Fisch et al., 2019)

Extensive efforts have been performed to increase the accuracy of the temperature measurements obtained by these sensors. They include the use of two different interrogators, the continuous calibration through calibration baths that are placed in line with most cables, and validation through Pt1000 precision temperature sensors.

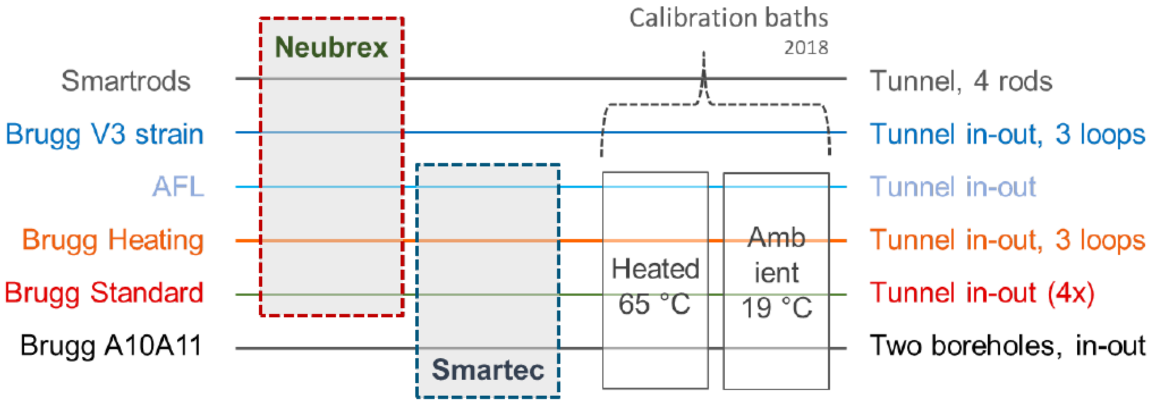


Figure 24 Different read-out devices and two calibration baths are integrated in the distributed FOS setup (Fisch et al., 2019)

It allowed NAGRA to formulate several conclusions with

To increase the performance of the TDR monitoring technology, an extensive calibration programme has also been carried out, including

Monitoring technology (TEM)

The monitoring technologies installed in the TEM setup can be grouped into the following categories:

- Wired sensors (conventional types)
    - Monitoring of the EBS behaviour through measurement of pore water pressure, total pressure and relative humidity.
- Cross-hole geophysical tomography based on repeated seismic measurements as a nonintrusive technique to observe the EBS development from the geosphere ;
- Low-frequency wireless techniques based on magneto-inductive (MI) technique;
    - a combination of the wireless data transmission method developed by Magneto-Inductive Systems Limited (MISL) and the data acquisition systems of Solexperts AG; tested and evaluated for the first time in an environment relevant to radioactive waste disposal.

At a later stage, in the frame of the EC MoDeRn project (2011), also high-frequency wireless measurement devices were installed.

Field realisation

Well planned, successful realisation.

Read-out systems for the distributed fibre optic cables prove to be fragile in underground conditions (e.g. need for conditioned cabinets or measurement racks).

Dedicated data management and presentation needed for the vast amount of data that are generated (in particular for those generated by the distributed fibre-optic sensing). This was realized through the development of the FE Information System (FEIS).

For TEM, the project follow-up of specific items was more subject to the project context (e.g., the high-frequency devices installed in 2011 in the frame of MoDeRn were not attended anymore after conclusion of this project). Now that the Modern2020 project has ended, some suggestions are made to valorise some key elements of the TEM setup further by continued testing, such as an improved calibration of the geophysical monitoring through an enhanced saturation/pressurization of the bentonite plug, and the demonstration of the load bearing capacity of the non-keyed concrete plug.

The operation of the wireless measurement system has provided interesting performance data (Figure 25). The MISL transmitter provided reliable data for more than six years (from begin 2007 to May 2013) almost continuously. Since May 2013, the transmission quality degraded, and one year later, only occasionally valid data could be detected in the transmissions. The most probable reason is the near end of lifetime of the batteries involved. More reliable battery systems would improve the transmission quality, and is a main issue if the wireless monitoring method would be applied further in other projects.

The high-frequency devices installed by AITEMIN in 2011 delivered data for about one year. They were not followed up anymore after conclusion of MoDeRn early 2013 (they seem to have provided data until November 2014). However, during a system review early 2016 after the start of Modern2020, no data were retrieved anymore.

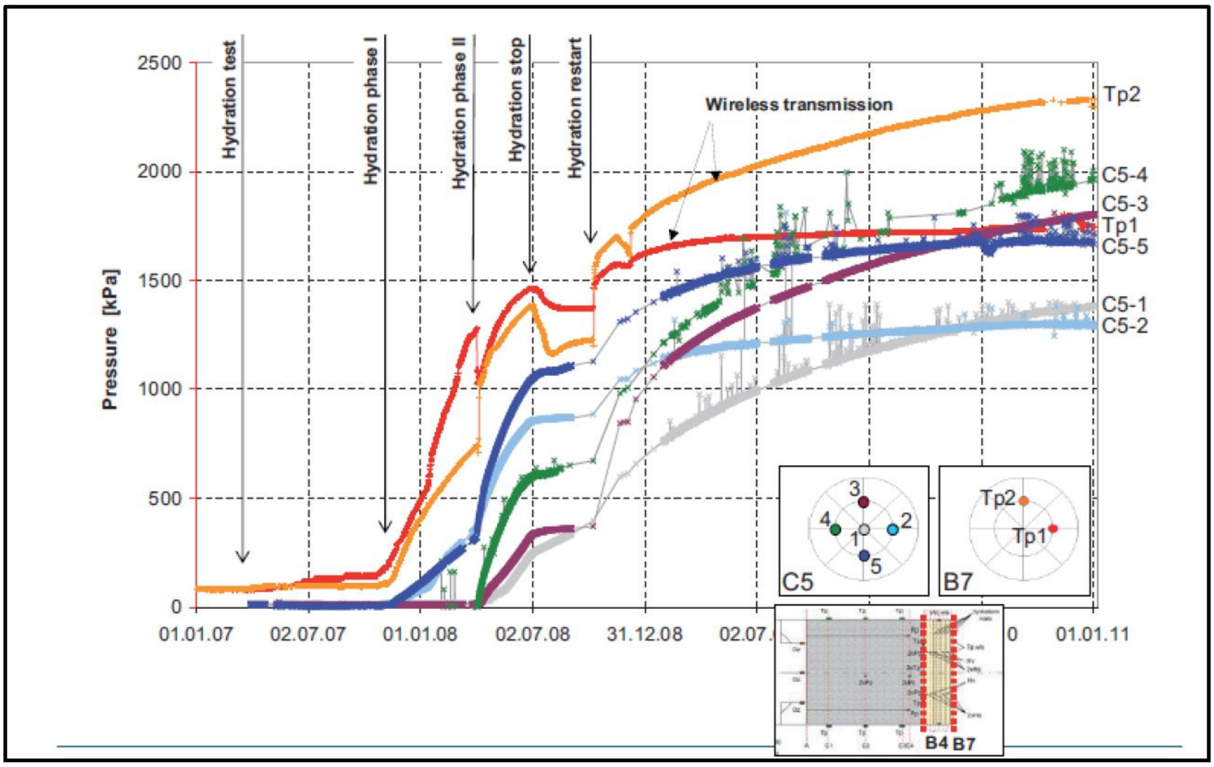


Figure 25 Comparison of wireless and wired monitoring (Tuñon Valladares et al., 2019)

It allowed, together with the work in WP3, to formulate some recommendations about the application of wireless transmission through EBS components.

Stakeholder interaction

The Mont Terri laboratory received many visitors.

4.1.5 PRACLAY (EURIDICE)

Design basis, monitoring strategy and decision-making

Within the design process of the PRACLAY heater test, there was not really a formal process to define the monitoring objectives in addition to the overall project objectives.

The Instrumentation Plan (EURIDICE, 2006) did not mention “monitoring objectives” explicitly; they were discussed in an initial chapter on “phenomena and processes of interest”. These include e.g. the THM behaviour of the Boom Clay (to demonstrate the reliability of the existing models), and the integrity of the gallery lining (to keep the retrievability option open).

Overall modelling (numerical prediction) has been performed to interpret the measured data, to improve estimations of material parameters,…

Scoping calculations have been performed to define measurement ranges (e.g. what is the maximum pore water pressure increase due to heating?).

In addition, alternative experiment scenarios were defined were made, in order to define response plans. These scenarios were simulated numerically, to assist in the definition of response plans, which have been developed prior to the start of the experiment. The alternative scenarios covered failure of the heater (and when to switch on the auxiliary heater), a leakage through the seal, excessive (and unexpected) pressures or temperatures,…

The setup was also carrying some safety risks, as it involved a 30 m long gallery at an elevated water pressure of up to 3 MPa, with a large buffer of available water due to the sand backfill. This meant that a leakage could result in a large or pressurized flow of nearly boiling water. The experimental section of the gallery was separated from the accessible part by the Seal, mainly a steel structure encased in the gallery lining. Inside this steel structure, a bentonite ring (composed of precompacted blocks) implements this sealing function.

At the Seal, which was considered as a critical component, the total (swelling) pressure at one section remained below the minimum value. The performance of the Seal (to enclose the heated and pressurized section of the experimental gallery from the accessible part) was therefore questioned, and first a clear view of the actual situation at the Seal (and of the bentonite ring in particular) had to be obtained. The validity of the sensor reading was questioned because it did not agree with the global picture obtained through the other measurements; a test programme based on gas breakthrough tests was performed, and allowed to obtain a clearer picture of this component. An expert committee was setup to discuss all observations; finally, the decision was made, based on the opinions of this committee, to skip the deviating value and to go ahead with the experiment.

A set of critical monitoring parameters were therefore defined, to detect any indication of leakage or sudden Seal movement. These parameters are reported in a “Daily Safety Report”. They are also continuously monitored through the database; an alarm is generated when set limits (upper, lower, or rate of change) are exceeded. An additional, independently wired, alarm system monitors the most critical parameters (such as leakage, heater failure, sudden pressure drops in the experimental gallery,…).

Monitoring technology

For the selection of the sensors and the monitoring technology, no formal procedure was available. It was based on the previous experiences, contacts with the manufacturers and other users or engineering consultants. Because of the good reliability in the past of the piezometers that are constructed in-house, and the versatility of the measurements (due to the strong THM coupling in the Boom clay, the pore water pressure is very sensitive to thermal and mechanical phenomena), and also the versatility of the device (allowing permeability tests, sampling,…), this sensor type (mostly integrated in multifilter borehole piezometers with twin-tube connection) made up a most important component in the monitoring system.

For the lining integrity, vibrating wire strain gauges (which are already functioning almost flawlessly for more than 15 years in the main gallery) were integrated in the lining segments. Some pressure and load cells provided additional data on the load.

The harshest conditions in the setup were located in the pressurized gallery; the design parameters in this part were a temperature of 100 °C, and 3 MPa water pressure. This was not only an issue for the sensors, but also for the cabling, as many sensors were installed in the lining and from the heated gallery into the host rock. The cable bundles were routed through this gallery and were finally fed through dedicated instrumentation flanges in the Seal. For the sensors, cable connections, etc. to be installed under these conditions, some short-term tests were performed in pressurized (water) environment, up to the design conditions, by subjecting the devices at pressures up to 3 MPa, and at elevated temperatures.

Regarding innovative technologies, optical fibre sensors were also installed. One type were the interferometric type of optical fibre strain gauges. Their long measurement base (up to 10 m) made them complementary to the vibrating wire strain gauges. They were installed in boreholes to serve as borehole extensometers, and also in the experimental gallery – to monitor the extension during the pressurisation and heating of the gallery. The other type of optical fibre sensors consisted of distributed Brillouin sensing, whose cables were installed alongside piezometer casings.

In addition, a microseismic monitoring set-up was installed, consisting of three boreholes instrumented with piezo-electric type transmitters / receivers, complemented with similar devices integrated in the lining after gallery construction. The idea of this setup was, to monitor the evolution of the host rock properties during the different experimental phases, from gallery excavation over ventilation, saturation and heating. The seismic velocities and other transmission characteristics (such as damping) can be used to estimate geomechanical parameters of the clay host rock.

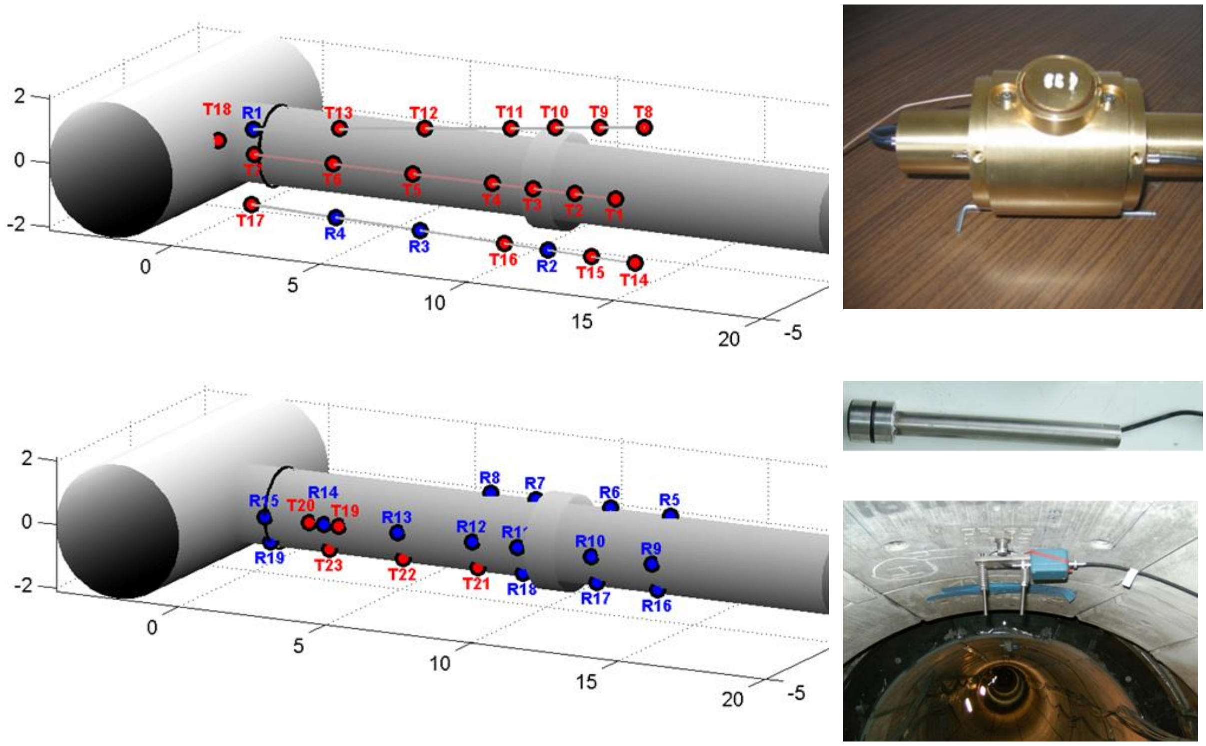


Figure 26 Layout of the microseismic sensors. Top: boreholes installed in 2006 with sensor type installed in borehole casing. Bottom: sensors integrated in the lining after gallery construction

Field realisation

The monitoring equipment was installed over a time span of many years, in line with the construction of the test set-up (starting with the excavation of the test gallery).

Because of the large number of sensors installed in the gallery lining (several hundred sensors), much effort went into the routing of the cabling and the tubing. No relevant leaks were caused by the cabling, except for the relative humidity (RH) sensors. The design of these sensors caused that, once the sensors were saturated, water could pass along the signal cable (between conductor and cable isolation). As these sensors were integrated into piezometer filters (in particular those installed in the bentonite blocks of the Seal), it also caused non-representative measurements as the pressure build-up in a piezometer filter could no be sustained by the draining effect of the RH sensors.

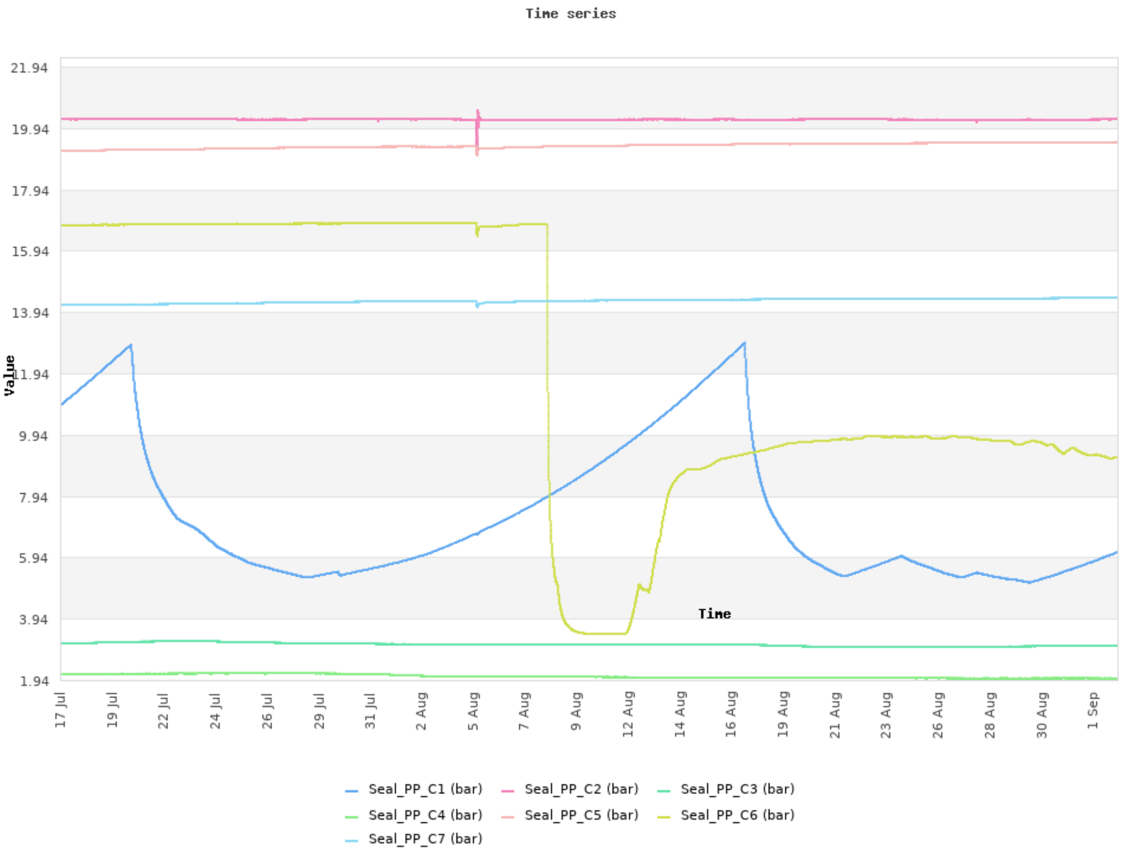


Figure 27 Erroneous evolution at some piezometers due to irregular drainage by integrated RH sensor

A similar effect was noted with the interferometric optical fibre strain gauges. These could finally not resist to the elevated water pressures, and also caused leakage. It must be noted however, that all leakages only carried a very low flow rate (drop – wise), and therefore had no detrimental effect for the experiment. In a repository however, such leakages would most probably not be accepted.

The design of the instrumented casings, with an open end at the borehole entrance, has always worked well when these boreholes were drilled from an open, accessible gallery. However, when installed from the experimental gallery, which became pressurized after installation of the Seal, unwanted effects resulted, such as convective heat transfer at the inside of these instrumented casings, rendering the temperature (and pressure) measurements useless. Other artefacts that became clear were due to long piezometer tubes between the filter and the pressure transmitter. The pressure measured is then sometimes influenced by temperature changes along this tubing, which results in pressure changes that are not representative for the actual

Due to the harsh conditions, a large number of sensors failed, mainly in the lining of the experimental gallery. Thermocouple failures are probably mainly related to water ingress (cable connections are a weak point at the longer term), while the vibrating wire strain gauges all failed in a short time period, when the thermal equilibrium (80 °C at the outside of the lining) was reached. It shows that a short-term test is often not sufficient to verify the reliability at longer term.

Stakeholder interaction

Although the PRACLAY setup is one of the main research items that is presented during field visits, it has not been used in a formal way for stakeholder interaction. At one meeting with local stakeholders, some measurement results of PRACLAY (including erroneous data) were used to illustrate the issue of data management, but no further follow-up has been organised.

Apart from citizen stakeholders, the PRACLAY data are used in international programmes or academic research.

4.1.6 ILW concrete liner monitoring program (Cigéo test case – ANDRA)

4.1.6.1 GCR gallery

Design basis, monitoring strategy and decision-making

- The instrumentation plan for the different HLW demonstrator was based on the monitoring strategy of Cigéo ILL concept.
- Partial modelling and calculation has been realized; the complete mechanical behaviour is still under progress

Monitoring technology

Sensors selection criteria

- **Fit with requirement of Cigéo project conditions:** the monitoring devices and installed equipment must further resist to the severe environmental conditions existing in a repository, which may include high temperatures, high pressures, humidity and/or submersion, chemically aggressive environments, and levels of radiation that may degrade electrical and optical cables performances. Typical requirements also include the longevity (several decades) of expected monitoring (without real possibility of accessibility to maintain equipment, except by robotized devices), the high level of needed confidence in signal reliability, and the absence of interference with barrier performances, in particular as pertaining to long-term safety. This is a key requirement of the monitoring system not to degrade the favourable conditions and expected performances for long-term safety of the repository
- **Technical performance:** to select the suitable technology, Andra is looking to the sensors characteristics (see criteria on Table 3) and specific criteria developed for the geological disposal.

  It also important to mention that redundancy is also a part of the Andra monitoring strategy during the monitoring period

Table 3: Sensors characteristics

Range	Difference between the maximum and minimum value of the sensed parameter
Resolution	The smallest change the sensor can differentiate. • For digital sensors, it is related to number of bits used • For analogue sensors, it is limited by low-level electrical noise
Sensitivity	Ratio of change in output to a unit change of the input • For digital sensors, sensitivity is closely related to resolution • For analogue sensors, sensitivity is the output slope vs. input line
Error	Difference between the measured value and the true value.

	Two classifications: bias (systematic error) and random
Accuracy	Inversely proportional to the error Sometimes related to the sensor's linearity
Precision	Ability to reproduce repeatedly with a given accuracy (sometimes called repeatability)
Linearity	Percentage of deviation from the best-fit linear calibration curve • Linearity means superposition principle • Most systems have nonlinear behaviour
Response time	The time lag between the input and output
Bandwidth	Frequency at which the output magnitude drops by 3 dB
Operating temperature	The temperature range in which the sensor performs as specified
Signal-to-noise ratio	Ratio between the magnitude of the signal and the noise at the output

Table 4: Sensor Selection Criteria

Dynamic range	is the ratio between the maximum output signal level and the noise floor at minimum signal amplification
Required resolution and sensitivity	This criteria is directly connected to the application and the requirement
Required accuracy and precision	This criteria is directly connected to the application and the requirement
Environmental conditions	The condition is one of major selection criteria. Ex: if you need to resist to radiation
Power available for sensing	As we measure something inside specific engineer barrier with safety requirement the presence of cables or not could be important
Availability	The availability of the technology could be an issue sometime. There is two aspects : • easy to found: the technology is well known and well deployed on the market or not • and availability with the time: example component obsolescence…etc./ interchangeability problem
Size and available space	Non-intrusive technology safety consideration
Material compatibility	Concern the compatibility between sensor material and the application in the geological disposal safety consideration
Ease of use /Required signal processing	It is an important criteria when we are at the stage of designing the monitoring system

Ease of maintenance	Free maintenance is required for each system
Cost	The cost must be considered in its entirety. The price of the sensor (sensitive part) could be very cheap. The cost must be analyse taking into account: sensor itself, calibration, cable length, implementation method (how many time you stop the construction), data acquisition system, data storage….
Feedback from other industries	As an example: VWS installed in Le Mont Larron dam have been in operation since 1950 and continue to provide reliable data. The principle of the measurement is based on the vibration of a steel wire, material known for its longevity. The simplicity of the measurement provides a fail proof system that does not require any drift correction, nor periodic maintenance. Andra has obtained internal feedback, especially from the low-level waste disposal facility, where VWS were installed in the 1990s, and more recently in the Andra Underground Laboratory, where VWS were installed to monitor the access shafts and galleries

A succinct description of the qualification process that Andra has put in place is provided. It entails testing and qualifying the complete measurement chain, by progressive steps, knowing, to be able to anticipate them, the failure rates and mastering the possible long-term drifts. The overall process is inspired from the qualification guide for non-destructive methods. The global test sequence includes four stages.

- Stage one consists in acquiring in-depth knowledge of the sensing technology, engineering solutions, practical implementation constraints. It aims at selecting the technologies best suited to the specific requirements of monitoring the geological repositories for long-lived nuclear wastes. When commercially available sensing chain performances do not fulfil requirements, research programs will be initiated.
- Stage two consists in carrying out laboratory tests, under fully supervised and/or controlled environmental conditions, to qualify the sensitive component and assess the complete measurement chain performances. Sensors are tested in air, and embedded in host material of interest.
- Stage three consists in outdoor tests, to evaluated field implementation influence. At this stage, the sensing chain is preserved from hazardous conditions, extreme temperature or gamma rays. Unexpected influence parameters might thus be revealed.
- Stage four involves hardening in view of the application environmental conditions. In the envisioned French geological repository, temperature would range from 25 °C to 90 °C. Gamma radiation rates reach Gy/h, total dose 10 MGy. Hydrogen release is also expected; its maximum levels could approach 100% hydrogen content in the atmosphere.

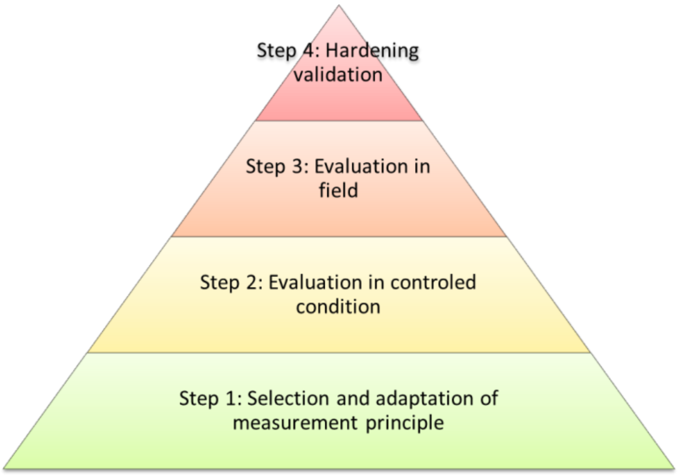


Figure 28 Qualification process for technology implementation in the Cigéo project.

To match these requirements, Andra has launched an ambitious R&D program to ensure that reliable, durable, metrologically qualified and tested monitoring systems will be available at the time of repository construction to respond to these monitoring objectives. The developments have emphasized (i) monitoring strategy, especially as pertaining to the distribution of monitoring systems throughout the disposal, (ii) the design of monitoring units according to a qualification procedure, and (iii) a comprehensive set of R&D activities to adapt, complement and qualify existing technology

Presently, THM sensors are finishing the qualification process while chemical and radiation sensors are still at the laboratory stage. More precisely, Andra's monitoring system will rely on platinum temperature probes (T), VWS (vibrating wire extensometers - M), strain and temperature distributed optical fibre sensors based on Raman and Brillouin scatterings (T, M)), water content sensors based on Time Domain Reflectometry probes (H), interstitial pressure cells based on VWS (M), long-based-field-extensometer

Field realisation

GCR experiment

A specific section of the GCR gallery was dedicated as a monitoring demonstrator. This section contains 129 point sensors and 11 distributed optical fibres sensors (OFS), providing THM measurements every 30 minutes (5 or 10 minutes in the first months). The sensors were installed in order to provide for some of the monitoring parameters point and distributed technologies for redundancy. The point sensors installed were:

- 14 Time Domain Reflectometry (TDR): water content in the near field rock and in the concrete ring
- 22 Vibrating Wire Extensometer (VWE): strain in the concrete liner
- 5 Pore Water Pressure (PWP): pore pressure in the rock near field
- 3 Total Pressure (TPC) load between concrete support and host rock
- Extensometer Multi-points Single-rod (EMS) displacement measurements of the rock

Andra had previously tested Raman temperature sensing into singlemode fibres in a surface building slab. This test highlighted the great sensitivity of Raman scattering in singlemode fibre to curvature, which can hardly be avoided in civil engineering structures. This is why two different sensing lines were implemented: multimode fibres were used for Raman temperature monitoring and singlemode fibres were installed for Brillouin strain sensing. More precisely, we used three different sensing cables, two for Brillouin measurements, composed of G652 and G657 fibre types to evaluate curvature sensitivity, and one for Raman sensing. The three cables were placed redundantly so that, finally, six sensing arches were embedded inside the concrete liner.

In order to ensure accurate positioning and maintaining during concrete pouring, sensing cables were attached to a thin piece of wire mesh, spitted on the retaining concrete.

Measurements were remotely performed every 15 minutes by commercially available instruments, a Brillouin-OTDA (optical Time Domain Analyser) and a Raman Distributed Temperature Sensing (DTS). Both devices were set at 0.5 m spatial resolution.

Instruments were located in another gallery of the underground laboratory. The full sensing line is approximately 500 m, with only 20 m embedded inside the concrete liner.

Electronics sensors, such as vibrating wire extensometers and platinum probes were installed next to the optical fibre sensors.

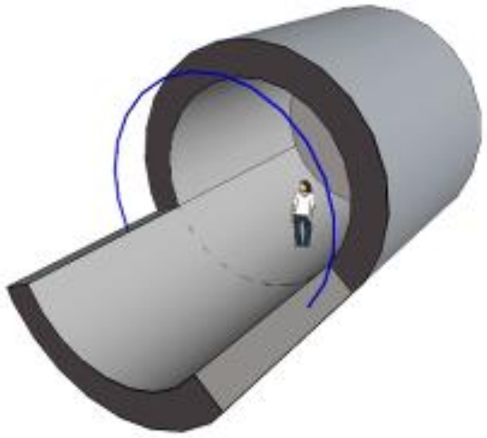


Figure 29: Scheme of gallery instrumentation by distributed sensing

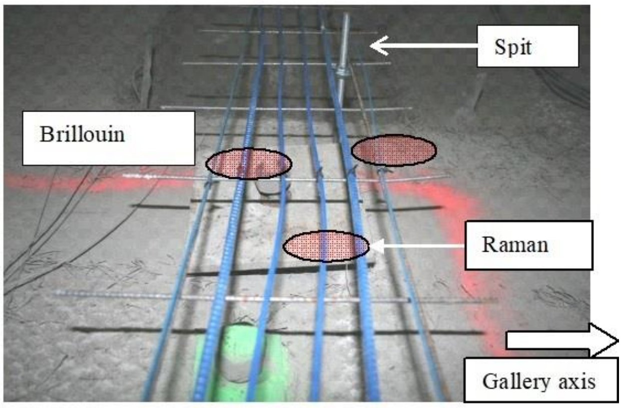


Figure 30: Picture of optical fibre cables installed on a gallery circumference, before concrete casting

4.1.6.2 GER gallery

Table 5 summarises the monitoring technology of the sensors installed in the GER gallery.

Boreholes (near field) were drilled in the four cardinal directions of some gallery sections, and equipped with inductive or resistive Displacement Sensors (DS), or/and distributed temperature and strain Fiber Optic Sensor (FOS). Pore Water Pressure sensors (PWP) with wireless transmissions provide PWP profiles around the gallery.

Shotcrete and poured concrete layers are monitored for strain, temperature and water content using innovative monitoring devices, like FOS of various types, tactile pressure sensor and pulse sensor or classical ones, like Vibrating Wire Extensometers (VWE), Total Pressure Cells (TPC) and Time Domain Reflectometry probes (TDR). In addition, different designs of monitored concrete samples were embedded in the concrete layer to serve as TH references for strain measurements.

Table 5 Summary of the sensor technology installed in the GER gallery

Technology	# Sensors
resistive displacement sensors	4
Interstitial pressure sensor	4
Distributed optical fibre	8
Thermal reference (for optical fibre)	3
TDR probes	10
Pulse system	4
Vibrating wire extensometer (VWE)	96

FOS cables for temperature and strain (from Brugg company) were installed in the shotcrete against claystone, and under compressive beams where present. This configuration was tested for the first time in Andra's URL. The cables were not expected to support high strains, but to survive enough long time to provide loading profile around the gallery for better behaviour of loading understanding. FOS cables were connected to the Raman readout device for temperature measurements and to the Brillouin readout for strain measurements.

Data treatment approach for distributed measurements is currently under development in Andra. Thanks to this method, strains obtained around the gallery, during about 10 days before FOS failure, are presented in Figure 31. It presents raw measurements of FOS and VWE placed on a compressive beam at the same location (bottom of the gallery). The shear punching mechanism, observed just before the loss of FOS signal, was consistent with site observations and fits with results observed on the collocated VWE sensor.

In Figure 31, strains and temperatures, for the same period at the bottom of the gallery, are presented. Measurements obtained by FOS, placed between claystone and beam, fit well with measurements acquired by VWE placed on the compressive beam. Indeed, strains increase in the shotcrete (FOS measure tensile stress); at the same time, the compressive beam is compressed (VWE measure compressive stress).

Figure 32 shows an advantage of distributed measurements: OFS are able to measure events along the whole cable, while classic sensors inform about a single location. Measurements obtained are consistent with expected behaviour of the shotcrete at this location.

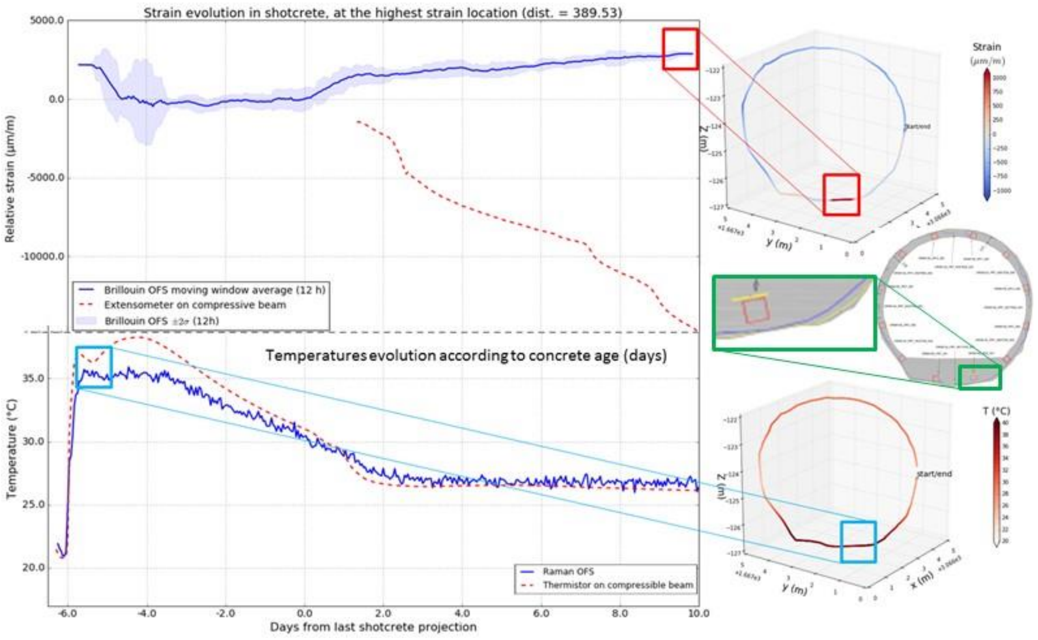


Figure 31: Strains and temperatures measured by OFS (plain blue line) placed around the gallery and extensometer (dashed red line) placed on compressive beam, both in the shotcrete. Left, a temporal presentation and on the right, a spatial presentation at a specific moment. The layout (in the middle right) indicates the localization of the OFS (blue line) and extensometer (yellow segment) placed on compressive beam (red box).

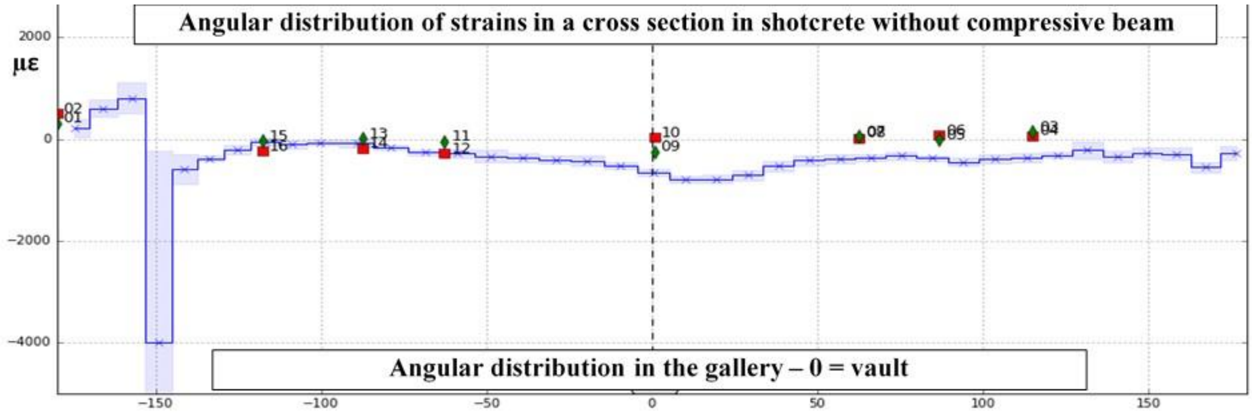


Figure 32 : Strains measured by FOS (blue segments) and VWE (red squares for intrados location and green diamonds for extrados) around the cross section of the gallery (0° in vault and 180° in the bottom). FOS measured is the average strain over segments of 0.5 m. The blue line represents the moving window average of 12 hours (95% confidence interval)

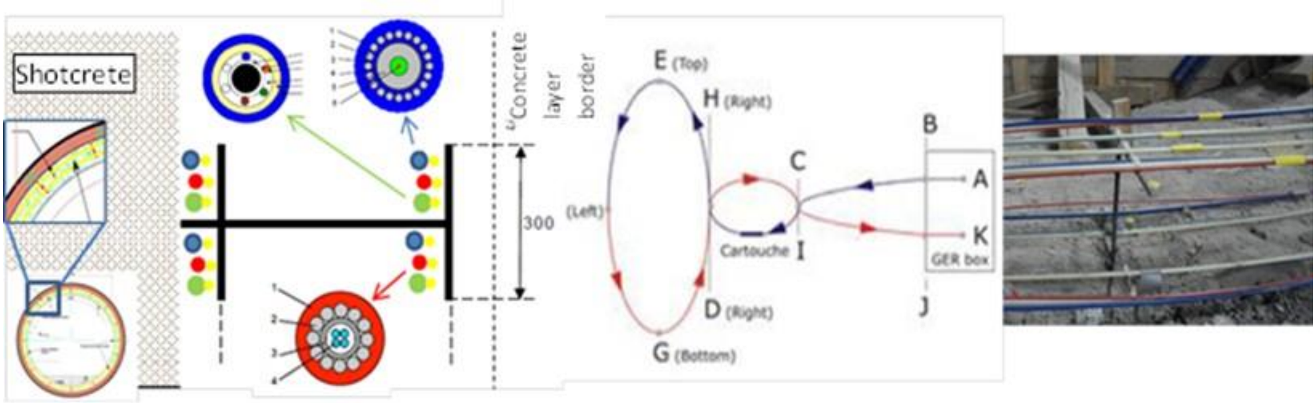


Figure 33: Schematic installation of FOS in the concrete layer in the GER gallery with three types of FOS cables, two for strains and one for temperature (left). Particular points for localization schema (middle) are presented and the photo of the installation (right)

4.1.7 FEBEX (AMBERG)

Design basis, monitoring strategy and decision-making

- EBS for HLW/SF disposal based on the “Spanish concept”
- Extensive modelling of thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) processes, as testing the capability of the THM and THG modelling codes was one of the objectives.

Monitoring technology

- Mainly conventional technologies (thermocouples, vibrating wires,...), although many sensors were customized (e.g. displacement transducers to monitor swelling of the bentonite blocks) to cope with the specific conditions.

Field realisation

- Successful installation through well prepared planning and development of procedures.
- Well organized follow-up of the measurement data, including formal data reporting and validation.
- Some leakage was observed along the cable bundles at the initial stage of the experiment. This could be resolved in a later stage.
- Dismantling was performed in two phases: a partial one in 2002 after 5 years of heating and natural saturation, and final dismantling in 2015 (after 18 years of operating); the fact that the same contractor was responsible for the installation, partial dismantling and final dismantling was considered as very beneficial; the existing knowledge and experience helped to save time and to improve the quality of the operation.
- During dismantling, removal of the dummy canister was more difficult than anticipated. This was an important lesson when considering retrievability.
- The sensors retrieved during the final dismantling were in better conditions than those retrieved at the partial dismantling. Overall, compared with other set-ups, a very good track record for the installed sensors.
- Long-term project management) was successful. The field setup was operated through different projects and partnerships over a time span of 20 years, but this caused operational problems.

4.1.8 Prototype Repository (POSIVA)

Design basis, monitoring strategy and decision-making

The setup was intended to simulate at full-scale the KBS-3V concept / safety case.

The objectives of this field test with regard to the operational permit (longer-term operation of the inner section) and license application (shorter operation of the outer section) were clearly defined.

More particular monitoring objectives were also defined (Pusch et al., 2004): measurement of THM processes in the buffer and the backfill "to determine the actual rate of heating and wetting, and the build-up of hydraulic and swelling pressures, which are all of fundamental importance to the function of the engineered barriers."

Monitoring technology

The prime principle in selecting sensors for the buffer, backfill and near-field rock was to choose among those that have been found to operate well in other projects and which could be manufactured with high quality. The final selection was based on the experience of the respective project participants. Special circumstances in the Prototype Repository are the geochemical conditions and the long time during which the test will be conducted and the related requirements that the sensor design and manufacturing will have to meet.

The required number of sensors became a compromise between the wish for complete instrumentation of the entire test set-up, and the number that actually could be put in with respect to the number and size of cables, and to the risk of interference of adjacent gauges.

The monitoring plan was therefore mainly based on proven, conventional sensors. To increase the reliability, two different sensors and monitoring technologies were used for some parameters (e.g. total and pore water pressure: both vibrating wire and piezoresistive sensors). For the measurement of the buffer saturation, both capacitive relative humidity sensors, as well as psychrometers were installed.

Some innovative technologies were however also applied: electrical resistivity to study the overall wetting (hydration) of the backfill in the deposition tunnel, and fibre optic gauges (commercially available) to monitoring the canister displacement. The initiative came from specific partners in this project.

Field realisation

The planning of the project started in 1998 and the installation was completed in 2003. This reflects a rather fast realisation. Several publications are available on the preparation and installation of the monitoring equipment, which indicates a thorough planning of it.

Nevertheless, many sensors, and some heaters, failed shortly after completion of the setup. A particular observation was the increased failure rate after the drainage of the deposition tunnel was closed, thereby leading to an increased water pressure. This indicates that the water tightness of some monitoring components might not have been optimal, in spite the detailed design of e.g. the sensor cabling (Sandén, 2001).

Dismantling

The outer sections was dismantled in 2011, after about seven years of operation. It resulted in several recommendations, including one specifically for the sensors (Svemar *et al.*, 2016) – indicating that representative sensors should be selected from the retrieved sensors to be investigated (e.g. recalibration) with the same methods that were used in the Project, with the objective to establish the accuracy of the recorded data collected during the operation. In the particular case of the vibrating wire sensors, where the manufacturer proposed two calibration formulas (a linear and a polynomial), it appeared that the linear calibration yielded an unsatisfactory accuracy, in contrast with the polynomial calibration. Therefore, the raw data of this type of sensors were recalculated with the polynomial formula to achieve a better accuracy, and hence a more reliable assessment of the predictive models (whose results were compared with the monitored data).

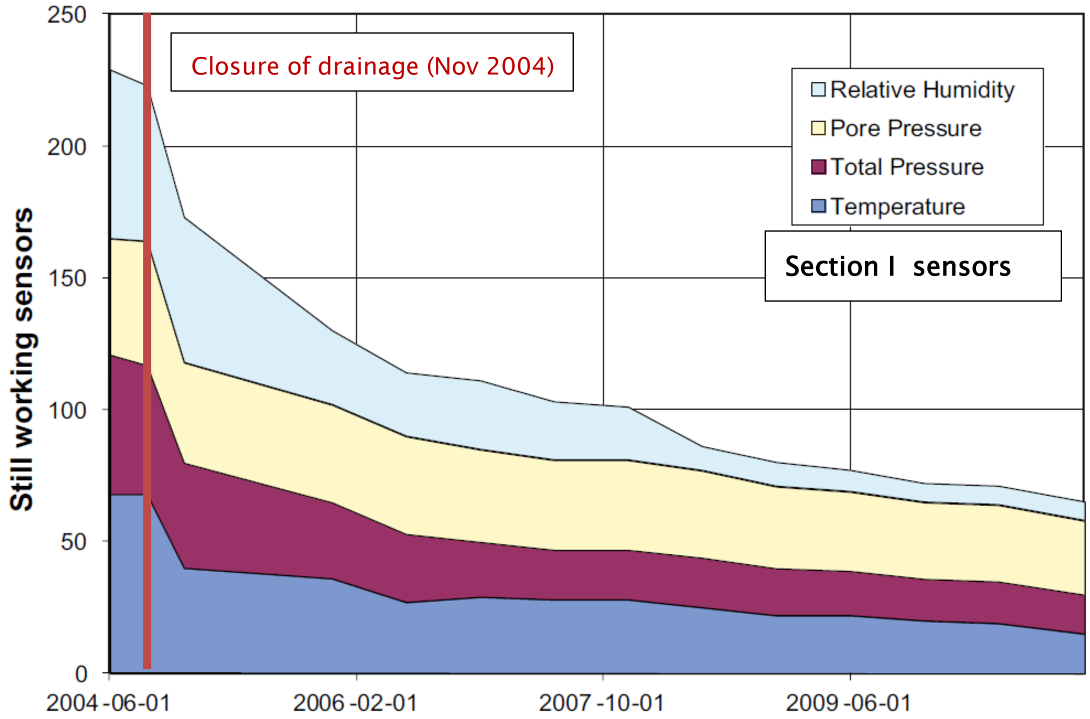


Figure 34 Several additional sensors failed in Section I when the drainage exit of the tunnel was closed (Goudarzi, 2012)

Stakeholder interaction

The Prototype Repository plays an essential role in the licence application (construction and operation), and therefore interaction with the regulator is evident.

Interaction with citizen stakeholders (beyond the typical visits) however has not been reported.

4.2 Synthesis of the results

When comparing the different cases, we see that the development (planning, design, realisation, operation,…) is different for each case, which is rather normal when considering the identifying elements of each case (national context, host rock, planning/timing of the repository implementation,…).

For some specific points, all these cases give a nice overview of different approaches that have been applied – or allow identifying some common features.

Most demonstrators have a clear link with the repository concept and the safety case that is linked to it. In some cases, a generic approach – e.g., where only parts of the repository design such as the near field are considered - is still applicable, as the concept has not crystallized yet in a final design.

Use of monitoring data for decision-making has not been detailed very much yet in the demonstrators. In e.g. the PRACLAY case, such decision-making is mainly related to ensure an operation of the setup that is both safe and that fulfils the experimental objectives (e.g. operating the heater at the right power level).

For the selection of monitoring technology and sensors, some formal decision processes have been introduced (e.g. EBS Monitoring Plan). In general, we see that the following aspects are typically relevant in the selection process

- Commercial availability (different levels of specifications or customization, e.g. other alloys to minimize corrosion risk);
- Using experiences of other tests;
- Formal decision process with criteria;
- Development and demonstration of (new or improved) monitoring techniques (require time and budget resources).

Regarding the wireless technology, two demonstrators (TEM and LTRBM) have given very relevant feedback, which has been summarized already in the D4.4 deliverable (Tuñon Valladares et al., 2019). The general conclusion is, that high frequency data transmission through the EBS components is not recommended, as higher frequencies show higher attenuation – in particular when the buffer saturation progresses. This was evidenced in the lower frequency chosen for the LTRBM prototypes.

Overall, the different technologies (wireless and wired – including the distributed fibre optics – and the geophysical methods) should be considered as a toolbox, of which for each application (prototype setup, witness cell, main repository) and for each phase in the repository operation, the most appropriate tools can be combined, considering the host rock and EBS components that are used in the repository design that is considered.

Scientific interpretation of the monitoring results is normally of the the main objectives of each demonstrator or field setup. Different groups, ranging from the organisation that runs the experiment to academic research groups, perform this. Such interpretation can only be performed when comparing with model predictions.

Relevant stakeholder interaction (in particular with citizen stakeholders) has remained limited. A systematic or structured discussion of the measurement data or results with citizen stakeholders was not reported for any of the cases discussed. Demonstrators allow illustrating monitoring concepts; currently, this is mainly achieved by field visits and presentation of processed monitoring data. In-depth discussion of the design or the demonstrator results was rather restricted to an academic or research audience. Nevertheless, the current demonstrators can give input to future dialogues with citizen stakeholders where relevant in the national context.

5. Conclusions and some considerations

This section presents the conclusions and some considerations about task 4.5 of the Modern2020 Project. The exercise was not fully performed due to the difficulties to find information and the resources allocated to the task.

Some experiments were selected based on the interest they offer from the monitoring system developed namely: EBS Monitoring Plan, AHA, LTRBM, FE and TEM, PRACLAY, GCR & GER, FEBEX and Prototype Repository.

A list of assessment criteria has been developed in the document based on methodologies and the results of the others Modern2020 work packages. The considerations have been developed based on these criteria.

Selection of Parameters and monitoring design (WP2 aspects)

All experiments developed a set of parameters mainly based on predictive model analysis. The methodology was not always clear, how the monitoring system has been determined, and how the sensors have been selected. The monitoring solution was driven, in the selected examples, by a better understanding of the system. The number of parameters were more important in way to guarantee the results.

The selected test cases are good examples to support the feasibility of monitoring when one thinks to develop the strategy.

Feedback on monitoring technologies (WP3 aspects*)*

The results obtained in Modern2020, considering both the development in WP3 and the WP4 demonstrators, show the potential of emerging sensor technologies, such as distributed optical fibre sensing, electro-resistive tomography, and wireless sensing and transmission of monitoring data.

Regarding the application of distributed optical fibre sensing, this technology brings many advantages in combination with a minimal invasive effects. It allows realizing a continuous measurement line with a thin cable that can handle the dimensions that are of interest in a waste disposal site (e.g., galleries of several hundreds of metres can be covered with one cable). A successful implementation depends however on several conditions. First, sufficient resources and competences are needed. Although the price of an optical fibre cable is minimal, the read-out equipment still carries an important price tag. More importantly, the signals that come out of such a monitoring system require a substantial amount of processing by skilled professionals to obtain meaningful and accurate data. Attention must be paid to essential issues such as an installation procedure that ensures that the fibre is sensing the actual environment (thereby avoiding artefacts), the integration of calibration features (e.g. strategically located precision point sensors for comparison reasons, or the integration of permanent calibration baths in the fibre optic loop), and a data management system that can process the vast amount of monitoring data that is generated by such a monitoring system. Such system should also make the processed data available (e.g. visualise) to the investigators in a convenient way.

The wireless sensing and transmission technologies show also a good perspective. The TEM setup has given us already a successful demonstration of such technology for more than a decade. The LTRBM setup however shows that the technology still is not completely mature. Nevertheless, many organisations assume that this technology will play an essential role in their monitoring strategies.

Demonstrators and stakeholder expectations (WP5 aspects*)*

The role of the demonstrators for stakeholders is quite important to consider method and results and to increase the confidence in the disposal concept. With the exception of the regulator, public stakeholders have done no deeper exchange on the monitoring system of the different demonstrators.

6. Outcomes

Collecting and analysis information should be continue with the adapted amount of resources. The method has to be consolidate and the number of test cases should be increase to be more representative and try to extract some recommendation. The work performed in Modern2020 should be consider as a starting point on this collection of feedback experience.

References

ANDRA (2019), Deliverable D4.2: Development of HA monitoring plan. Modern2020 Work Package 4 – Deliverable 4.2.

E. Bohner, H. Kivikoski, K. Raunio, J. Hansen, M. Niskanen, P. Rantamäki, D. Luterkort, L.-E. Johannesson (2019). Deliverable D4.1: EBS monitoring plan - Spent fuel disposal concept at crystalline host rock. Modern2020 Work Package 4 – Deliverable 4.1.

M. Collin, L. Börgesson (2001). Prototype Repository – Instrumentation of buffer and backfill for measuring THM processes. SKB International Progress Report IPR-02-03; SKB (Stockholm, Sweden).

EURIDICE (2006) - PRACLAY Instrumentation Plan (2006) *(not published)*

R. Farhoud, J. Bertrand, A. Guzik, F. Bumbieler, B. Helmlinger, K. Kushida (2019). Qualification of diameter change monitoring system of inaccessible steel tube. Poster presented at the 2nd International Conference on Monitoring in Geological Disposal of Radioactive Waste, April 2019, Paris, France.

H.R. Fisch, B. Firat Lüthi, A. Reinicke & T. Sakaki (2019). Modern2020 WP4.4 - Full-Scale Emplacement (FE) Experiment, Mont Terri (Switzerland) – Field realisation - Nagra Working Report, NAB 19-32; Nagra (Wettingen, Switzerland).

J.-L. Garcia-Siñeriz, M. Rey Mazón, F. Kober (2017). Dismantling activities of the FEBEX "in-situ" test. Poster presented at the 7th Int Conf on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. 24-27 September 2017, Davos, Switzerland.

R. Goudarzi (2012). Prototype Repository – Sensor data report (period 100917-110101) Report no 24. SKB Report P-12-12; SKB (Stockholm, Sweden).

R. Goudarzi (2019). Prototype Repository – Sensor data report (period 010917-180101) Report no 29. SKB Report P-18-22; SKB (Stockholm, Sweden).

IRSN (2019), Deliverable D4.3: As-built of the Long Term Rock Buffer Monitoring demonstrator. Modern2020 Work Package 4 – Deliverable 4.3.

H. R. Müller, B. Garitte, T. Vogt, S. Köhler, T. Sakaki, H. Weber, T. Spillmann, M. Hertrich, J. K. Becker, N. Giroud, V. Cloet, N. Diomidis, T. Vietor. (2017) Implementation of the full-scale emplacement (FE) experiment at the Mont Terri rock laboratory. Paper #14 of the Mont Terri Special Issue of the Swiss Journal of Geosciences.

R. Pusch, L. Börgesson, C. Svemar (eds.) (2004). Prototype Repository – Final Report (Deliverable D36). SKB International Progress Report IPR-04-27; SKB (Stockholm, Sweden).

T. Sandén (2001). Prototype Repository - Detailed design of lead throughs and cable protections in the Prototype Repository, Section I. SKB International Progress Report IPR-01-18; SKB (Stockholm, Sweden).

C. Svemar, L.-E. Johannesson, P. Grahm, D. Svensson, O. Kristensson, M. Lönnqvist, U. Nilsson (2016). Prototype Repository – Opening and retrieval of outer section of Prototype Repository at Äspö Hard Rock Laboratory. Summary report. SKB Technical Report TR-13-22; SKB (Stockholm, Sweden).

S. Tuñon Valladares, J. L. García-Siñeriz, T. Spillmann & B. Frieg (2019). Evolution of TEM experiment at the Grimsel Test Site (GTS) during the timeframe of Modern2020 project - Nagra Working Report, NAB 19-33; Nagra (Wettingen, Switzerland).