Deliverable 17.3: Lessons for Repository Monitoring from Underground Research Laboratory Experiments

Work Package 17 MODATS

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Executive Summary

Waste management organisations (WMOs) will collect significant quantities of data during repository monitoring programmes. These data are likely to be used for the purposes of aiding decision making and building further confidence, particularly in the safety case. Confidence must exist in the collected monitoring data to successfully fulfil the aims of repository monitoring programmes. Confidence will be built by demonstrating that:

- Appropriate repository monitoring system designs are implemented.
- Effective methods are used to acquire, manage and use monitoring data.

Work Package (WP) 17 of the EURAD programme - Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (MODATS), addresses monitoring data acquisition, management and analysis development needs through research activities in Task 2 (Data Treatment for Increased Confidence in Repository Monitoring).

The most relevant monitoring system design and data acquisition, management and analysis knowledge and experience to date has been gained from monitoring activities in underground research laboratory (URL) experiments because, in the main, repositories are not yet operating.

A survey of URL experiments has been undertaken to learn lessons for monitoring in repositories during construction, operation and closure to support the research and development activities in Task 2. Seventeen experiments have been surveyed. Some of these experiments are completed and have been dismantled, while others are ongoing. They are conducted in different engineered barrier system (EBS) components and in different host rocks. Some of the experiments aim to understand the behaviour and test the performance of individual EBS components, while others aim to develop further understanding of one or more thermal, hydraulic, mechanical, chemical, gas and radionuclide transport (THMCGR) processes in one component of the multi-barrier system or in full-scale repository concepts. Some of the experiments also test materials and emplacement technologies.

The MODATS WP is using five Reference Experiments to underpin the research and development activities in Task 2, for example, by providing results to support the development of data management approaches. The MODATS Reference Experiments are:

- The ALC1605 experiment (Bure URL, in France).
- The Full-Scale Emplacement (FE) experiment (Mont Terri URL, Switzerland).
- The Posiva Plug (POPLU) experiment (ONKALO, Finland).
- The Preliminary demonstration test for CLAY disposal of highly radioactive waste (PRACLAY) experiment (HADES URL, Belgium).
- The Prototype Repository II experiment (Äspö Hard Rock Laboratory, Sweden).

The Reference Experiments are included in the survey.

This report summarises the survey responses to develop lessons for repository monitoring relating to the design of monitoring systems and the acquisition, management and use of monitoring data. The lessons are discussed in detail in Section 3 of this report. It should be noted that the lessons are exclusively learned from the survey. However, further understanding of these aspects of monitoring is available elsewhere.

The lessons for repository monitoring are presented below, along with some related gaps in understanding.

Monitoring System Designs

Monitoring Parameter Selection

- The aims of the repository monitoring programme should dictate the parameters that will be monitored.
- The selection of parameters is closely related to the selection of technologies.
- The selection of monitoring parameters should follow a structured process and the resulting decisions should be justified and documented.
- The Modern2020 screening methodology provides a structured process for parameter selection based on international consensus, which could be tailored to the needs of the specific repository monitoring programme.

Monitoring Technology Selection

- A broad range of technologies are available for repository monitoring, with considerable experience and knowledge of their use and capabilities.
- The selection of technologies is likely to involve close collaboration between technology providers and the monitoring team.
- Detailed requirements on technology performance should be defined during the monitoring system design phase and be used to inform technology selection.

Monitoring System Layout

- Repository monitoring system layouts are likely to be supported by knowledge of design and installation, and the processes occurring in the near-field gained, in part, from URL experiments.
- Sensors should be arranged in cross-sections oriented perpendicular to parameter gradients.
- Sensors should be clustered in locations within cross-sections where they fulfil information requirements.
- Repository monitoring systems are expected to use a lower density of sensors compared to URL experiments.

Design Considerations

- Greater confidence in repository monitoring data could be gained by using redundancy in the design, specifically in the number of sensors and types of technology for monitoring the same parameter.
- Repository monitoring system designs should consider several factors, such as data requirements, installation and operational feasibility, creation of artefacts, operational safety, cost, data management and geological features.
- There needs to be justification and documentation of design decisions for future understanding and knowledge management.
- Failure mechanisms of sensors are well understood and the learning from URL experiments can be used to mitigate the risk of sensor failures in repositories.

Monitoring System Performance

- Monitoring systems are capable of providing accurate and reliable THM data for in excess of two decades, in specific environments.

Monitoring Data Acquisition

QA / QC

- Standardised QA / QC approaches tailored to repository monitoring would be beneficial to demonstrate consistent good practices and to build further confidence in the monitoring data.

Installation

- Detailed technical drawings or 3D models of the monitoring systems should be developed to support the installation of monitoring systems in repositories.
- Installed sensor locations should be measured and stored as metadata to aid data visualisation and analysis.
- Good practice for sensor naming conventions is to include the sensor type and location in the name.
- Considerable periods may exist between monitoring system installation and the start of repository monitoring. The management of these periods should be detailed in operational plans.

Calibration and Other Testing

- Rigorous and standardised approaches to monitoring system calibration and testing should be used to build confidence in monitoring data.
- Accessible sensors should be recalibrated through the lifecycle of the repository monitoring programmes.
- *In situ* recalibration systems could be used to recalibrate inaccessible sensors.
    - However, it must be demonstrated that they can be implemented and operated without unacceptably impacting the behaviour of the multi-barrier system.
- Testing of sensors after dismantling of experiments has modified data, but has not changed the fundamental understanding of THM processes.

Further research is required to understand the best QA / QC practices for repository monitoring programmes. Research in MODATS Task 2 will aim to address this knowledge gap in understanding through the development of guidance documentation on Quality Assurance Project Plans (QAPPs) (Deliverable 17.4).

Monitoring Data Management

Monitoring Data Storage

- Effective data management plans should be developed during the design of repository monitoring systems to ensure data are traceable and readily accessible for use as required in the future.
- Raw monitoring data should be stored, alongside metadata.
- Good practice for monitoring data storage is to structure and organise databases around different aspects of the monitoring system, e.g. the process being monitored, the component the process is being monitored in.

Monitoring Data Treatment

- Data cleansing processes should be used to ensure, as much as possible, data quality, including the removal of null values and obvious errors.
- Repository monitoring would benefit from automated data cleansing processes, owing to the large amounts of data that are expected to be collected over the lifetime of the programme.

Further research is needed to develop semi-automated and automated data cleansing tools for use in repository monitoring programmes. Planned data management research in MODATS Task 2 aims to partly address this research need.

Monitoring Data Analysis and Use

Monitoring Data Visualisation and Analysis

- Repository monitoring data are expected to be visualised and analysed using graphical approaches.
- Databases should include functionality to interactively visualise monitoring parameter data in space and time. They should also include functionality to automatically generate monitoring data reports, as required.
- Metadata should be used to aid graphical data visualisation and analysis.

Use of Monitoring Data in Repository Programmes

Repository monitoring data are likely to be used to aid decision making, as well as in optimisation and engagement, but these topics have not been addressed in the URL experiment survey.

In the surveyed experiments, monitoring data have been used to understand THMCGR processes, particularly by integrating modelling and monitoring datasets. Further research is required to define the modelling approaches that will be used in repositories. It is also necessary to understand the monitoring data that will be required (i.e. information and data requirements), and the methods by which it will be used in these models. It is possible that digital representations of components of the multi-barrier system, i.e. digital twins, could be used to support safety cases in repository monitoring programmes, by checking system behaviour to ensure it is consistent with the safety case arguments. However, it is unclear how monitoring data will be integrated and used in these systems. This knowledge gap is being considered in MODATS WP through research into the integration of monitoring and modelling data and the development of digital twins.

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List of Acronyms

BCV:	Černý Vrch Bentonite
BIM:	Building Information Modelling
DAS:	Data Acquisition System
EBS:	Engineered Barrier System
FBG:	Fibre Bragg Grating
FDR:	Frequency Domain Reflectometry
FEIS:	FE Information System
QAPP:	Quality Assurance Project Plan
QA / QC:	Quality Assurance / Quality Control
SAGD:	Système d'Acquisition et de Gestion des Données
S/B:	Sand/Bentonite
SQL:	Structured Query Language
TDR:	Time Domain Reflectometry
THMCGR	Thermal, Hydraulic, Mechanical, Chemical, Gas and Radionuclide Transport (processes)
URL:	Underground Research Laboratory
WMO:	Waste Management Organisation

1. Introduction

1.1 Background and General MODATS Task 2 Objectives

Waste management organisations (WMO) will collect significant quantities of data during repository monitoring. These data will be used to address different objectives, which will be dependent on the monitoring strategy of the WMO. Objectives include checking the behaviour of the system during the construction and operational phases of the repository or to fulfil regulatory requirements. Monitoring will be used to inform decision making and build further confidence in the safety case.

Appropriate repository monitoring system designs are likely to enhance confidence in the monitoring data collected. Repository monitoring systems are expected to be spatially limited owing to the potential impacts of the monitoring systems on the passive safety of the disposal system. They will include different sensors, at different locations for redundancy and diversity reasons. Raw repository monitoring data will, therefore, be acquired in different formats and at varying spatial and temporal scales.

Furthermore, not all the acquired monitoring data will be valid owing to possible failures. For example, measurement drift is a failure signal relating to the progressive shift in the measurement value relative to the true value over time. Invalid data could fall outside the predicted range of values, in which case, it may be easy to identify. Alternatively, they could sit within the predicted range and be difficult to differentiate from valid data [1 § 7.2].

Methods need to be developed to efficiently and effectively manage monitoring data so that it is easily accessible when required. In particular, methods are needed to collate, store and treat repository monitoring data to ensure its accuracy and allow its effective and efficient use in the long term. Effective data management will allow the data to be used to fulfil the objectives of the monitoring programme. However, the processes and tools by which monitoring data will be used to inform decision making and build confidence in the safety case are not yet fully established. It is possible that digital representations of the disposal system could be built for these purposes, i.e. digital twins, but it is unclear how monitoring data will be integrated and used in these systems.

Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (MODATS), which is Work Package (WP) 17 of the EURAD programme, addresses these data acquisition, treatment, management and analysis methodological needs through research and development activities in Task 2 (Data Treatment for Increased Confidence in Repository Monitoring). The WP also involves 3 other tasks: Task 1 relates to the WP project management, Task 3 addresses the need for novel repository technologies and Task 4 deals with WP communication.

MODATS Task 2 is subdivided in 5 sub-tasks (Sub-Task 2.1 to 2.5, Table 1.1). Sub-Task 2.1, Monitoring Programme Experience and Future Needs, will document current knowledge and experience in monitoring. The most relevant knowledge and experience to date comes from monitoring activities in underground research laboratory (URL) experiments. There have been numerous URL experiments performed over the last 30 years, from which, lessons can be learned for repository monitoring. A survey of URL experiments has been undertaken in Sub-Task 2.1 to identify monitoring data acquisition, treatment, management and analysis lessons.

Sub-Task 2.1 also includes the development of best-practice guidance documentation on monitoring quality assurance project plans (QAPP; Deliverable 17.4) and technology roadmaps to identify any outstanding technology issues that need to be addressed before implementation in repository monitoring programmes. The results of the URL survey provide information to develop the QAPP and technology roadmaps.

Sub-Tasks 2.2 to 2.4 will develop new methods for monitoring data management, including data processing and data QA/QC, and data analysis (Table 1.1). These developments will use data and understanding from five reference experiments, which are AHC1605 (Bure URL), FE experiment (Mont Terri URL), POPLU (ONKALO), PRACLAY (HADES URL), Prototype Repository II (Äspö Hard Rock Laboratory), as well as the lessons learned in the URL survey in Sub-Task 2.1. The aim is that these methods will then be used to the develop different digital twins approaches and applications, which could be used to follow the evolution of the repository system via monitoring, make reliable predictions on its future development and, therefore, support decision making.

Finally, Sub-Task 2.5 continues the development of an integrated vision of how monitoring data will contribute and develop a shared understanding of the repository system for different stakeholders, including civil society.

Table 1.1 - Overview of the sub-tasks in MODATS Task 2 (Data Treatment for Increased Confidence in Repository Monitoring).

Sub-Task	Overview
2.1	Monitoring Programme Experience and Future Needs
2.2	Data Management
2.3	Development of Enhanced Understanding through Integration of Monitoring Data and Models
2.4	Development of the Digital Twin
2.5	Enhanced System Understanding, Multi-Party Dialogue

As part of Sub-Task 2.1, this report summarises the URL experiment survey responses and identifies lessons that could be applied in repository monitoring programmes.

1.2 Survey of URL Experiments

1.2.1 Objective, Scope and Content

The objective of the URL experiment survey was to learn lessons for repository monitoring. In particular, the survey aimed to identify lessons related to monitoring system design and monitoring data acquisition, management and analysis. The survey was composed of 21 questions, covering the following topics:

- The general context of the URL experiment (e.g. location, aims and basic designs).
- Monitoring parameters.
- Monitoring technologies.
- The design of the monitoring system.
- Quality assurance and quality control (QA / QC) approaches throughout the monitoring system lifecycle.
- Data management and interpretation.

The survey is provided in Appendix A.

The survey principally aimed to identify unpublished learning from individual experts based on their expertise and experience. For example, although the parameters measured in a given URL experiment may be published, the reasons why these parameters were selected and the workflows used to select the parameters may not be documented in published reports.

1.2.2 Schedule and Approach

The survey was developed by Galson Sciences Ltd, with support from Andra and Nagra, in August 2021, following preliminary discussions regarding its content with MODATS Task 2 partners at Task 2 Workshop 1 (August 18 and 19 2021). This workshop was also used to discuss the URL experiments that could be included in the survey. In particular, it was agreed that the five MODATS Task 2 Reference Experiments would be surveyed to provide a common thread through the Task 2 research activities. Other relevant experiments were identified by partners, including some experiments that were led by non-partners.

The survey was distributed to respondents in September 2021, based on their preliminary agreement. Following the survey distribution, a briefing session was held with the respondents, where the aims, scope and content of the survey were detailed.

A workshop was held on 13 January 2022 to discuss and identify the lessons learned from URL experiment monitoring that could be applied to repository monitoring [2].

1.3 Surveyed URL Experiments

Seventeen URL experiments have been surveyed, including the five MODATS Reference Experiments. The surveyed experiments have a range of different aims, which can generally be summarised as one or more of:

- Building further understanding of thermal, hydraulic, mechanical, chemical, gas and radionuclide transport (THMCGR) processes.
- Understanding the behaviour and testing the performance of multi-barrier system materials.
- Understanding the implementation procedures to install engineered barrier system (EBS) components.
- Testing the performance of monitoring technologies or implementation procedures to install monitoring technologies.

The experiments are conducted in different EBS components and in different host rocks. Some of the experiments aim to understand the behaviour and test the performance of individual EBS components. Other experiments investigate one or more coupled THMCGR processes in one component of the multi-barrier system or in full-scale repository concepts. Finally, some of the experiments test materials and technologies for implementation of individual components of the EBS. It is important to note that none of the surveyed experiments focus on a specific feature, e.g. fault, within the geological environment.

The experiments date from the early nineties to the current time. Some of these experiments are completed and have been decommissioned, while others are currently at different stages of the experimental operations.

This section introduces these 17 experiments; specifically, it outlines their aims and illustrates their designs. The MODATS Reference Experiments are introduced in Section 1.3.1), while the other surveyed experiments are introduced in the Section 1.3.2. Table 1.2 and Table 1.3 summarise the main details of the Reference Experiments and the other surveyed experiments, respectively.

The information presented in this section is mainly summarised from the responses to the context questions in the URL survey (Question C.1 and C.2, Appendix A), with the addition of relevant information from published literature.

The experiments surveyed in this research involve or have involved global WMOs, research institutes and service providers. The survey respondent for each experiment is listed in Table 1.2 and Table 1.3, but the full list of organisations involved in the experiments is outlined in Appendix B.

Table 1.2 - Summary of key information relating to the MODATS Reference Experiments, which were included in the survey. The experiment construction year is the year in which excavation of the experiment area began. The experiment start year is the year in which data were first collected, while the experiment end year corresponds to the year in which data collection ended.

Experiment	**Experiment *construction* and start year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
ALC1605 [3, 4]	*2018* 2021	Ongoing	Andra	Bure URL, France	Callovo-Oxfordian Clay	GAN Gallery	Horizontal micro tunnel (termed alveolus) with 14, two m-long instrumentation tubes and five heating elements	Alveolus: 0.75 m x 28.5 m
Full-Scale Emplacement Experiment (FE) [5, 6]	*2010* 2014	Ongoing	Nagra	Mont Terri URL, Switzerland	Opalinus Clay	FE Cavern and FE Tunnel	The FE Tunnel contains three heaters positioned on pedestals composed of bentonite blocks; the tunnel is backfilled with granulated bentonite mixture and sealed with a concrete plug	FE Tunnel: 3 m x 50 m (Experiment length = 35 m)
Posiva plug (POPLU) [7]	*2015* 2016	Some monitoring of the geosphere still ongoing	Posiva	ONKALO	Granite	Demonstration Tunnel 4, Demonstration Area	A wedge plug composed of low pH concrete and stainless steel reinforcements, with a filter layer adjacent to the concrete backwall	Concrete plug: 6 m long by 3.5 to 5.5 m wide

Experiment	**Experiment *construction* and start year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
Preliminary demonstration test for CLAY disposal of highly radioactive waste (PRACLAY) Heater Test [8, 9, 10]	*2007* 2014	Ongoing	EIG EURIDICE	HADES URL, Belgium	Boom Clay	PRACLAY Gallery	The PRACLAY Gallery is lined with steel and concrete and has heaters positioned on the gallery wall; the gallery is backfilled with sand and closed with a bentonite seal Monitoring instrumentation is placed in the concrete liner and in boreholes surrounding the gallery	PRACLAY Gallery: 2.5 m x 30 m long in heated section (40 m in total)
Prototype Repository II [11, 12, 13, 14]	2003	2011	SKB	Äspö Hard Rock Laboratory, Sweden	Granodiorite and granite	Deposition tunnel	Full-scale test of the KBS-3V disposal concept, with six vertical deposition holes below the deposition tunnel; each deposition hole included a canister with a heater and a bentonite buffer; the deposition tunnel was backfilled with crushed rock and bentonite	Deposition tunnel: 5 m x 65 m Deposition holes: 1.75 m x 8 m

1.3.1 MODATS Reference Experiments

This section outlines the aims and designs of five MODATS Reference Experiments (Table 1.2).

1.3.1.1 ALC1605, Bure URL (2021-present)

The ALC1605 demonstrator experiment in the Bure URL is designed to replicate the reference disposal concepts for high-level waste cells in Cigéo, as closely as possible [3].

This experiment aims to further understand the behaviour of the reference disposal concept EBS and the clay host rock under thermal loads. It also aims to test monitoring technologies in repository-like conditions, specifically distributed temperature sensing optical fibre systems and chemical sensors. More generally, Andra’s demonstrator experimental programme, which includes other demonstrator experiments (e.g. AHA1605), aims to test monitoring system implementation procedures and designs in repository-like conditions to demonstrate monitoring capabilities [3].

The ALC1605 experiment design consists of a 0.75 m-diameter, 28.5 m-long alveolus with 14, 2 m-long instrumentation tubes made of low-carbon steel. Five heating elements have been placed inside these tubes across a 15 m length between 10 and 25 m along the alveolus. The annular gap between the tube and the surrounding clay rock is filled with a cement-based grout material that creates corrosion-limiting environmental conditions [3].

1.3.1.1 FE Experiment, Mont Terri URL (2014-present)

The primary aim of the FE Experiment is to investigate spent fuel- and high-level waste (HLW)-repository-induced THM coupled effects on the Opalinus Clay at full scale, to validate existing coupled THM models. This experiment also aims to verify the technical feasibility of constructing a disposal tunnel using standard industrial equipment and to test and evaluate various monitoring technologies [5].

The FE Experiment is conducted in the FE Tunnel, which is 3 m in diameter and 50 m long. This tunnel is supported by shotcrete, apart from the deepest section which is supported with steel sets (interjacent sealing section; Figure 1.1) [5].

Three individual heaters with similar dimensions to those envisaged for waste canisters (i.e. 1.05 m in diameter and 4.6 m long) have been emplaced on top of bentonite block pedestals (Figure 1.1). The remaining tunnel space has been backfilled with a granulated bentonite mixture. The tunnel has been sealed with a concrete plug, which holds the bentonite buffer in place and reduces air and water fluxes [5].

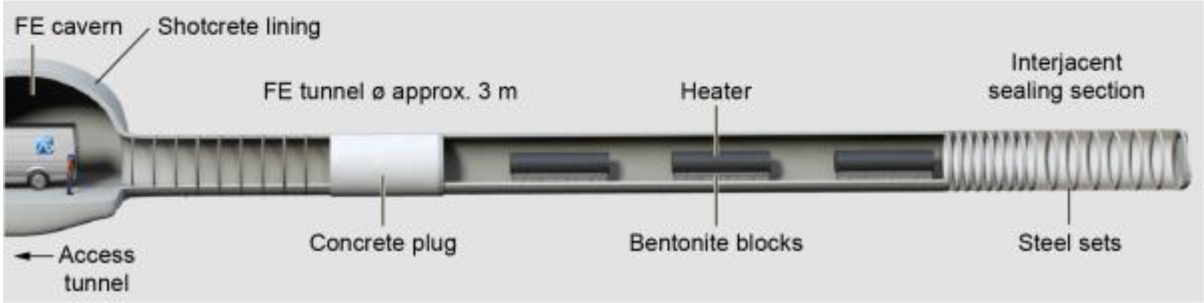

Figure 1.1 - Cross-section of the FE Experiment in the Mont Terri URL [5].

1.3.1.1 POPLU, ONKALO (2016-present)

The POPLU experiment tests the performance of a wedge-shaped deposition tunnel end plug under pressurised conditions in the ONKALO underground rock characterisation facility [7].

The design of the plug is illustrated in Figure 1.2. It is composed of two separately cast sections of low-pH concrete with steel reinforcements. In total, the plug is 6 m long with a width that tapers from 3.5 m on the tunnel wall to 5.5 m. A lead-through tube, which passes through the plug for potential air and water exchange to the area behind the plug, is included as a precautionary measure. Circumferential strips of bentonite tape and grouting tubes are placed at the plug-to-tunnel rock interface for improved watertightness. A filter layer composed of lightweight concrete blocks in positioned between the concrete plug and the tunnel [7 § 5.2 and 5.3].

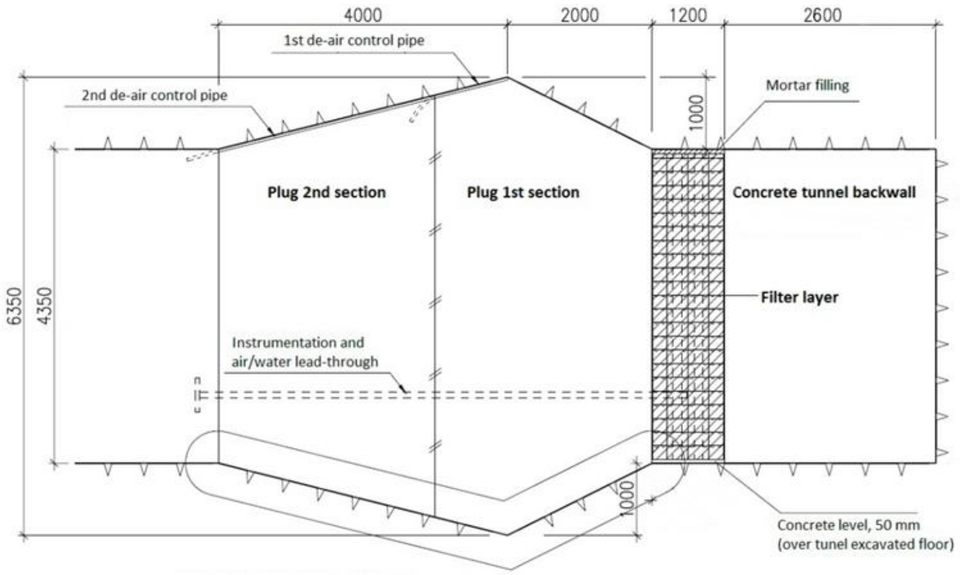

Figure 1.2 - Simplified drawing of the POPLU wedge-shaped plug [7].

1.3.1.2 PRACLAY Heater Test, HADES URL (2014-present)

The PRACLAY experiment in the HADES URL comprises three tests:

- The Gallery and Crossing Test to further examine and demonstrate the feasibility of constructing an underground repository using industrial methods, and also to examine the feasibility of constructing a crossing between galleries without the use of a starting chamber for the Tunnel Boring Machine.
- The Seal Test to examine the feasibility of creating a seal in a horizontal drift.
- The Heater Test aims to understand the impact of heat on the THM behaviour of the Boom Clay in conditions that are representative of an actual waste repository [8, 9, 10].

The survey response and this report mainly focusses on the PRACLAY Heater Test, which is conducted in a 30-m section of the PRACLAY Gallery, known informally as the heated section. This section is lined by steel and concrete with heaters positioned on the gallery walls. It is backfilled with sand and separated from the non-heated section by a seal composed of a bentonite ring supported by a cylindrical steel structure (Figure 1.3). The backfill in the heated section is water-saturated. Owing to the swelling capacity of the bentonite in the seal, the seal hydraulically isolates the saturated heated section from the non-heated section of the gallery [8, 9, 10].

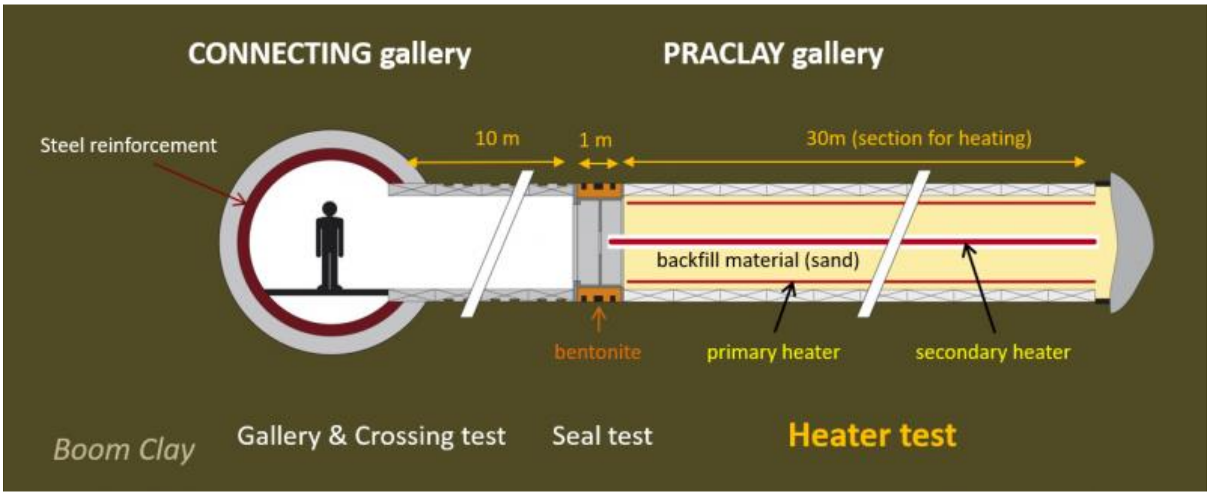

Figure 1.3 - Cross-section of the PRACLAY Heater Test in the HADES URL [8].

1.3.1.3 Prototype Repository II, Äspö Hard Rock Laboratory (2003 to 2011)

The Prototype Repository experiment aimed to simulate full-scale repository conditions for the KBS-3V disposal concept, to test the performance of the engineered barriers and to further understand THM processes and their evolution [11 and 13 § 2.2].

The Prototype Repository experiment design is a full-scale replica of the KBS-3V disposal concept [11]. It consists of a deposition tunnel (5 m in diameter and 65 m-long) with 6 vertical deposition holes positioned on the tunnel floor, each of which is 1.75 m in diameter and 8 m long (Figure 1.4). Four deposition holes are positioned in Section 1, while the other 2 are positioned in Section 2[1].

Each deposition hole contains a dummy copper canister with a heating element (Figure 1.4). The deposition holes are backfilled with bentonite and the overlying tunnel is backfilled with crushed rock and bentonite. A concrete plug that is designed to withstand full water and swelling pressures separates the experimental area from the open tunnel system, while a second concrete plug separates Sections 1 and 2 [11].

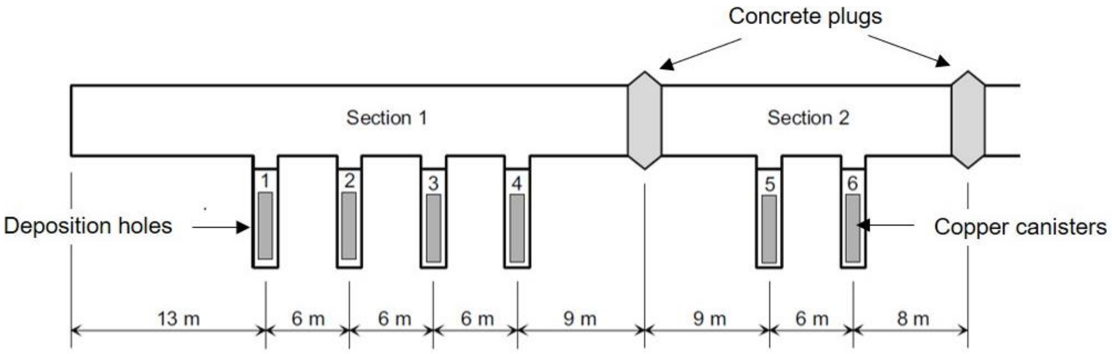

Figure 1.4 - Cross-section of the Prototype Repository in the Äspö Hard Rock Laboratory [14].

1.3.2 Additional URL Experiments

This section summarises the aims and designs of the other URL experiments included in the survey in chronological order (Table 1.3).

1.3.2.1 ATLAS, HADES URL (1993-2012)

The ATLAS experiment, the final phase of which finished in 2012, was a heater test that aimed to understand THM behaviour in the Boom Clay under thermal load [15]. Heaters were placed in a 19-m-long horizontal borehole drilled from the Test Drift in HADES. The borehole was lined with a stainless steel casing and four heater elements were positioned between 11 and 19 m along its length. Five observation boreholes that were either horizontal or inclined were drilled around the main heater borehole (Figure 1.5).

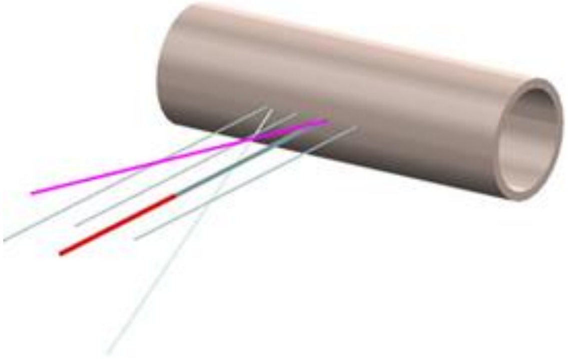

Figure 1.5 - 3D view of the ATLAS experimental setup. The main borehole with heated section is marked in red. The remaining boreholes represent the observation boreholes [15].

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[1] The survey response for the Prototype Repository relates to Section 2 only, which is referred to as Prototype Repository II.

Table 1.3 - Summary of key information relating to the other surveyed URL experiments . The experiment construction year is the year in which excavation of the experiment area began. The experiment start year is the year in which data were first collected, while the experiment end year corresponds to the year in which data collection ended. The experiments are ordered chronologically according to the experiment start year.

Experiment	**Experiment *construction* and start year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
Admissible Thermal Loading for Argillaceous Storage (ATLAS) [15, 16]	*1992* 1993	2012	EIG EURIDICE	HADES URL, Belgium	Boom Clay	Horizontal test drift	One borehole with a heater surrounded by five observation boreholes	Boreholes range from 19 to 25 m in length with diameters of less than 0.2 m
Full-scale Engineered Barriers Experiment (FEBEX); 4 phases FEBEX I, II, NP-PRO and FEBEXe [17, 18]	FEBEX-I: *1995* 1997	FEBEX-e: 2014	Amberg	Grimsel Test Site, Switzerland	Granite and granodiorite	Horizontal drift (FEBEX Gallery)	Full-scale engineered barrier system in the test area, including two carbon steel heaters surrounded by bentonite with a concrete plug	Horizontal drift: 2.3 m x 70.4 m Test area: 2.3 m x 17.0 m
CLay Instrumentation Programme for the EXtension of an underground research laboratory (CLIPEX) [19, 20, 21]	1998	2003	EIG EURIDICE	HADES URL, Belgium	Boom Clay	Test Drift and Connecting Gallery	Eight instrumented boreholes drilled from a drift (Test Drift), two boreholes drilled from a vertical shaft the (Second Shaft) and four instrumented liners in the gallery between the drift and the shaft (Connecting Gallery)	Connecting Gallery: 90 m x 4.8 m Test Drift: 67 m x 4.9-5.1 m

Experiment	**Experiment *construction* and <u>start</u> year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
Engineered Barrier Emplacement Experiment in Opalinus Clay (EB) [22, 23]	*2000* <u>2002</u>	2012	Amberg	Mont Terri URL, Switzerland	Opalinus Clay	Experimental drift	A dummy canister on a bed of concrete and bentonite blocks; the upper part of the drift was backfilled with granular bentonite material; the system was sealed with a concrete plug	Experimental drift: 2.7 to 3 m x 6 m
Large Scale Gas Injection Test (LASGIT) [24, 25]	*2003* <u>2005</u>	2020	SKB/ BGS	Äspö Hard Rock Laboratory, Sweden	Granodiorite and granite	Tunnel boring machine assembly hall	Vertical deposition hole, containing a full-scale KBS-3 canister, backfilled with bentonite and sealed by a steel lid	Deposition hole: 1.75 m x 8.5 m
Observation of liners and supporting structure (ORS) [26, 27]	<u>2011</u>	Ongoing	Andra	Bure URL, France	Callovo-Oxfordian-Clay	GCR Gallery	A concrete ring was poured *in situ* in a section of the GCR Gallery; it is built with three types of liner; multiple observation boreholes surround the gallery and concrete ring	GCR Gallery: 5.4 m x 65 m Monitoring has been conducted in a small section of the GCR Gallery in a cross-section that is 4.3 m x 3.6 m

Experiment	**Experiment *construction* and start year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
Gas-Permeable Seal Test (GAST) [28, 29]	*2011* 2012	Ongoing	Nagra	Grimsel Test Site, Switzerland	Granite and granodiorite	WT Tunnel	Eight m-long sand/bentonite seal constructed in layers, surrounded by granular bentonite and bentonite blocks at both ends of the tunnel; retaining walls and a concrete plug confine the seal in place	WT Tunnel: 3.5 m x 11.9 m
Experimental Pressure and Sealing Plug (EPSP) [30]	*2013* 2015	2016	CTU	Josef URL, Czech Republic	Volcanic and volcano-sedimentary rocks	M-SCH-Z/SP-59 niche he	Deposition tunnel plug composed of bentonite pellets sandwiched between two fibre glass concrete plugs, one of which is adjacent to a wall made of concrete blocks	Plug: 3.6 to 5.4 m x 7.2 m

Experiment	**Experiment *construction* and <u>start</u> year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
Influence of Humidity on the Cyclic and Long-Term Deformation Behaviour of the Opalinus Clay (CD-A) [31, 32]	*2018* <u>2019</u>	Ongoing	BGR and UFZ	Mont Terri URL, Switzerland	Opalinus Clay	Gallery 2018	Two twin niches (without shotcrete linings) that are adjacent to each other and oriented perpendicular to bedding One of the niches is open to natural atmospheric conditions, while the other is closed by a lock door; the climate of the closed niche is controlled by a ventilation system	Twin niches: 11 m x 2.3 m
High Temperature Effects on Bentonite Buffers (HotBENT) [33, 34]	*2020* <u>2021</u>	Ongoing	Nagra	Grimsel Test Site, Switzerland	Granite	FEBEX Gallery / HotBENT Cavern	Four heaters placed in a horizontal tunnel on bentonite block pedestals; the tunnel is backfilled with granulated bentonite mixtures and closed with a plug	HotBENT Cavern: c. 2 m x 36 m

Experiment	**Experiment *construction* and start year**	**Experiment end year**	**Organisation Providing Survey Response**	**URL and Country**	**Host Rock**	**Location in the URL**	**Experiment Components and Materials**	**Dimensions**
VSEAL [35, 36]	*2019* 2021	Ongoing	IRSN	Tournemire URL, France	Toarcian shales and marls	Gallery	A vertical borehole with a 3.5 m-long core of bentonite pellets contained between two lids and overlain by a six m-long section of concrete	Vertical borehole: 1 m x 10 m
Diffusion and Retention (DR-C) [37]	*2021* *Installation still ongoing*	n/a	UFZ	Mont Terri URL, Switzerland	Opalinus Clay	Gallery 2018	Two vertical experimental boreholes: a reference borehole at ambient temperature and other at 80 °C Three vertical observation boreholes	Experimental boreholes: 5 m x 0.08 m Observation boreholes: 11 m x 0.08 m

1.3.2.2 FEBEX, Grimsel Test Site (1997-2014)

The FEBEX experiment, which finished in 2014, was based on the ENRESA disposal concept in crystalline rock, where waste canisters were positioned in a horizontal drift and surrounded by a bentonite buffer. This experiment aimed to demonstrate the feasibility of constructing this disposal concept and to further understand the coupled THM processes active in the surrounding near-field rock [17].

It consisted of a horizontal drift, known as the FEBEX Gallery, which was 2.3 m in diameter and 70.4 m long. Two carbon steel heaters, with similar dimensions and weight to the disposal concept waste canisters, were placed within the test area of the FEBEX Gallery and were backfilled with bentonite blocks. A plain key-type concrete plug was used to confine the bentonite blocks to the test area (Figure 1.6 [17]).

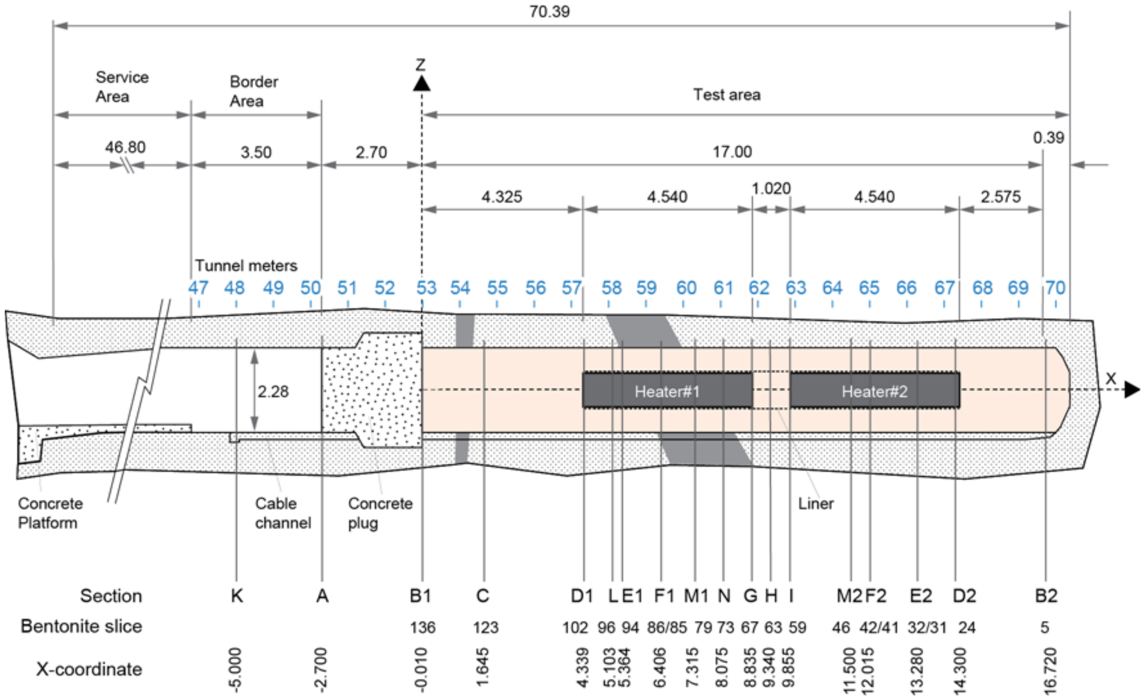


Figure 1.6 - Cross-section of the FEBEX Experiment at the Grimsel Test Site [17].

The FEBEX experiment was dismantled in two stages. In 2002, after 5 years of continuous operation at 100 °C, heater 1 was removed, along with the surrounding bentonite and the concrete plug. A second concrete plug was installed and heater 2 continued to operate for a total of 18 years. This section of the experiment was then dismantled between 2014 and 2017.

1.3.2.3 CLIPEX, HADES URL (1998-2003)

The CLIPEX experiment used the construction of the Connecting Gallery in the HADES URL to understand the short-term HM response of the Boom Clay to excavation [19]. To do this, eight instrumentation boreholes were drilled from the existing Test Drift and 2 were drilled from the second shaft. Excavation of the Connecting Gallery was undertaken from the second shaft in 2002. A tunnelling shield was used to protect the instrumented boreholes during excavation (Figure 1.7).

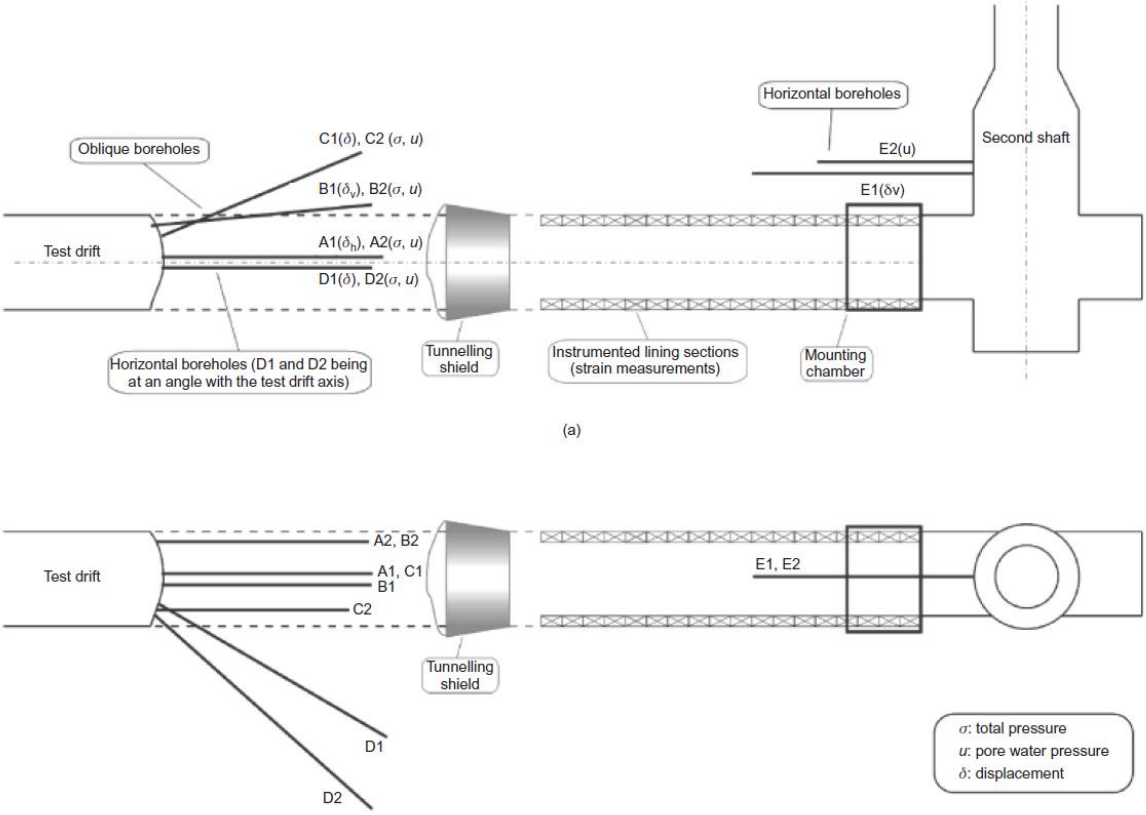


Figure 1.7 - Cross-section and plan view of the Test Drift and Connecting Gallery in the HADES URL, including the instrumentation boreholes (A1, A2, B1, B2, C1, C2, D1, D2, E1 and E2) [19].

1.3.2.4 EB, Mont Terri URL (2002-2012)

The EB experiment in the Mont Terri URL aimed to demonstrate the construction, emplacement and backfilling techniques for a new disposal concept for HLW and spent fuel in the Opalinus Clay, with waste canisters positioned on top of concrete and bentonite blocks. It also aimed to understand the HM evolution of the engineered barrier system and the Opalinus Clay in this disposal concept, specifically in the excavation disturbed zone surrounding the experiment drift, and to use this understanding to build representative models [22].

The experiment was conducted in a horizontal drift that was between 2.7 to 3 m in diameter and 6 m long [22]. A steel dummy canister was emplaced on a concrete bed and bentonite blocks in the middle of the horizontal drift. Granular bentonite material was used to backfill the drift, which was sealed with a concrete plug (Figure 1.8). A hydration system was used to accelerate the hydration of the bentonite materials in the engineered barrier system. Following 11 years of operation, the EB experiment was dismantled in 2012.

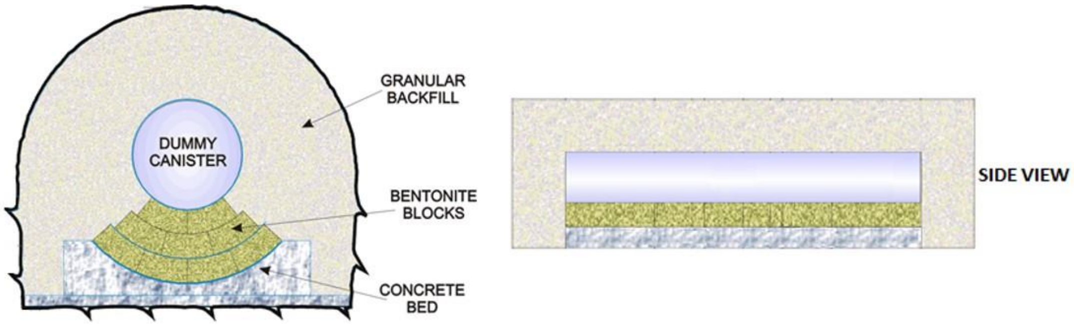


Figure 1.8 - Illustration of the EB experiment design in the Mont Terri URL [22].

1.3.2.5 LASGIT, Äspö Hard Rock Laboratory (2005-2020)

The LASGIT experiment involved a series of gas injection tests in a full-scale KBS-3V deposition hole. This experiment aimed better to understand gas migration behaviour in bentonite and test/validate gas migration modelling approaches. It also aimed to understand the impact of gas migration on performance of the buffer in this disposal concept. The gas injection tests ended in 2020 and the experiment was decommissioned in 2021 [24, 25].

The experiment was conducted in a 1.75-m-diameter and 8.5-m-long vertical deposition hole in the Äspö Hard Rock Laboratory (Figure 1.9). A full-scale KBS-3V canister was emplaced in the deposition hole, along with filters and filter mats for gas injection and hydration, respectively. The deposition hole was backfilled with pre-compacted bentonite blocks and bentonite pellets and sealed with a conical concrete plug and a steel lid. A gas laboratory was housed in a fully insulated pre-fabricated shipping container in the Tunnel Boring Machine assembly hall, overlying the deposition hole. This laboratory housed the experimental circuits, as well as data acquisition and telemetry systems [24, 25].

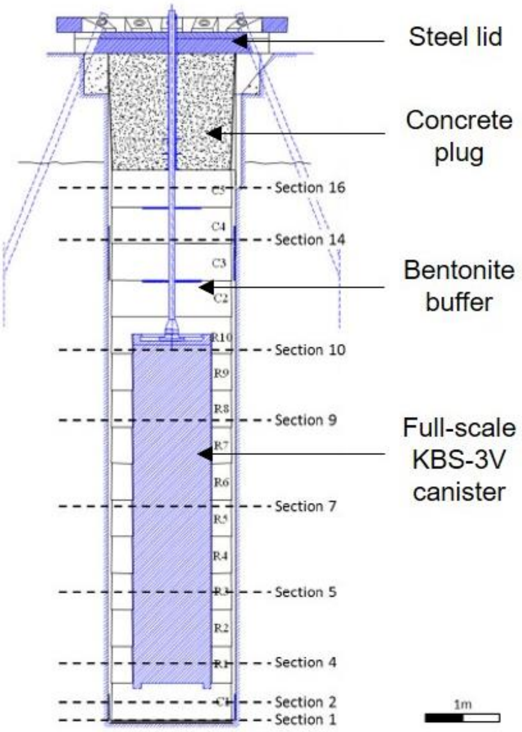


Figure 1.9 - Cross-section of the LASGIT experiment design in the Äspö Hard Rock Laboratory. Monitoring sections are highlighted with dashed black lines [25].

1.3.2.6 ORS, Bure URL (2011-present)

Andra plans to dispose of intermediate-level waste (ILW) in the Cigéo repository in disposal cells that could be 8 to 12 m in diameter and hundreds of metres long. The GCR Gallery, which has a diameter of 5.4 m, has been excavated in the Andra URL [26]. A section of this gallery has been lined with shotcrete and 3 layers of concrete to represent part of an ILW disposal cell. The ORS experiment investigates the medium to long-term THM evolution of the excavation damaged zone (EDZ) and the concrete-lined section. It also tests the implementation and performance of monitoring technologies [26].

1.3.2.7 GAST, Grimsel Test Site (2012-present)

The GAST experiment at the Grimsel Test Site focusses on the sealing behaviour of sand/bentonite, which could be used as gas permeable sealing or backfilling material in ILW repositories, where gas generation is expected. In particular, the GAST experiment investigates sand/bentonite behaviour during saturation and its gas transport properties once saturated. It also aims to demonstrate the effective functioning of gas-permeable seals at a realistic scale and within realistic conditions, and to validate and refine the conceptual models of resaturation and gas transport processes. Gas flow tests are expected to begin in 2022 following saturation of the backfill. These tests are anticipated to last for several years, with experiment dismantling planned for 2024 [28].

The experiment consists of an 8 m-long 80/20 sand/bentonite (S/B) seal section compacted into 10 cm-thick horizontal layers (Figure 1.10). Granular bentonite is positioned above and below the seal, while sand/gravel filters are located adjacent to the seal for the purposes of water and gas injection. Bentonite blocks have been installed next to the filters. A concrete wall has been installed at the end of the tunnel, while on the gallery side, a concrete plug and retaining wall are used to confine the experiment materials (Figure 1.10).

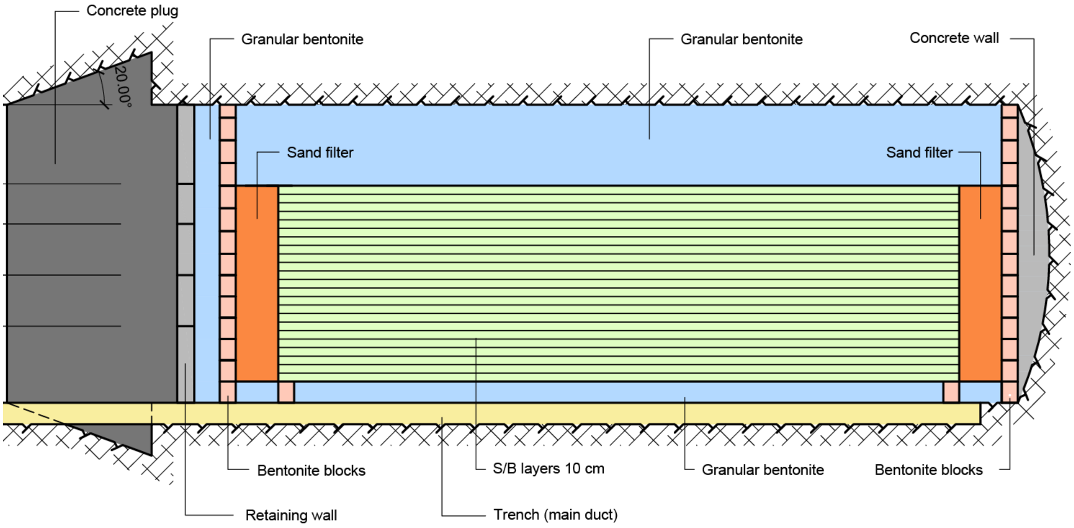


Figure 1.10 - Cross-section of the GAST experiment in the Grimsel Test Site [28]; S/B denotes sand/bentonite.

1.3.2.8 EPSP, Josef URL (2015-2016)

The EPSP experiment in the Josef URL was the first experiment carried out by SÚRAO to investigate plugs and seals. The EPSP does not relate to a specific repository plug or seal, however, it has been constructed at a similar scale to deposition tunnels plugs. The experiment aimed to investigate the design basis and reference designs and to test the materials and technology used for the implementation of this plug. It did not aim to test the performance of the plug [30, 38].

The design of the plug is illustrated in Figure 1.11. It is 7.2 m in length with a diameter ranging from 3.6 to 5.45 m. It contains two 1.85 m-thick plug sections (inner and outer), which are composed of sprayed glass-fibre concrete with a relatively low pH.

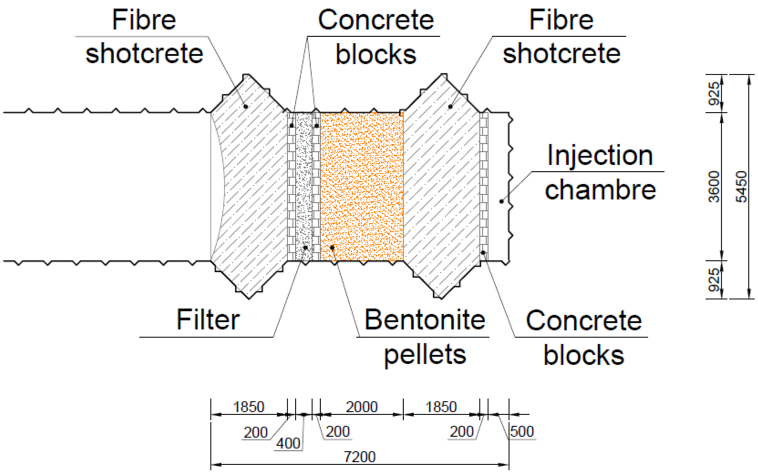


Figure 1.11 - Cross-section of the EPSP experiment at the Josef URL [30].

These plugs are adjacent to a 2-m-thick seal composed of bentonite pellets. Walls composed of concrete blocks have been used to facilitate the construction of the structure, while a pressure chamber (or injection chamber) has been installed to pressurise the inner concrete plug. This chamber contains an inlet valve and a drain valve to fill the chamber with gas, water or bentonite slurry. Finally, there is a filter layer between the bentonite seal and the outer concrete plug, which is designed to collect water that that is not absorbed by the seal [30].

Five phases of water or bentonite slurry injection and pressurisation have been conducted, with tests ending 2016 [30].

1.3.2.9 CD-A, Mont Terri URL (2019-present)

The CD-A experiment investigates coupled HM processes in the Opalinus Clay using two niches constructed in Gallery 18 of the Mont Terri URL in 2018 and 2019. These niches are oriented parallel to each another and perpendicular to bedding and are 2.3 m in diameter and 11 m in length (Figure 1.12). One of the niches is closed to atmospheric conditions using a door at its entrance. High humidity is maintained in this closed niche to limit the desaturation of the Opalinus Clay. The other niche remains open and under “natural conditions”, i.e., the conditions are similar to the atmospheric conditions in the other parts of the URL. The Opalinus Clay in this niche will desaturate over time [31, 32].

The monitoring campaign of the CD-A experiment is intended to last for at least 10 years. Monitoring data from the open niche will be used to provide an understanding of the coupled HM effects resulting from excavation and desaturation, while data from the closed niche will provide an understanding of these effects resulting from excavation only [31, 32].

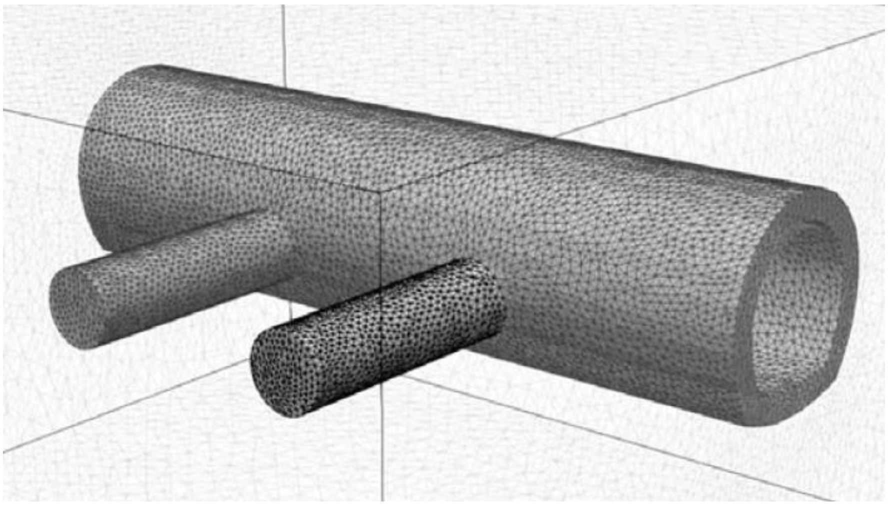


Figure 1.12 - Finite element mesh of the CD-A niches in Gallery 18, in the Mont Terri URL [31].

1.3.2.10 HotBENT, Grimsel Test Site (2021-present)

The HotBENT experiment in the Grimsel Test Site aims to improve the understanding of the effect of high temperatures on bentonite in full-scale *in situ* repository conditions [33]. The experiment is conducted in a 36-m-long section of the HotBENT Cavern (formerly the FEBEX Gallery), which is approximately 2 m in diameter. Four heaters have been emplaced on bentonite pedestals in centre of the cavern in separate two sectors (Figure 1.13). In Sector 1, the heaters are backfilled with Wyoming-type bentonite. An intermediate concrete plug (Plug 1; Figure 1.13) separates Sector 1 and 2. Sector 2 is backfilled with Wyoming-type bentonite and Černý Vrch bentonite (BCV) and is capped by a final concrete plug (Plug 2; Figure 1.13).

In Sector 1, the heaters are set to different temperature; 200 °C and 175 °C. This sector is planned to be dismantled after approximately 20 years because modelling suggests full saturation of the bentonite will have occurred at the ambient conditions in this period. On the other hand, Sector 2, in which the heaters are both set to 175 °C, will be dismantled after 5 years. The intermediate plug will allow Sector 2 to be dismantled without disturbing Sector 1 [33, 34].

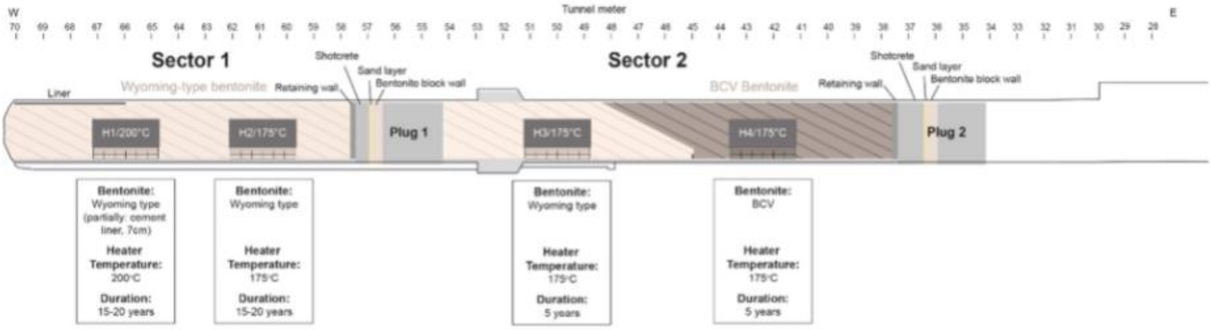


Figure 1.13 - Cross-section of the HotBENT experiment at the Grimsel Test Site [34].

1.3.2.11 VSEAL, Tournemire URL, (2021-present)

The VSEAL experiment investigates shaft sealing systems. It aims to further understand the impact of gas during saturation of the bentonite seal and gas migration processes through saturated bentonite.

The experiment consists of a vertical borehole, 1 m in diameter and 10 m long, with a 3.5-m-thick core of MX80 bentonite. Lids hold the bottom and top of the bentonite in place, along with a 6.5 m-thick section of concrete at the top of the borehole (Figure 1.14). Water is injected from the top surface using injection lines connected to the top lid, causing the saturation of the bentonite core from the top downwards. After reaching full saturation, which will take approximately 15 years, gas will be injected from the bottom surface to observe the gas-inducted perturbation induced by gas [35].

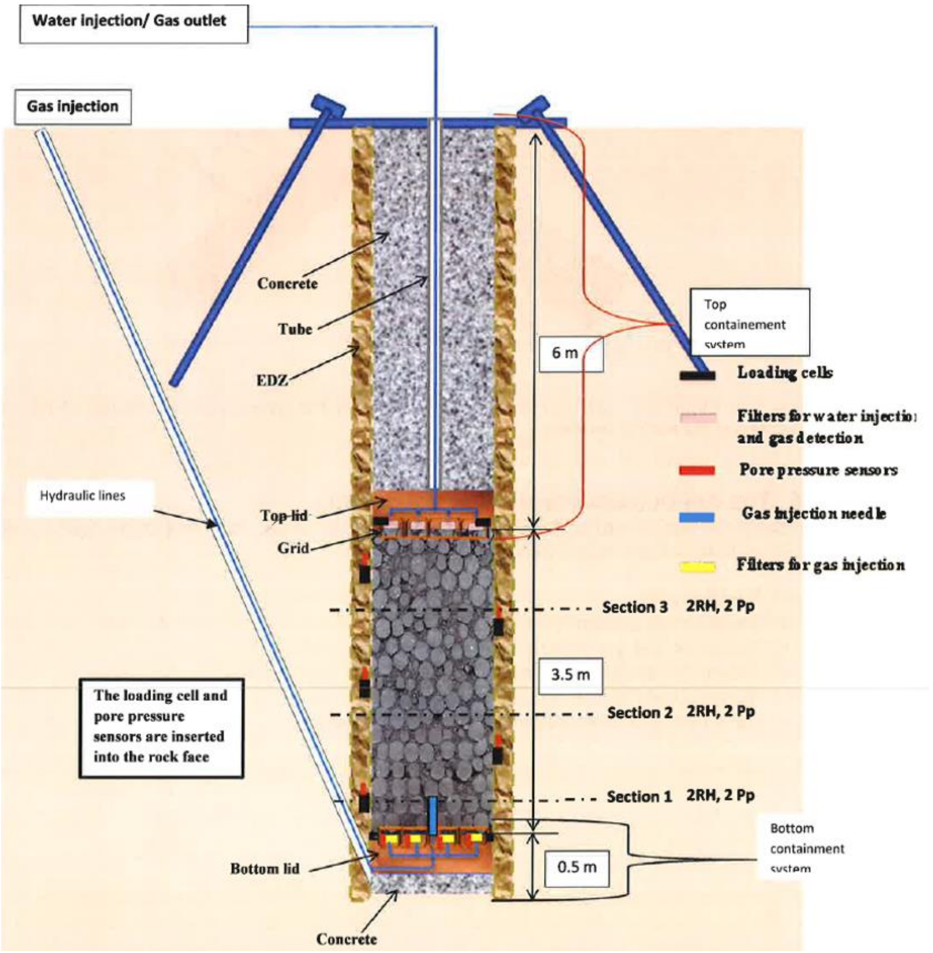


Figure 1.14 - Cross-section of the VSEAL experiment in the Tournemire URL [35].

1.3.2.12 DR-C, Mont Terri URL (Installation ongoing)

The DR-C experiment investigates the effect of temperature on radionuclide migration in the Opalinus Clay, in the Mont Terri URL [37]. It is normally assumed that radionuclides could migrate away from emplaced waste canisters after the thermal phase because canisters are not expected to fail during the thermal phase. Therefore, “base-case” safety assessment scenarios do not typically consider elevated temperatures in the migration of radionuclides. This experiment considers the highly unlikely alternative, “worse-case” scenario, where radionuclides migrate away from the emplaced waste canister during the thermal phase.

Two experiment boreholes, which are 0.08 m in diameter and 5 m long, have been drilled in Gallery 18 with a horizontal separation of c. >10 m. They have been equipped with packer systems and connected to tracer injection and sampling modules (Figure 1.15). The first borehole, termed the reference borehole, is maintained at ambient temperature, whilst the second borehole is heated to 80 °C. Three observation boreholes, 0.08 m in diameter and 11 m long, were drilled surrounding the 80 °C experiment boreholes, with monitoring systems installed in August 2021 [37]. The experiment will begin with the onset of heating in June 2022. Radioactive tracers are expected to be injected in June 2023, with monitoring continuing until June 2024.

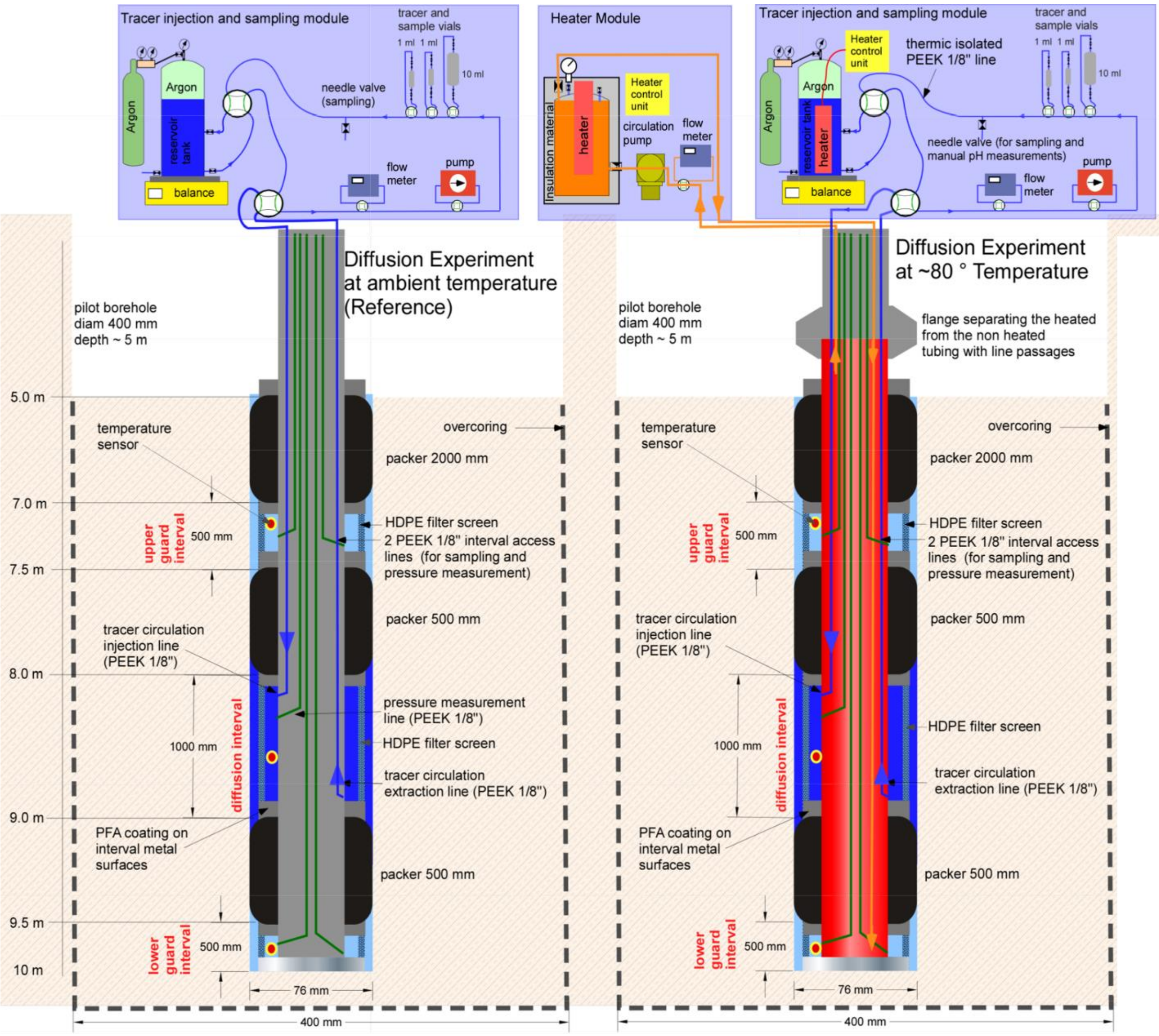


Figure 1.15 - Cross-section of the boreholes in DR-C experiment in the Mont Terri URL, which are separated by c. >10 m horizontal distance in Gallery 18 [37].

1.4 Expected Differences Between Monitoring in URL Experiments and Repositories

In order to develop lessons for repository monitoring from URL experiments, it is necessary first to understand the context of the experiments and to understand how repository monitoring and URL experiment monitoring may differ.

First, the aims of monitoring in URL experiments, as summarised above (Section 1.3), are expected to be different to the aims of repository monitoring. Monitoring of the multi-barrier system during repository operations could be used to help build further confidence in post-closure safety and provide information to support periodic updates to the safety case. Depending on the monitoring strategy / national context, repository monitoring may aim to check the behaviour of the disposal system following its installation, and/or fulfil regulatory requirements.

The designs of the monitoring systems in repositories are expected to be different compared to URL experiments owing to the differences in the monitoring aims. In repositories, fewer parameters may be monitored with less sensors to fulfil the aims, but also to limit the disturbances to the disposal system.

The technologies used in repositories are likely to have to meet different requirements, compared to URL experiments. They will need to have a minimal impact on passive safety of the disposal system; in some instances, wireless data transmission technologies, optical fibre systems and / or remote geophysical techniques may be preferential in repositories, rather than wired sensors. The monitoring technologies may need to operate for several years in URL experiments, while they are likely to have to operate for much longer periods in the repository, possibly with no access for maintenance, such as recalibration. Finally, artificial systems are sometimes used in URL experiments to accelerate slow natural processes; for example, hydration systems are typically installed to accelerate hydration in *in situ* conditions where the process would naturally be slow (e.g. GAST; Section 1.3.2.7). Repository monitoring systems may, therefore, require different technologies that are capable of measuring at greater parameter sensitivities, compared to a wider range of parameter values in URL experiments.

1.5 Report Structure

This report summarises the URL experiment survey responses and identifies lessons that could be applied in repository monitoring programmes. The lessons focus on the following aspects of monitoring:

- Monitoring system designs.
    - Monitoring parameters.
    - Monitoring technologies.
    - Monitoring system layouts.
    - Monitoring system performance.
- Monitoring data acquisition.
    - Monitoring system QA / QC.
    - Monitoring system installation.
- Monitoring data management.
    - Monitoring data storage.
    - Monitoring data treatment.
- Monitoring data analysis and use.
    - Monitoring data visualisation and analysis.
    - Monitoring data use.

Following this introduction, the report is divided into three sections. Section 2 summarises the responses to the questions in the URL survey. Using these summaries, Section 3 discusses the monitoring system design and monitoring data acquisition, data management and data analysis lessons learned for repository monitoring programmes. Section 4 provides a conclusion of lessons learned and highlights gaps in our existing knowledge.

The survey responses are not included in this report in their original raw format, because information is not easily accessible to the reader and some responses contain confidential data. Section 2 concisely summarises the information in an organised and accessible format.

2. Summary of the URL Survey Responses

This section of the report summarises the URL experiments survey responses. The responses are organised into the following sections:

- Monitoring system design.
- Monitoring data acquisition.
- Monitoring data management.
- Monitoring data analysis and use.

The correspondence between the results presented in these sections and the URL survey questions (Appendix A) is outlined in Table 2.1.

Table 2.1 - Summary of the correspondence between the URL survey questions, presented in Appendix A, and the results presented in this section.

Section	URL Survey Question
2.1 Monitoring System Design	
2.1.1 Monitoring Parameters	Question 1.1: What processes and parameters are/were monitored in the experiment? Question 1.2: Please describe the processes by which the parameters were selected and incorporated into the monitoring programme of the experiment.
2.1.2 Monitoring Technologies	Question 2.1: What monitoring technologies and sensors are/were used in the experiment? Question 2.2: What processes were used to select monitoring technologies and sensors?
2.1.3 Monitoring System Layouts	Question 3.1: How many monitoring sensors/probes are/were used to monitor the selected parameters in the experiment? Question 3.2: What are/were the geometrical arrangements of the monitoring sensors/probes in the experiment? Question 3.4: What was the process used to select the number and location of the monitoring sensors/probes? Question 3.5: How did the design of monitoring sensor system account for the practicalities of its installation?
2.1.4 Monitoring System Performance	Question 4.4: What was learnt about the monitoring method performance during operations and decommissioning?
2.2 Monitoring Data Acquisition	
2.2.1 Monitoring System QA / QC	Question 4.1: Please provide the definition, scope and objective of 1) quality assurance and 2) quality control with respect to the installation, operation and decommissioning of the monitoring sensor system.
2.2.2 Monitoring System Installation	Question 3.3: How were the monitoring sensors/probes installed?

Section	URL Survey Question
	Question 4.2: What are/were the quality assurance and quality control arrangements for the experiment? Question 4.3: Please describe any problems that were encountered during the installation of monitoring sensors/probes.
2.3 Monitoring Data Management	
2.3.1 Monitoring Data Storage	Question 5.1: Please describe the data acquisition system. Question 5.2: Please describe the data management system, including the database.
2.3.2 Monitoring Data Treatment	Question 5.3: What processes are/were used to treat the data?
2.4 Monitoring Data Analysis and Use	
2.4.1 Monitoring Data Visualisation and Analysis	Question 5.2: Please describe the data management system, including the database.
2.4.2 Monitoring Data Use	Question 5.4: How are/were the monitoring data compared to numerical models? Question 5.5: How are/were monitoring data used to update numerical models of the processes investigated in the experiment?

2.1 Monitoring System Designs

The designs of monitoring systems include the parameters that are monitored and the technologies that are used to monitor these parameters, specifically the technology types and their layouts. Effective monitoring system designs could provide confidence in the acquired data and ensure their effectual use in repository programmes. This section summarises the monitoring system designs in the surveyed experiments. It also summarises information about the performance of monitoring systems in URL experiments, which could be used to support monitoring system designs.

2.1.1 Monitoring Parameters

The main parameters monitored in the surveyed experiments are outlined in Table 2.2. Temperature, pore pressure, total pressure and displacement are monitored in the majority of the surveyed experiments (i.e. in more than 75 % of the experiments). Even where isothermal conditions are anticipated (e.g. GAST [28]), temperature monitoring is conducted for the purposes of compensating other monitoring parameter values and to establish reference conditions. Relative humidity, water saturation, water content, suction and strain are also parameters that are often monitored (i.e. in more than 60 % of the experiments).

In general, monitoring parameters were selected using an informal approach in URL experiments, e.g. expert judgement panels [30], with documentation of the decisions in internal memos or test plans [e.g. 5, 8].

The aims of the experiment commonly dictate the selection of monitoring parameters. For example, in the FE Experiment, key monitoring parameters, such as temperature, pore pressure, water saturation and deformation (total pressure, displacement and strain) were identified to fulfil the aim of calibrating and validating THM models [5].

In the DR-C experiment, the processes and parameters that impact radionuclide migration were identified to aid the selection of relevant monitoring parameters. In particular, temperature affects the diffusion (effective diffusion coefficient) and the sorption of radionuclides in clay, while porewater pressure and strain could influence porosity, which impacts radionuclide migration. As a result, temperature, porewater pressure and strain were selected as the key monitoring parameters [37].

Andra have used a structured approach to select monitoring parameters in the AHC1605 and ORS experiments [3, 26]. This approach is based on a workflow adapted from the Modern2020 Screening Methodology [39, Figure 2.7]. It integrates knowledge of safety functions and their components, as well as THMCGR process understanding from phenomenological analysis of repository situations (PARS) to undertake qualitative safety analyses (Figure 2.1). These analyses have been used to understand the impact of these processes on safety functions and, therefore, to identify “parameters of influence” [40 § Appendix C, 5.2].

Finally, in some experiments, parameter selection was dictated by the availability of technologies with proven capabilities to accurately monitor a given parameter, or by the aim of testing the capabilities of prototype technologies [5].

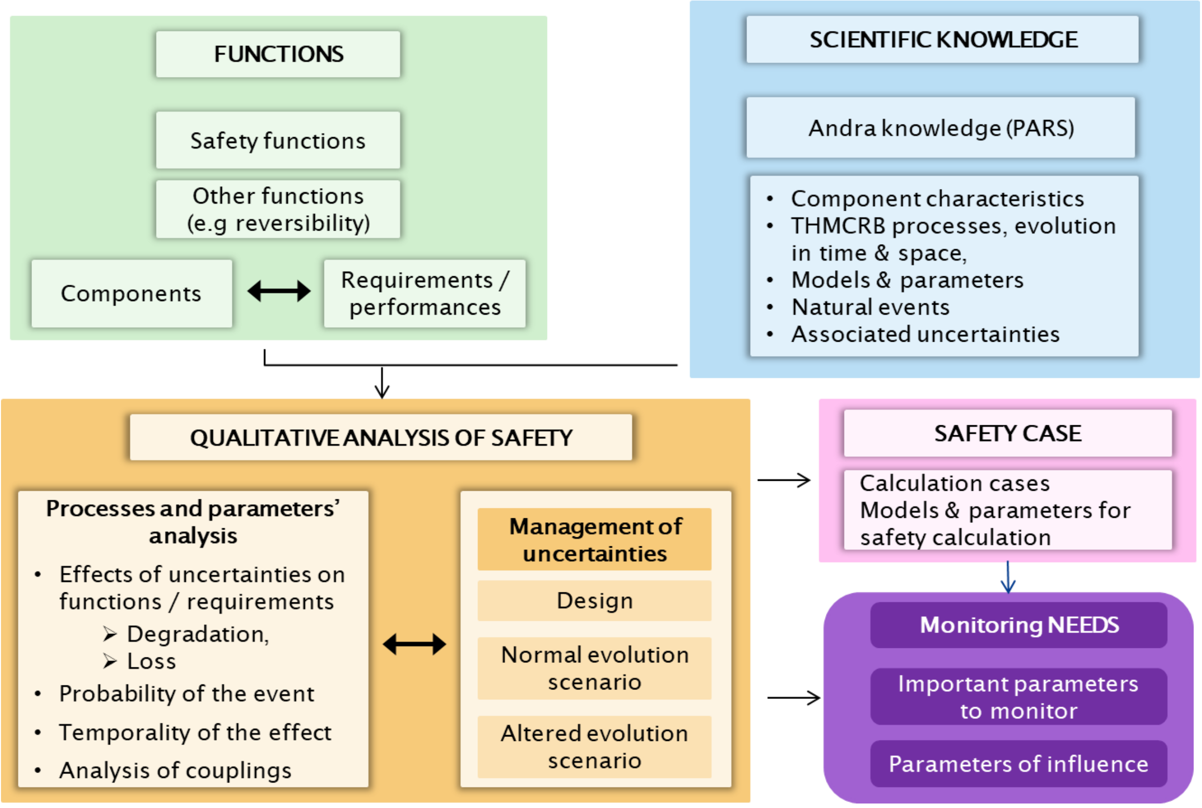


Figure 2.1 - Schematic summary of the approach used by Andra to select monitoring parameters in the ALC1605 experiments [3].

Table 2.2 - Summary of the main monitoring parameters in the surveyed URL experiments. T, H, M, C, G and R denote thermal, hydraulic, mechanical, chemical, gas and radionuclide transport processes respectively. The MODATS Reference Experiments are shaded in light blue.

Experiments **Parameters**	**ALC1605**	**FE Experiment**	**POPLU**	**PRACLAY**	**Prototype Repository II**	**ATLAS**	**FEBEX**	**CLIPEX**	**EB**	**LASGIT**	**ORS**	**GAST**	**EPSP**	**CD-A**	**HotBENT**	**VSEAL**	**DR-C**
Monitored processes	**THMCG**	**THMG**	**THM**	**THMC**	**THM**	**THM**	**THMG**	**HM**	**HM**	**HMG**	**THM**	**HMG**	**THM**	**THM**	**THMC**	**HMG**	**THMCR**
Temperature	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓
Thermal conductivity		✓													✓		
Pore pressure	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Relative humidity	✓	✓	✓	✓	✓		✓		✓			✓	✓	✓	✓	✓	
Water saturation / content / suction		✓			✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	
Volumetric flow rate			✓							✓		✓	✓				
Total pressure	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Displacement	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		
Strain	✓	✓	✓	✓	✓			✓		✓	✓		✓	✓			✓

Experiments **Parameters**	**ALC1605**	**FE Experiment**	**POPLU**	**PRACLAY**	**Prototype Repository II**	**ATLAS**	**FEBEX**	**CLIPEX**	**EB**	**LASGIT**	**ORS**	**GAST**	**EPSP**	**CD-A**	**HotBENT**	**VSEAL**	**DR-C**
Monitored processes	**THMCG**	**THMG**	**THM**	**THMC**	**THM**	**THM**	**THMG**	**HM**	**HM**	**HMG**	**THM**	**HMG**	**THM**	**THM**	**THMC**	**HMG**	**THMCR**
Porewater pH	✓																✓
Corrosion rate	✓	✓		✓													
Gas pressure		✓					✓			✓		✓					
Gas concentrations (e.g. oxygen and hydrogen)	✓	✓													✓		
Radioactivity																	✓
Heater parameters (e.g. heating power)	✓			✓		✓	✓										

2.1.2 Monitoring Technologies

Table 2.3 summarises the technologies that are used in the experiments to monitor temperature, pore pressure, relative humidity, water saturation, water content, suction, total pressure, displacement and strain. A summary of the type and number of monitoring technologies used to measure temperature, pore pressure and total pressure in each experiment is outlined in Table 2.4.

A wide range of technologies are used to monitor temperature, whereas pore pressure and total pressure are almost exclusively monitored using piezometers and pressure cells, with different types of pressure transducers. Relative humidity is monitored using hygrometers, while psychrometers, reflectometry techniques and nuclear magnetic resonance are used to monitor water suction and water content. Displacement is monitored using a wide range of technologies, in part because different technologies are required to measure the displacement in different components of the multi-barrier system in experiments, and strain is measured using strain gauges or optical fibre systems (Table 2.3 and Table 2.4).

Experimental teams make the decisions regarding the selection of monitoring technologies, drawing on contractor knowledge and experience. The decisions are based on the definition of performance requirements [e.g. 8]), i.e. requirements that the technology must be capable of fulfilling to be implemented in the experiment, and the identification of technologies that fulfil the requirements. A range of performance requirements have been defined in the surveyed experiments, including:

- Parameter measurement range, resolution and accuracy.
    - The use of calibrated sensors to minimise inaccuracies.
- Operating conditions (e.g. maximum operating temperature and pressure [8]).
- Operational longevity.
- Durability.
    - In the LASGIT experiment, sensor durability was stated as one of the main requirements for the selected monitoring technology [24]; it is worth noting that this experiment was planned to operate for 5 years, however, it continued for 17 years with a 5 % sensor failure rate.
- Sensor and cable materials.
    - Sensors composed of materials that compatible with the multi-barrier system components they are intended to be emplaced in (e.g. corrosion-resistant materials).
- Sensor dimensions.
    - Small dimensions to minimise the creation of artefacts in the experiment resulting from the emplacement of the sensor [e.g. 8].
- Cable specifications.
    - Durable and resistant to the ingress of water and gases.
- Wireless capabilities.
    - To minimise the creation of artefacts and to avoid issues relating to durability of cables and their resistance to water / gas ingress.
- Supplier capabilities to adapt the sensor designs as required.
- Compatibility with data acquisition systems (DASs).
- Delivery time.
- Ease and speed of sensor installation.
    - In the Boom Clay in the HADES URL, boreholes are known to quickly converge after drilling, therefore, a requirement of the selected sensors is that they must be capable of quick installation [19].
- Cost.

Scoping calculations are commonly used to obtain estimates and a basic understanding of the evolution of relevant parameters. These estimates are used, in turn, to inform the definition of monitoring performance requirements, e.g. parameter ranges, resolutions and accuracies, maximum operating temperatures and pressures, and operational longevities.

In the VSEAL experiment, scoping calculations were performed to provide an understanding of the hydro-mechanical evolution of the seal during the saturation phase. These calculations provided an estimate of the expected ranges of parameter values, and, therefore, the required measurement ranges of the monitoring technologies [35]. Scoping calculations were used in the GAST experiment to quantify the period required to saturate the sand/bentonite seal in different experimental set-ups. This information was used to define the operational lifetime requirement of the monitoring technologies [28].

Monitoring technologies are also selected based on proven performance from previous experiments. For example, twin-tube piezometers were used in the CLIPEX experiment in the HADES URL, because they had been used in previous experiments in the HADES URL (e.g. ATLAS) and had performed satisfactorily [19].

Several experiments have selected two or more different types of technology to monitor the same parameter [e.g. 3, 5, 11, 17, 35]. This approach is used for two reasons; to provide measurement redundancy and to ensure the complete range of parameters values can be monitored.

Redundancy can be used to mitigate measurements errors, such as drift. Sensors operating on different measurement principles will be unlikely to suffer the same drift. Therefore, if sensor values deviate significantly, measurement errors could be identified and the confidence in the monitoring data could be improved. In the FEBEX experiment, three different types of technology were implemented to monitor hydraulic properties in the rock and the buffer (Figure 1.6); specifically:

- Capacitive hygrometers: relative humidity ranging from 0 to 100 %, with an accuracy in the range 0 to 90 % of 1 to 2 %.
- Psychrometers: water suction ranging from 95 % relative humidity (7 MPa suction) to 99.95 % (50 kPa suction), with an accuracy of 6 %.
- TDR: water content ranging from 0.2 to 5 % volumetric content, with an accuracy of 1 to 2 %.

This approach ensured that the complete range of water saturations in different phases could be accurately monitored. It also provided some measurement redundancy [17].

In the ATLAS experiment, total pressure sensors were selected based on their compatibility with the instrumentation casing and also because they provided measurement redundancy. However, these aspects of the sensor design were only possible because the technology supplier customised existing sensors.

Table 2.3 - Summary of the main types of THM monitoring technologies used in the surveyed URL experiments.

Parameters	Monitoring Technologies
Temperature	Resistance temperature detectors (e.g. Pt-100 or Pt-1000) Thermocouples Thermistors Digital and analogue thermometers Optical fibre Bragg gratings (FBG) Optical time distributed temperature sensing
Pore pressure	Piezometers (vibrating wire, piezoresistive, twin-tube and optical fibre)
Relative humidity	Capacitive hygrometers Monolithic hygrometers
Water content / suction	Psychrometers Time domain reflectometry (TDR) Frequency domain reflectometry (FDR) Nuclear magnetic resonance
Total pressure	Pressure cells (vibrating wire, piezoresistive and piezoelectric) Stress meters (vibrating wire)

Parameters	Monitoring Technologies
	Optical fibres
Displacement	Extensometers (vibrating wire) Deformation meters (vibrating wire) Potentiometers Crack meters (linear variable displacement transformer) Inclinometers Deflectometers LiDAR Optical fibres
Strain	Vibrating wire strain gauges Optical fibre distributed strain sensing Optical fibre Bragg gratings (FBG)

Table 2.4 - Summary of the monitoring technology types used to measure temperature, pore pressure and total pressure in the surveyed URL experiments. The MODATS Reference Experiments are shaded in light blue.

Parameters **Experiments**	**Temperature**		**Pore Pressure**		**Total Pressure**	
	Type	**Number or length**	**Type**	**Number**	**Type**	**Number**
ALC1605	Resistance temperature detectors	5	Vibrating wire piezometers	8	Optical fibres	*Not specified*
	Optical fibre distributed temperature sensing	394 m	Optical fibres	*Not specified*		
FE Experiment [44]	Resistance temperature detectors	87	Piezoresistive piezometers	114	Piezoresistive pressure cells	19
	Thermocouples	497				
	FBGs	72			Vibrating wire pressure cells	18
	Optical fibre distributed temperature sensing	660 m				
POPLU [7]	Thermocouples	8	Vibrating wire piezometers	7	Vibrating wire pressure cells	7
	Integrated sensors in relative humidity, strain gauge and pore pressure sensors	*Not specified*				
PRACLAY	Thermocouples	344	Piezometers	219	Piezoresistive pressure cells	59 (number

Parameters **Experiments**	**Temperature**		**Pore Pressure**		**Total Pressure**	
	Type	**Number or length**	**Type**	**Number**	**Type**	**Number**
					Vibrating wire flapjacks (pressure cells)	of types of total pressure sensors not specified)
					Vibrating wire biaxial stress meters	
Prototype Repository II [41]	Thermocouples	128	Piezoresistive piezometers	22	Piezoresistive pressure cells	30
	Optical fibres	*Not specified*	Vibrating wire piezometers	21	Vibrating wire pressure cells	40
ATLAS	Thermistors	2	Piezoresistive piezometers	4	Piezoresistive pressure cells	4
	Thermocouples	35	Vibrating wire piezometers	2	Vibrating wire flapjacks (pressure cells)	8
			Twin tube piezometers	8	Vibrating wire biaxial stress meters	2
FEBEX [42]	Thermocouples	189	Piezoresistive piezometers	124	Vibrating wire pressure cells	40
			Vibrating wire piezometers	52		
CLIPEX	*Not monitored*		Twin tube piezometers	37	Miniaturised piezoresistive pressure transducers	23

Parameters Experiments	Temperature		Pore Pressure		Total Pressure	
	Type	Number or length	Type	Number	Type	Number
					Vibrating wire flapjacks (pressure cells)	12
EB	*Not specified*		*Not specified*	12	*Not specified*	16
LASGIT	Thermocouples	5	*Not specified*	26	*Not specified*	32
ORS	Resistance temperature detectors	42	Vibrating wire piezometers	5	*Not specified*	3
	Optical fibres	*Not specified*			Optical fibres	*Not specified*
GAST	Resistance temperature detectors	3	*Not specified*	49	Vibrating wire pressure cells	23
EPSP	Digital and analogue thermometers	*Not specified*	Vibrating wire piezometers	*Not specified*	Vibrating wire pressure cells	*Not specified*
CD-A [31]	Resistance temperature detectors (Pt-1000) integrated into relative humidity and extensometers sensors	38	Mini piezometers	12	*Not monitored*	
HotBENT	Optical fibre distributed temperature sensing	800 m	Vibrating wire piezometers	355	Vibrating wire pressure cells	70
	Resistance temperature detectors (Pt-100) and thermocouples	387				

Parameters **Experiments**	**Temperature**		**Pore Pressure**		**Total Pressure**	
	Type	**Number or length**	**Type**	**Number**	**Type**	**Number**
VSEAL	*Not monitored*		Piezoresistive piezometers	6	Vibrating wire or piezoelectric (not specified) pressure cells	14
DR-C	FBGs	20	Piezoresistive piezometers within packer systems	9	*Not monitored*	
	Resistance temperature detectors (Pt-1000)	9				

2.1.3 Monitoring System Layouts

Monitoring system layouts relate the numbers and geometrical arrangements of monitoring technologies. This section summarises the different monitoring system layouts in the surveyed experiments and outlines the factors that influence the design decisions.

2.1.3.1 Monitoring System Densities

It is difficult to meaningfully compare the number of sensors between experiments owing to the different scales of the experiments, and their different aims. However, the number of sensors used in the monitoring systems varies considerably between the different experiments (Table 2.4). A comparison of the numbers of temperature sensors implemented in a given volume in the FE and Prototype Repository II experiments demonstrates different approaches to monitoring system design.

In the Prototype Repository II, 128 thermocouples were used in the deposition holes, in the backfill and in the rock surrounding the backfilled tunnel. Optical fibre sensors were also used on the dummy copper canisters. By comparison, in the FE experiment, temperature is monitored using 87 resistance temperature detectors, 497 thermocouples, 72 FBGs on the heaters, and 660 m of optical fibre on FE Tunnel walls (Table 2.4; 11 and 5). Using approximations of the excavated volumes in both experiments, which could be considered representative of the scales of the experiments, approximately 1 temperature sensor has been used in every 3 m^3 in the Prototype Repository II, while an estimated 3 temperature sensors are implemented in each 1 m^3 in the FE Experiment. These estimations consider the number of temperature sensing technologies implemented in boreholes, but do not consider the volume of the boreholes. They also exclude the lengths covered by optical fibre distributed temperature sensing.

Generally, this crude comparison demonstrates a key difference in the density of the monitoring systems in the surveyed experiments, specifically for key parameters; some experiments implement high-density monitoring systems with considerable redundancy, while other experiments use lower density monitoring systems with less redundancy.

Furthermore, the density of the monitoring systems varies according to the experiment components. For example, in the PRACLAY experiment, the seal at the end of the PRACLAY Gallery includes a high density of temperature, pore pressure and total pressure sensors (approximately >10 per m^3). In contrast, the gallery lining and boreholes surrounding the PRACLAY Gallery have much lower densities of these sensors (approximately 1 per m^3 and significantly less than 1 per m^3, respectively) [8].

The factors that influence the decisions on the density of the monitoring systems are interlinked to those that influence the decisions on the geometrical arrangements of the monitoring systems. These factors are discussed in Section 2.1.3.3, following a description of the geometrical arrangement of the monitoring systems in the surveyed experiments.

2.1.3.2 Geometrical Arrangements of Monitoring Systems

In the majority of experiments, monitoring technologies are geometrically arranged in cross-sections oriented perpendicular to parameter gradients. In the EPSP experiment, for example, monitoring technologies have been symmetrically arranged in cross-sections oriented perpendicular to fluid flow gradients, from the injection chamber to gallery (Figure 2.2, F and A; 38).

Several experiments position monitoring technologies in boreholes surrounding the main test area or test borehole. The monitoring boreholes are similarly oriented perpendicular to parameter gradients, but also, specifically in clay rocks, are positioned parallel and perpendicular to bedding to understand anisotropy in the monitored parameters. For example, in the FE experiment, in addition to the monitoring technologies that are positioned surrounding the heaters and on the tunnel walls, numerous boreholes were drilled perpendicular and parallel to bedding, surrounding the FE Tunnel and were equipped with monitoring technologies (Figure 2.3).

Monitoring technologies are intentionally positioned in certain locations within cross-sections that avoid disturbing the EBS materials they are emplaced in. This monitoring system design is used to minimise the creation of artefacts, which may influence the processes being monitored [e.g. 24, 35].

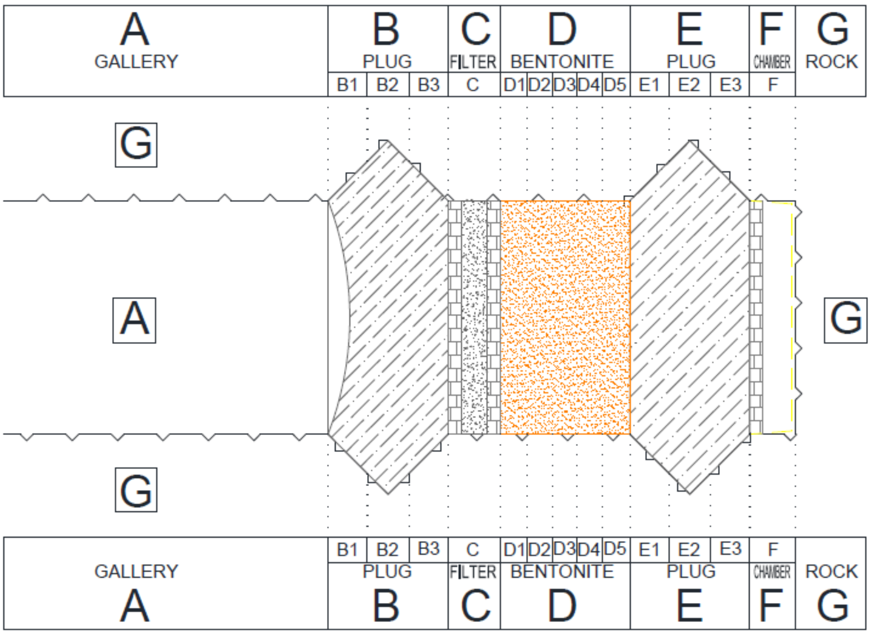


Figure 2.2 - Cross-section of the EPSP experiment, illustrating the location of monitoring cross-section (dashed lines) [38].

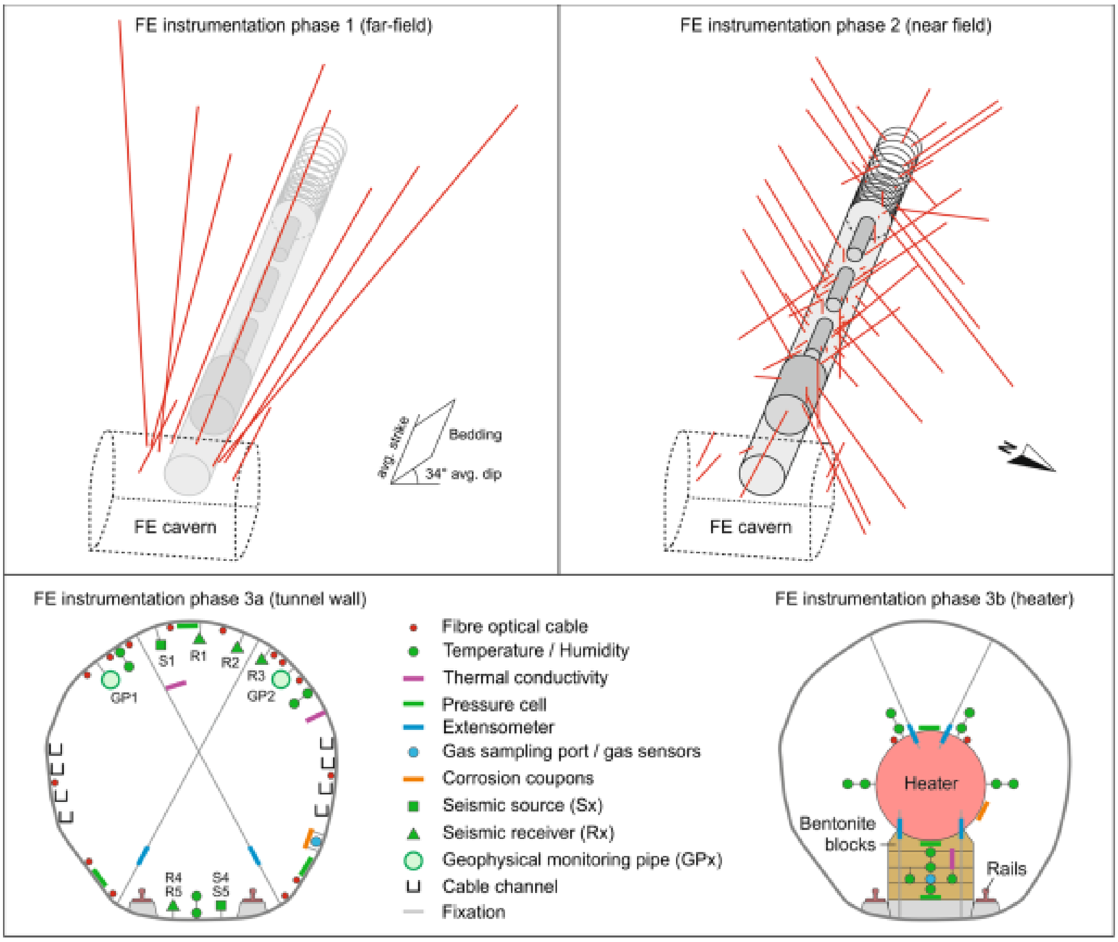


Figure 2.3 - Cross-sections and 3D views of the FE experiment showing the monitoring technology arrangements. The red lines in the top two panels denote the position of boreholes, where monitoring technologies are positioned, with respect to bedding in the Opalinus Clay [5].

For example, in the LASGIT experiment, pore pressure and total pressure sensors were positioned in nine cross-sections oriented perpendicular to the deposition hole (and perpendicular to the hydration gradient) (Figure 2.4) [24, 25]. Five of these sections were positioned adjacent to the dummy copper canister. In these 5 sections (Figure 2.4, sections 4, 5, 7, 9 and 10), sensors were only positioned on the deposition hole wall; no sensors were placed in the bentonite between the canister and the deposition hole wall in order to minimise the creation of fluid flow pathways that could influence the hydration of the bentonite and gas migration processes. Sensors were also positioned above and below the canisters to ensure the required pressure data could be collected, but only in limited numbers, to avoid the creation of fluid flow pathways (Figure 2.4).

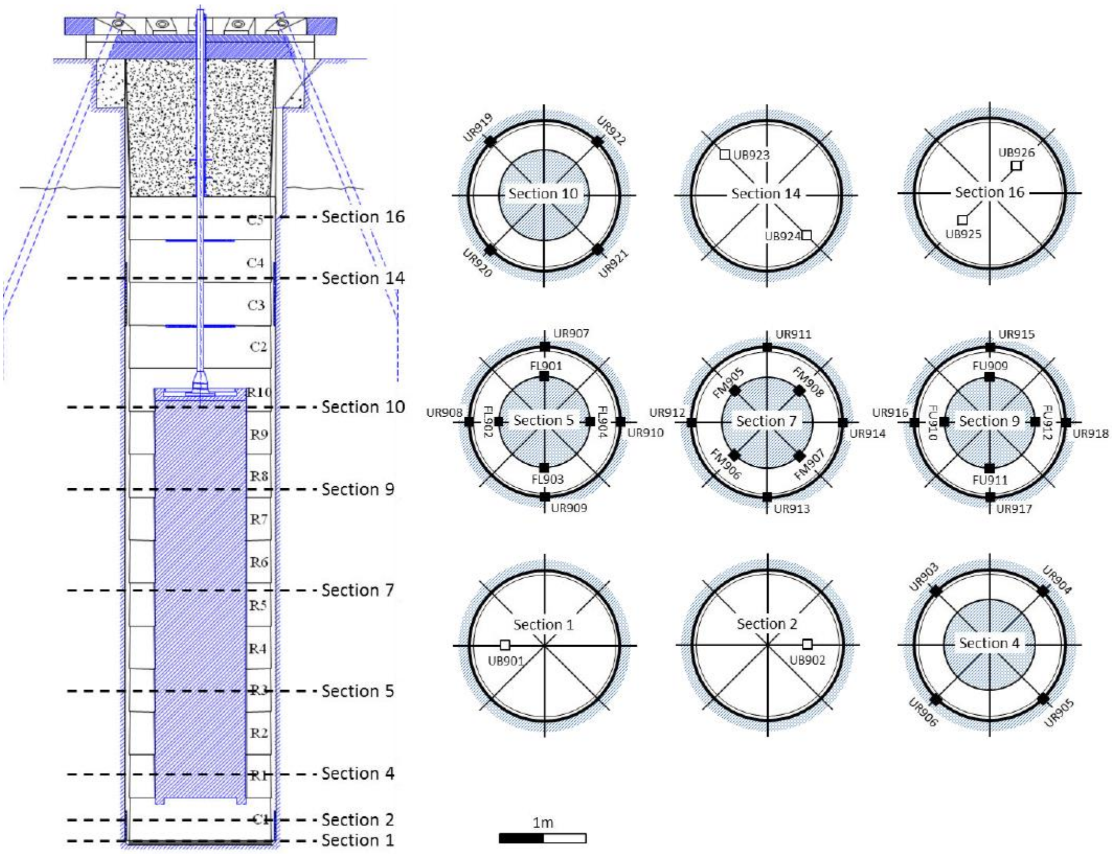


Figure 2.4 - Cross-section of the LASGIT deposition hole, showing the locations of monitoring cross-sections and the positions of technologies within these cross-sections (black and white squares with labels beginning with U). In cross-sections 5, 7 and 9, pressure transducers associated with the hydration mats are positioned on the canister surface (black squares with labels beginning with F) [25].

Technologies are also arranged according to the parameter they are monitoring. In the ALC1605 demonstrator, two different optical fibre sensor arrangements have been implemented on the demonstrator tubing; a spiral arrangement along the axis of the tube to provide distributed deformation monitoring (i.e. monitoring of the ovalisation of the tubing) and a longitudinal arrangement along the tubing axis for distributed temperature and strain monitoring (Figure 2.5) [3].

2.1.3.3 Factors Influencing the Monitoring System Layouts

The factors that influence design decisions relating to the number and geometrical arrangements of monitoring systems in the experiments include:

- Experimental and modelling data requirements [e.g. 8], such as:
    - Experiment size.
    - Parameter boundary conditions (estimated using scoping calculations).
    - Temporal and spatial evolution of parameters (also estimated using scoping calculations).
    - Property anisotropy.
    - Measurement redundancy.

- Feasibility to install the sensors and cables in the experiment materials and geological environment and the available space [e.g. 8, 28, 30, 33].
- Minimisation of the creation of artefacts relating to installed sensors and cables that could impact the processes being monitored [e.g. 8].
- Avoidance of electrical disturbance [e.g. 28].
- Safety considerations associated with high temperatures and high pressures [e.g. 8].
- Resources, such as total cost and expertise for installation, maintenance and data acquisition.

Data management considerations, such as the number of data points and the approach to data storage, have not been factored in the monitoring system designs in the majority of experiments. The only exception is the late design phases of the monitoring system in the FE experiment [5].

Scoping calculations and numerical modelling have been used to aid the design of the monitoring systems in the majority of the surveyed experiments. Modelling has been used to aid decisions on the number and locations of the sensors.

In the CLIPEX experiment, for example, preliminary numerical modelling was carried out to gain an understanding of the hydro-mechanical disturbances induced by the excavation of the Connecting Gallery in the Boom Clay (Figure 1.7) [19]. In particular, it provided an understanding of the extent of the radial plastic zone associated with the excavation and provided estimates of the:

- Axial displacements ahead of the gallery.
- Radial convergence on the tunnel wall.
- Total stress.
- Pressure on the excavation lining [19].

This information was used to optimise the location of pore pressure, total pressure and displacement sensors; as a result of this information:

- Pore pressure and total pressure sensors were installed along the axis of the Connecting Gallery up to a radial extent of 12 m.
- Displacement sensors were installed along the axis of the Connecting Gallery up to a radial extent of 7 m.
- Sensors were installed in two perpendicular planes to observe possible mechanical anisotropy [19].

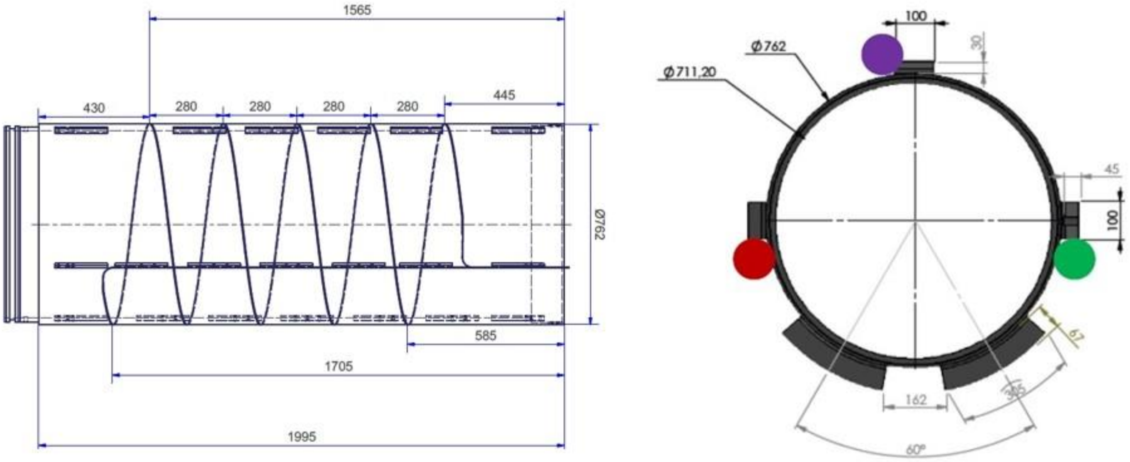


Figure 2.5 - Cross-sections of the ALC1605 demonstrator tubing, illustrating the different geometrical arrangements of the optical fibre systems. Left: spiral arrangement along the axis of the tubing. Right: three longitudinal optical fibres (red, blue and green) along the axis of the tubing [3].

In the HotBENT experiment, a data worth analysis was undertaken to optimise the design of the monitoring system [33]. Data worth analysis evaluates the potential ability of datasets to reduce uncertainty in estimated parameters and predicted system states [44 § 2.6]. In the context of monitoring in the HotBENT experiment, data worth analysis was performed to understand the value of monitoring data at specific locations.

The layout of the monitoring system in the VSEAL experiment was based on lessons learned from a previous related experiment SEALEX, where the arrangement and location of sensors were tested [35]. It also used monitoring system designs from mock-up tests. Similarly, the design of monitoring system in the LASGIT experiment used hydromechanical understanding gained from extensive laboratory testing to support the decisions regarding the locations of sensors [24].

In the GAST experiment, studies were undertaken to investigate the feasibility to install sensors in certain locations. The resulting understanding was used to aid design decision making [28]. Installation feasibility was also a decisive factor in the design of the monitoring system in the PRACLAY experiment. Boreholes could only be drilled from the existing underground openings. Furthermore, the position of the boreholes around the galleries was limited by local geological and hydrogeological features, specifically a water-bearing layer in the Boom Clay, approximately 10 m above the PRACLAY Gallery, which may have caused borehole drilling failures. As a result of these drilling constraints, the majority of monitoring boreholes surrounding the PRACLAY Gallery were drilled horizontally in the first experiment phase [8].

In addition to the feasibility of borehole drilling, the speed and ease of sensor installation in the boreholes is an important design consideration in the HADES URL. Owing to the *in situ* conditions and rock properties in the Boom Clay in the HADES URL, boreholes naturally converge and close quickly after drilling, therefore, it is necessary to select sensors and technologies that can be installed within the available timeframes and in the natural conditions [8, 19].

Cable routing influenced the number of sensors that were installed in the EPSP and PRACLAY experiments [8, 30]. To avoid the creation of artefacts that could have influenced the monitored processes, sensor cables were run perpendicular to the plug axis in the EPSP experiment, through boreholes and into adjacent niches, where DAS were positioned. The diameter of the boreholes limited the maximum number of cables that could be routed and, therefore, limited the number of sensors in the experiment [30].

In some experiments, the process of backfilling excavated sections of the experiments influenced the design of the monitoring systems. In particular, in the HotBENT and FE experiments, the backfilling process impacted the location of the sensors [5, 33]; foldable and erectable sensor holders have been used on the heaters in the FE experiment to ensure the backfilling machine could operate effectively in the FE Tunnel without damaging the sensors [5].

In the PRACLAY experiment, a high density of sensors was installed in the gallery seal to understand its evolution for the purposes of safety, as well as further developing technical understanding. The gallery seal separates the heated and pressurised PRACLAY Gallery from the open Connecting Gallery (Figure 1.3) and, therefore, is characterised by high thermal and hydraulic gradients. It was necessary to implement a high density of monitoring to validate the behaviour of the seal and ensure it was safe to begin heating [8].

2.1.4 Monitoring System Performance

Once finished, the dismantling of URL experiments and the careful retrieval of the sensors can provide opportunities to understand monitoring system performance and the mechanisms through which any monitoring system failures may have occurred. This information can be used to support monitoring system designs.

URL experiments that have been operating for several years or more also provide some opportunities to understand the performance of monitoring systems, although a complete understanding of any monitoring system failures is typically achieved following dismantling. Of the experiments included in the survey, the FEBEX and Prototype Repository II experiments have finished and been dismantled [11, 17]; Figure 2.6 shows the FEBEX experiment during dismantling.

The survey responses have provided examples of monitoring systems that have been capable of providing data for almost two decades. In the LASGIT experiment, 95 % of the installed sensors were still operating after 15.5 years, even though the experiment and monitoring system was designed to operate for five years [24], while in FEBEX, sensors were still providing THM data after 18 years [17].

A leakage in the GAST experiment setup in 2014 resulted in the experiment being shut-down. Repairs were conducted and the experiment restarted. However, by shutting the experiment down and undertaking repairs, a significant number of monitoring sensors failed. Several total pressure cells and the complete seismic array were damaged by the repairs and no longer functioned. As a result, the

GAST experiment experienced a notably high sensor failure rate of approximately 50 % after 10 years [28].

In general, the performance of monitoring technologies is dependent on the type of technology. Table 2.5 shows the percentage of operational sensors in the FE experiment, after approximately five years of operation.

Figure 2.6 - Image of the FEBEX experimental set-up during dismantling [43].

TDR and FDR probes have been some of the most reliable technologies used in the surveyed experiments to date. In the FE experiment, 99 % of deployed TDR and FDR probes were still operational after approximately five years (Table 2.5) [5].

Relative humidity sensors have a notably high failure rate (45 %; Table 2.5). Capacitive hygrometers are known to fail when they reach 100 % saturation; however, this failure is not necessarily an issue because by the time they have failed, they have provided data on the complete saturation process. The FEBEX experiment similarly showed the high failure rates of capacitive hygrometers; approximately 40 % remained operational after five years of the experiment. Laboratory analyses of the sensors following dismantling in the FEBEX experiment demonstrated that they provided accurate data [17].

Psychrometers were prone to failure in the bentonite buffer in the FEBEX experiment, with only 20 % still operational at the end of the experiment. Laboratory tests conducted on psychrometers operational at the end of the experiment showed that there were sensitive to salt contamination in certain locations, but otherwise provided accurate data [17].

Custom-built sensors (e.g. the custom-built total pressure sensors in the FE experiment; Table 2.5) also show a relatively high rate of failure, most likely because they have not been extensively tested [15].

In general, sensor failure mechanisms relate to:

- Water ingress (leading to short circuits).
- Heat.
- Deformation.
- Salt contamination and corrosion.

In the CLIPEX experiment, one of the extensometers failed owing to damage relating to the differential movement of the shotcrete shell on which the measurement head was installed (Table 2.5). Evidence of corrosion damage was also recorded in this sensor, as well as in some of the inclinometers [19]. Some sensors were positioned in the joints between bentonite blocks in the FEBEX experiment. These zones experienced significant mechanical deformation during bentonite swelling, which led to sensor damage and failures [17]. In the ATLAS experiment, biaxial stress meters failed during the first year of the experiment owing to water ingress and corrosion [15].

Table 2.5 - Summary of operational percentage of specific sensor types in the FE experiment as of 31/08/2020 and at the completion of the CLIPEX experiment [19, 44].

Parameters	**Monitoring Technologies**	**Number of sensors**			**Percentages of sensors**	
		Installed	**In operation**	**Not providing data / not working**	**In operation**	**In operation (overall)**
FE experiment; as of 31/08/2020						
Temperature	Pt-1000	87	79	8	91	82
	TERMYA Type T	132	123	9	93	
	Thermocouples	365	274	91	75	
Absolute pore pressure	Keller PAA-23SY	38	33	5	87	96
	Keller PAA 33X	76	76	0	100	
Relative humidity	EE33	9	4	5	44	55
	HYT939	55	46	9	84	
	SHT75 V6	34	8	26	24	
	EE99-1	15	4	11	27	
Water content	FDR	39	39	0	100	99
	TDR	32	31	1	97	
Total pressure	Geokon 4810	8	8	0	100	70
	Geokon 3500	13	13	0	100	
	Geokon custom-built Titanium	10	5	5	50	
	Geokon 3500 custom-built	6	0	6	0	
Absolute pressure	Keller PAA-23SY	38	33	5	87	96
	Keller PAA 33X	76	76	0	100	

Parameters	Monitoring Technologies	Number of sensors			Percentages of sensors	
		Installed	In operation	Not providing data / not working	In operation	In operation (overall)
Displacement	Potentiometric extensometers	48	45	1	94	91
	KL 250 SE crack meters	2	0	2	0	
	Linear Variable Differential Transformer sensors	19	15	4	79	
	Inclinometers	80	76	4	95	
CLIPEX experiment; at completion						
Pore pressure	Twin-tube piezometers	44	44	0	100	100
Total pressure	Miniaturised piezoresistive pressure transducers	23	17	6	74	87
	Vibrating wire flapjacks (pressure cells)	13	13	0	100	
Displacement	Extensometers	6	5	1	83	92
	Inclinometers	35	32	3	91	
	Deflectometers	20	20	0	100	
Strain	Vibrating wire strain gauges	270	268	2	99	99

A graph of the number of operating sensor systems in the PRACLAY experiment over time is presented in Figure 2.7.

All installed piezometers are functioning to date, whereas total pressure sensors, thermocouples and vibrating wire strain gauges have been impacted by high temperatures and / or pressures in the PRACLAY Gallery. Within a few months of the temperature reaching 80 °C, all the vibrating wire strain gauges in the PRACLAY Gallery lining failed [8]. Furthermore, since the start of heating:

- 50 % of the thermocouples in the gallery lining and 75 % within boreholes failed.
- 50 % of total pressure cells within boreholes failed.

Similarly, Figure 2.8 shows the number of operating sensor systems over time in the Prototype Repository II. A notable decrease in the operating relative humidity sensors occurred as a result of the closure of the drainage system, and the saturation of the buffer and backfill. Similarly, a gradual decrease in the operating pore pressure and total pressure sensors followed the closure of the drainage system. These failures were thought to be related to increasing pore and swelling pressures, as well as the high temperatures, which damaged sensor welds [11]. Additionally, some of the DASs that were positioned in the tunnel adjacent to the Prototype Repository II failed owing to the high humidity [11].

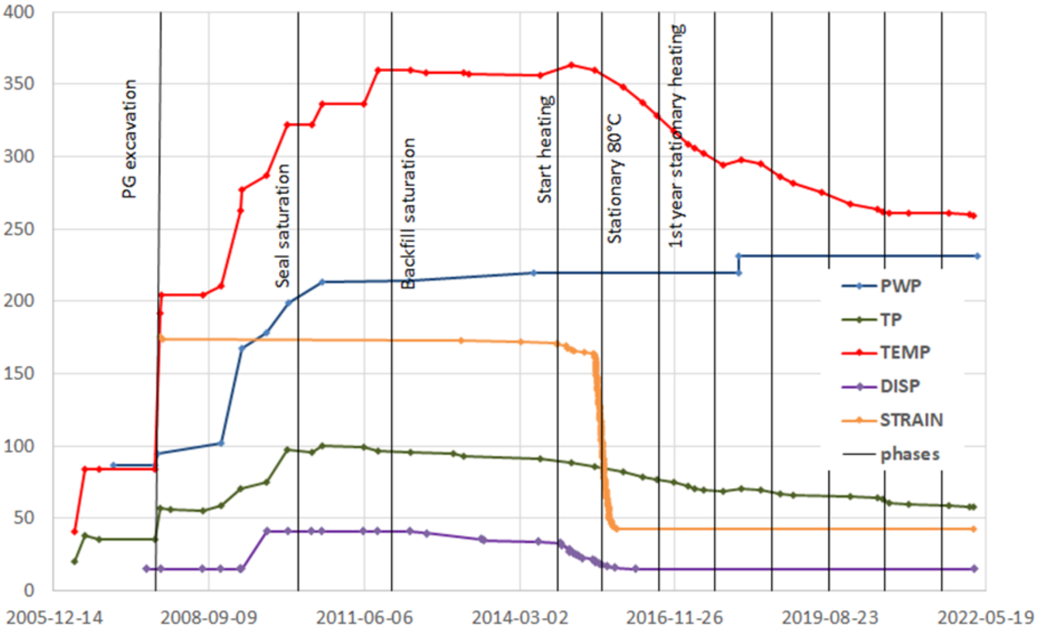


Figure 2.7 - Graph of the number of operating sensors over time in the PRACLAY Experiment, relative to experiment phases. PWP: porewater pressure sensors; TP: total pressure sensors; TEMP: all thermocouples; DISP: inclinometer, foam panel potentiometers and optical fibre sensors; STRAIN: vibrating wire strain gauges [8].

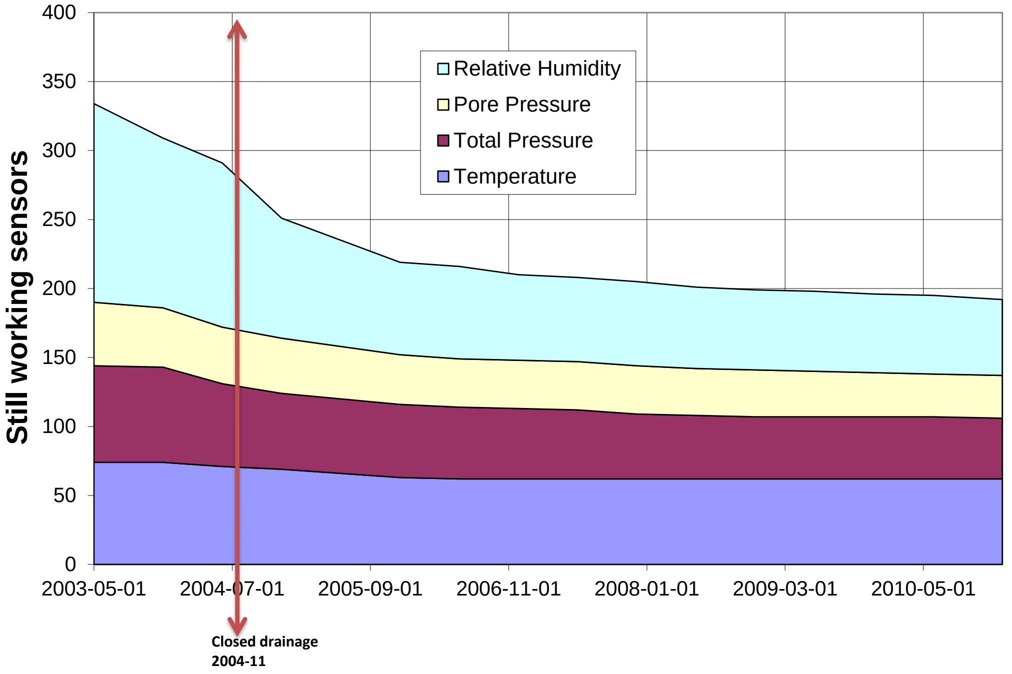


Figure 2.8 - Graph of the number of operating sensors over time in the Prototype Repository II experiment [11].

During dismantling of Section 2 in the Prototype Repository experiment, the functionality and performance of the total pressure sensors in the buffer and backfill were analysed. This analysis showed that minimal operational deviations had occurred and that all the total pressure sensors had provided reliable data [11].

In the ALC1605 demonstrator, there was a partial failure of the optical fibre system resulting from breaks, specifically at discrete locations where the glue, which had been used to fix the optical fibre to the tubing, expanded owing to heating. It was recognised prior to installation that the glue would expand because of heat. However, the extent of the thermal expansion was underestimated. To mitigate this issue, continuous gluing of optical fibre system has been used to fix fibres to tubing in subsequent experiments, rather than gluing at discrete locations [3].

In the LASGIT experiment, the cabling associated with the monitoring technologies is thought to have created a pathway for the migration of gas during the gas injection tests. This is because one of the pore pressure sensors was intercepted by gas. Despite this, the overall impact of this potential localised gas migration along cabling was minimal with little influence on the migration of gas through the deposition hole [24].

2.2 Monitoring Data Acquisition

Monitoring data acquisition relates to the methods used to ensure raw monitoring data are effectively obtained, including general QA / QC procedures, as well specific QA / QC procedures associated with monitoring system installation. This section documents QA / QC and installation procedures in the surveyed experiments.

2.2.1 Monitoring System QA / QC

QA and QC are interrelated aspects of quality management [35]. With respect to monitoring systems, QA relates to the processes used to build components and install the system to the design specifications, particularly those processes that are used to prevent defects [3, 33], whereas QC refers to the processes used to verify the system is operational to the required standards once built and installed [3, 33, 35].

QA is the responsibility of the experimental team and the contractors used to install the monitoring system, while the experiment project manager is responsible for QC. The experiment project manager is usually an employee of the waste management organisation, technical support organisation or research entity conducting the experiment.

QA documentation includes quality management plans, as well as design, build and installation reports written, while QC documentation includes calibration certificates and reports [22].

In the GAST experiment, for example, a quality management plan has been created and managed by the project manager. It includes quality-relevant documentation for delivery control, as well as order forms, production sheets, certificates and specification sheets for the equipment [28].

In the PRACLAY experiment, a quality management system is operated, which includes a “measuring equipment” process. This process is designed to manage the installed technologies. It includes the maintenance of a monitoring system inventory, as well as instructions for technology calibration. The process is managed by EURIDICE staff and is subject to internal and external audits [8].

The main contractor for the GAST experiment monitoring system installation was Solexperts, who are certified by the International Organization for Standardization (ISO-9001:2008) and operate a quality assurance system. Quality-securing measures for the GAST experiment have been documented in Solexperts quality management handbook, which contains the overall concept, the internal and external processes and the responsibilities [28].

Some specific QA / QC processes implemented to install and verify the operation of the monitoring systems in the surveyed experiments are outlined in the next section.

2.2.2 Monitoring System Installation

The installation of monitoring systems involves multiple steps:

- Preparing the materials in which the sensors will be emplaced.
- Installing sensors, cables and DASs.
- Documenting the sensor locations.
- Naming the sensors.
- Testing the functionality and performance of the sensors.
- Calibration of sensors.
- Water tightness tests of the cables and sensors.

- Testing the data acquisition system.

The order in which these steps are completed depends on the approach adopted in the experiment. Several of these steps are overlapping.

Quality management systems have been implemented to ensure the quality of the installed monitoring systems. In some experiments, the complete multi-step process has been subjected to a quality management system, while in others, it has been applied to certain steps only.

In more recent experiments, detailed plans of the monitoring technologies have been created prior to their installation. In the FE experiment, surveys were conducted to build a 3D model of the FE Tunnel, in which the borehole axes and the locations of sensors were planned and documented. The boreholes were then drilled according to these plans [5]. Prior to the installation of the sensors and directly after drilling, as-built surveys of the boreholes were conducted to determine their geometry (Figure 2.9) [5, 19].

Figure 2.9 - Images showing the optical surveying of boreholes in the HADES URL [19].

In the Prototype Repository II, technical drawings of each bentonite block and each backfill section were created, documenting the location and size of individual sensors. Using these drawings, bentonite blocks were prepared in advance of their installation by drilling holes for the sensors and milling tracks for cable tubes. This preparatory work enabled time-efficient installation of sensors in the bentonite in the deposition holes. The technical drawings were also used to position and install sensors in the backfill, although, the backfill materials could not be prepared in advance, and the backfilling process had to stop to allow the installation of the sensors at the planned locations [11].

In the GAST experiment, errors in reading the technical drawings, in part owing to similarities in symbols, led to two sensors being installed in the wrong locations [28]. Furthermore, some of the sensors could not be installed in the locations specified in the technical drawings because multiple sensors were positioned in exactly the same place on the drawing; only one sensor was installed in the designed position and the other sensors were installed as close to their designed position as possible, but ensuring that none of the sensors were touching or crossing cables [28].

The approaches used to install the monitoring system depend on the monitoring technologies that have been selected and the locations that they are being installed in.

Monitoring technologies installed in boreholes have typically been inserted in casing (e.g. in ATLAS [15] CLIPEX [19] and PRACLAY [8]) or in prefabricated tubing in the ALC1605 experiment [3]. The casing and tubing have then been inserted into the boreholes. In the ALC1605 demonstrator, the prefabricated tubing incorporates centring and anti-roll technology [3]. In the ATLAS experiment, all of the pore and total pressure sensors that were installed on the casing surrounding the heater failed, most likely owing to stray current from the welding of the casing segments [15]. Inclinometers in one of the CLIPEX boreholes failed because of uneven convergence of the borehole, which resulted in deformation of the inclinometer casing. To avoid similar failures in later boreholes, the inclinometers were installed in steel casings [19].

The approach to filling the space between the borehole casing or tubing and the borehole wall depends on the host rock. In the Boom Clay, the space naturally converges on the timescales of days to weeks, depending on the size of the space [8, 15, 19]. In the Callovo-Oxfordian Clay in the Bure URL, grouts that are compatible with the host rock and EBS materials are used to fill these spaces [3]. During the grouting of boreholes in the FE experiment, some optical fibre strain sensors failed, most likely owing to leakage into the fibre because of the high grouting pressures and insufficient sealing capacity of the fibre [5].

In excavated areas, such as on excavation walls, or within EBS components, such as bentonite, monitoring technologies have been installed by creating recesses according to the technical plans and positioning the technologies into these recesses [24, 28]. Cables have been bundled together and installed within tubes that are positioned in drill holes [17].

Several of the surveyed experiments reported that the installation of the monitoring system took longer than was planned [5, 17, 33]. In the HotBENT experiment, the delays in the monitoring system installation were caused by the ingress of water into the HotBENT Cavern, and the impact this had on installing the monitoring technology and the backfill [33].

Once the technologies have been installed, as-built surveys have been undertaken using optical and laser systems to document their position. These surveys defined the coordinates of the installed monitoring technologies. Different types of coordinate systems have been measured. In the Prototype Repository II, two sets of coordinates were defined:

- Coordinates relative to location in the experiment, e.g. relative to the deposition hole or the deposition tunnel.
- Coordinates relative to Äspö Hard Rock Laboratory, termed the Äspö 96 coordinate system [11].

In addition to local coordinates, some experiments also use national coordinates systems, e.g. in the Swiss coordinate system [5] or the Lambert72 coordinates (national grid in Belgium) [19]. The as-built coordinates have been recorded, along with the intended design coordinates, in QA documentation (e.g. in instrumentation emplacement QA sheets in GAST; Figure 2.10 [28]).

Systematic sensor naming conventions have been implemented in the surveyed experiments, specifically based on the type of sensor and its locations relative to key components of the experiment. For example, in the HotBENT experiment, the following naming convention has been used:

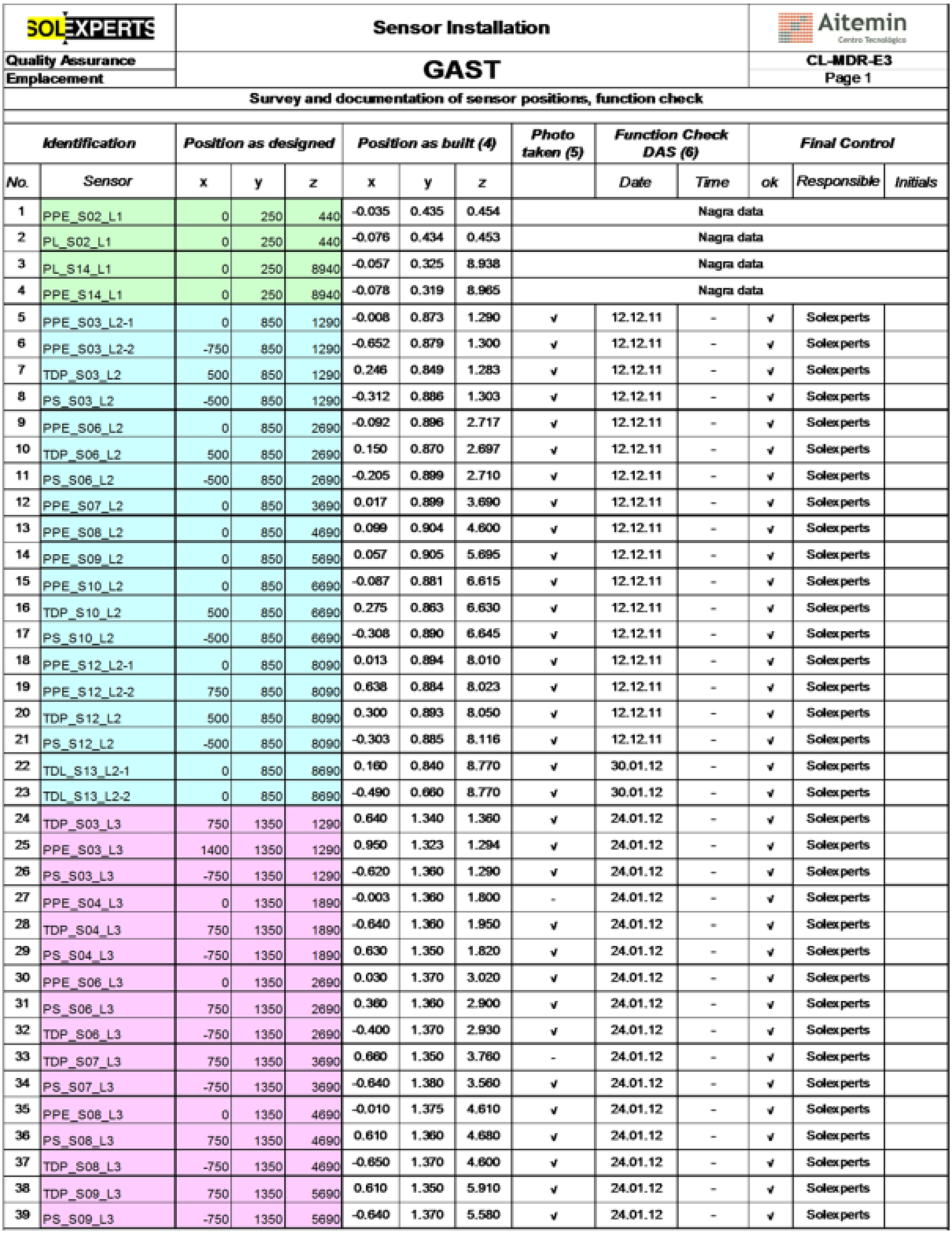
- A_B_C_D

  Where *A* is the type of sensor and *B*, *C* and *D* relate to its position relative to the HotBENT Cavern:

  - *B* is distance along the HotBENT Cavern from the gallery side.
  - *C* is the angle of the sensor relative to the top of the Cavern.
  - *D* is the distance from the centre of the cavern.

For example, TP_5000_090_114, relates to a total pressure sensor, which is positioned 5000 cm from the gallery entrance, at an angle of 90 ° from the top of the cavern and 114 cm from the centre of the cavern [33].

The timing of installation of monitoring systems relative to the start of monitoring varies, depending on the sensor type and their location. For example, in the Boom Clay, six to nine months are generally required after the installation of piezometers in boreholes to obtain porewater pressure values that are representative of the environment prior to borehole drilling [8]. In other instances, monitoring begins as soon as the monitoring system is installed. However, the installation of other components of the monitoring system or EBS may delay the start of monitoring in those sensors that are already installed. In PRACLAY experiment, monitoring could not begin in the sensors installed around the PRACLAY Gallery until the gallery seal installation work was complete because their cabling was disturbed by this installation work [8].



SOLEXPERTS
Sensor Installation
Aitemin
Quality Assurance Emplacement
GAST
CL-MDR-E3
Page 1
Survey and documentation of sensor positions, function check

Identification		*Position as designed*			*Position as built (4)*			*Photo taken (5)*	*Function Check DAS (6)*		*Final Control*		
No.	*Sensor*	x	y	z	x	y	z		*Date*	*Time*	*ok*	*Responsible*	*Initials*
1	PPE_S02_L1	0	250	440	-0.035	0.435	0.454	Nagra data					
2	PL_S02_L1	0	250	440	-0.076	0.434	0.453	Nagra data					
3	PL_S14_L1	0	250	8940	-0.057	0.325	8.938	Nagra data					
4	PPE_S14_L1	0	250	8940	-0.078	0.319	8.965	Nagra data					
5	PPE_S03_L2-1	0	850	1290	-0.008	0.873	1.290	✓	12.12.11	-	✓	Solexperts	
6	PPE_S03_L2-2	-750	850	1290	-0.652	0.879	1.300	✓	12.12.11	-	✓	Solexperts	
7	TDP_S03_L2	500	850	1290	0.246	0.849	1.283	✓	12.12.11	-	✓	Solexperts	
8	PS_S03_L2	-500	850	1290	-0.312	0.886	1.303	✓	12.12.11	-	✓	Solexperts	
9	PPE_S06_L2	0	850	2690	-0.092	0.896	2.717	✓	12.12.11	-	✓	Solexperts	
10	TDP_S06_L2	500	850	2690	0.150	0.870	2.697	✓	12.12.11	-	✓	Solexperts	
11	PS_S06_L2	-500	850	2690	-0.205	0.899	2.710	✓	12.12.11	-	✓	Solexperts	
12	PPE_S07_L2	0	850	3690	0.017	0.899	3.690	✓	12.12.11	-	✓	Solexperts	
13	PPE_S08_L2	0	850	4690	0.099	0.904	4.600	✓	12.12.11	-	✓	Solexperts	
14	PPE_S09_L2	0	850	5690	0.057	0.905	5.695	✓	12.12.11	-	✓	Solexperts	
15	PPE_S10_L2	0	850	6690	-0.087	0.881	6.615	✓	12.12.11	-	✓	Solexperts	
16	TDP_S10_L2	500	850	6690	0.275	0.863	6.630	✓	12.12.11	-	✓	Solexperts	
17	PS_S10_L2	-500	850	6690	-0.308	0.890	6.645	✓	12.12.11	-	✓	Solexperts	
18	PPE_S12_L2-1	0	850	8090	0.013	0.894	8.010	✓	12.12.11	-	✓	Solexperts	
19	PPE_S12_L2-2	750	850	8090	0.638	0.884	8.023	✓	12.12.11	-	✓	Solexperts	
20	TDP_S12_L2	500	850	8090	0.300	0.893	8.050	✓	12.12.11	-	✓	Solexperts	
21	PS_S12_L2	-500	850	8090	-0.303	0.885	8.116	✓	12.12.11	-	✓	Solexperts	
22	TDL_S13_L2-1	0	850	8690	0.160	0.840	8.770	✓	30.01.12	-	✓	Solexperts	
23	TDL_S13_L2-2	0	850	8690	-0.490	0.660	8.770	✓	30.01.12	-	✓	Solexperts	
24	TDP_S03_L3	750	1350	1290	0.640	1.340	1.360	✓	24.01.12	-	✓	Solexperts	
25	PPE_S03_L3	1400	1350	1290	0.950	1.323	1.294	✓	24.01.12	-	✓	Solexperts	
26	PS_S03_L3	-750	1350	1290	-0.620	1.360	1.290	✓	24.01.12	-	✓	Solexperts	
27	PPE_S04_L3	0	1350	1890	-0.003	1.360	1.800	-	24.01.12	-	✓	Solexperts	
28	TDP_S04_L3	750	1350	1890	-0.640	1.360	1.950	✓	24.01.12	-	✓	Solexperts	
29	PS_S04_L3	-750	1350	1890	0.630	1.350	1.820	✓	24.01.12	-	✓	Solexperts	
30	PPE_S06_L3	0	1350	2690	0.030	1.370	3.020	✓	24.01.12	-	✓	Solexperts	
31	PS_S06_L3	750	1350	2690	0.360	1.360	2.900	✓	24.01.12	-	✓	Solexperts	
32	TDP_S06_L3	-750	1350	2690	-0.400	1.370	2.930	✓	24.01.12	-	✓	Solexperts	
33	TDP_S07_L3	750	1350	3690	0.660	1.350	3.760	-	24.01.12	-	✓	Solexperts	
34	PS_S07_L3	-750	1350	3690	-0.640	1.380	3.560	✓	24.01.12	-	✓	Solexperts	
35	PPE_S08_L3	0	1350	4690	-0.010	1.375	4.610	✓	24.01.12	-	✓	Solexperts	
36	PS_S08_L3	750	1350	4690	0.610	1.360	4.680	✓	24.01.12	-	✓	Solexperts	
37	TDP_S08_L3	-750	1350	4690	-0.650	1.370	4.600	✓	24.01.12	-	✓	Solexperts	
38	TDP_S09_L3	750	1350	5690	0.610	1.350	5.910	✓	24.01.12	-	✓	Solexperts	
39	PS_S09_L3	-750	1350	5690	-0.640	1.370	5.580	✓	24.01.12	-	✓	Solexperts	

Figure 2.10 - Instrumentation emplacement QA sheet for the GAST experiment [28].

2.2.2.1 Calibration and Other Testing

Monitoring technologies have been calibrated by manufacturers in the laboratory prior to their installation in experiments [24, 33]. In general, the calibration process has involved the comparison of the parameter value measured by the sensor to a known reference parameter value. Calibration certificates or reports, which document key information relating to the calibration, such as measurement errors, have been produced and stored. Analyses of some calibration documentation provided for sensors in the HotBENT experiment show that manufacturers use a variety of different calibration procedures [33]. These include the comparison of:

- One measurement to one known value.
- Measurements to a range of known values.
- Multiple averaged measurements to a range of known values.

The measurement principle of some sensors depends on temperature. In sensors with temperature-dependent measurements, some calibration procedures involve comparisons at a fixed temperature, while other involve comparisons at a range of temperatures. Furthermore, the criteria that are used to compare the values (i.e. the error values associated with the comparisons) also vary according to manufacturer.

Typically, experiment teams have not been involved or inputted into the calibration of sensors. However, in the FE experiment, the experiment team stipulated that temperature sensors should be calibrated across the complete range of expected temperatures in the experiment [5].

Sensors have not been calibrated *in situ* during installation in any of the surveyed experiments, although the functionality of installed sensors has been tested in some experiments. For example, in the VSEAL experiment, the functionality of all sensors was tested during installation. Functionality and tightness tests were conducted on the sensors and cables installed in the GAST and HotBENT experiments to ensure, as much as possible, the sensors would be capable of functioning under the expected pore pressures [28, 33]. Furthermore, in the GAST experiment, the functionality of the data acquisition system was tested after its installation, including under elevated temperatures and pressures. The results of these functionality and tightness tests were recorded in QA documentation (e.g. Figure 2.10 [28]).

In the VSEAL experiment, certification of the robustness of wireless sensors under *in situ* conditions (i.e. in bentonite at various saturation states) was required by the experiment team. To fulfil this request, the contractor, implemented a test bench to investigate the sensor robustness in a configuration similar to the experiment [35].

After the start of monitoring and / or the experiments, accessible sensors have been maintained, which includes recalibration. For example, pore pressure sensors installed in the instrumentation casing within boreholes in the PRACLAY experiment, are regularly accessed to perform recalibration [8]. Accessible sensors and equipment have been replaced if they fail. Dynamic recalibration of *in situ* optical fibre distributed temperature sensors is regularly undertaken in the FE and HotBENT experiments, using specially designed calibration baths that are maintained at appropriate temperatures (Figure 2.11) [5 and 33].

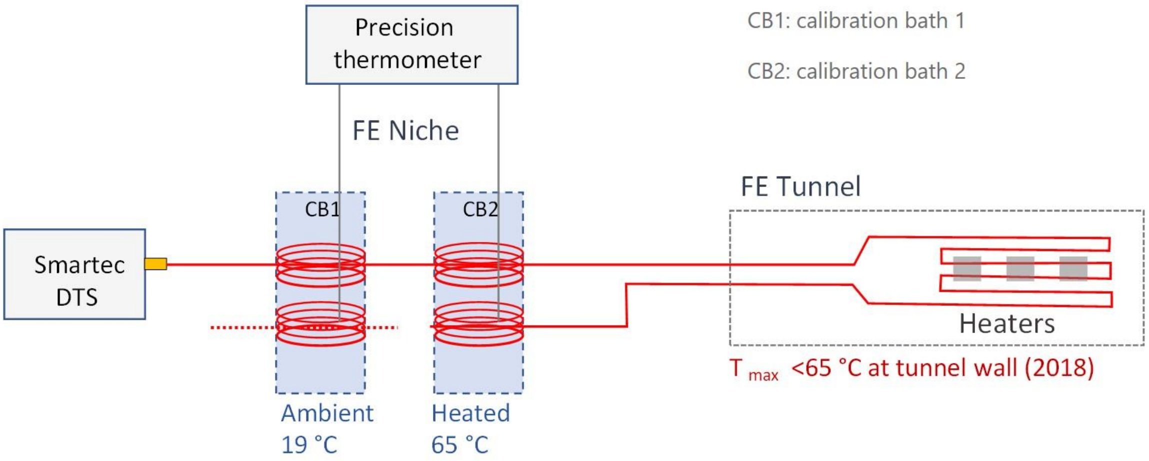


Figure 2.11 - Schematic diagram of the dynamic recalibration of the optical fibre distributed temperature sensors, used in the FE experiment [44].

Asides from the distributed temperature sensors in the FE and HotBENT experiments, inaccessible sensors have not been recalibrated after the start of monitoring and / or the experiment. However, in the PRACLAY experiment other diagnostic methods have been implemented to understand the performance of inaccessible sensors, such as continuity measurements across signal cables [8].

2.3 Monitoring Data Management

Monitoring programmes in URL experiments acquire data relating to multiple parameters (see Section 2.1), using different technologies (see Section 2.1.2) in a range of different locations (see Section 2.1.3). These data are acquired at different frequencies and over different timescales.

There is significant variability in the frequency of monitoring measurements in the experiments, depending on the parameter and the experimental phase. For example, in the HotBENT experiment, temperature is measured every five minutes, while thermal conductivity is measured weekly or monthly (Table 2.6) [33]. In the ALC1605 demonstrator, the frequency of temperature measurements varies from one measurement per minute during grouting to one measurement per day over the long term [3]).

Millions or even billions of data points can be collected over the lifetime of the experiments. In the FE experiment, for example, 40 billion data points, amounting to approximately 500 GB of data, have been collected from point sensors and the distributed temperature sensors as of May 2020 [5, 45]. Effective data management approaches are, therefore, required to enable the use of monitoring data. This section outlines data management approaches in the surveyed URL experiments.

Table 2.6 - Frequency of measurements in the HotBENT experiment, which is planned to operate for 15 to 20 years in Sector 1 and 5 years in Sector 2 (Figure 1.13) [33].

Parameter	Monitoring Technologies		Frequency of measurements
	Type	Number	
Temperature	Pt-100 sensors, thermocouples and optical fibres	387 point sensors and approximately 800 m of optical fibre	1 measurement every 5 minutes
Thermal conductivity	Thermal conductivity needle sensor	48	1 measurement every week
	Optical fibres	Approximately 800 m of optical fibre	1 measurement every month
Pore pressure	Vibrating wire piezometers	355	1 measurement every 5 minutes
Relative humidity	*Not specified*	333	1 measurement every 5 minutes
Water content	TDR	120	1 measurement every 4 hours
Total pressure	Vibrating wire total pressure cells	70	1 measurement every 5 minutes
Displacement	*Not specified*	36	1 measurement every 5 minutes
Oxygen concentration	Oxygen sensor	8	1 measurement every 4 hours

2.3.1 Monitoring Data Storage

In general, monitoring technologies are connected to DASs or data loggers via cables. The data acquisition units or data loggers are positioned in the gallery or tunnels adjacent to the experiment. In the VSEAL experiment, sensors wirelessly transmit data to data loggers in the overlying gallery, although some conventional wired sensors connected to data loggers via cables are also used [35]. In some experiments, data are stored in the DASs or data loggers and downloaded at regular intervals [19], while in the majority of experiments the data are immediately transferred to databases and are available in near real time or real time [e.g. 3, 5].

In the FE experiment, cables are routed from given sensors to specific DASs out of the FE Tunnel to the FE-A Niche (Figure 2.12). The data are then transmitted to data acquisition computers on the file transfer protocol servers of each contractor and then onwards to the FE information system (FEIS) via the internet, where they are accessible in near real time [5].

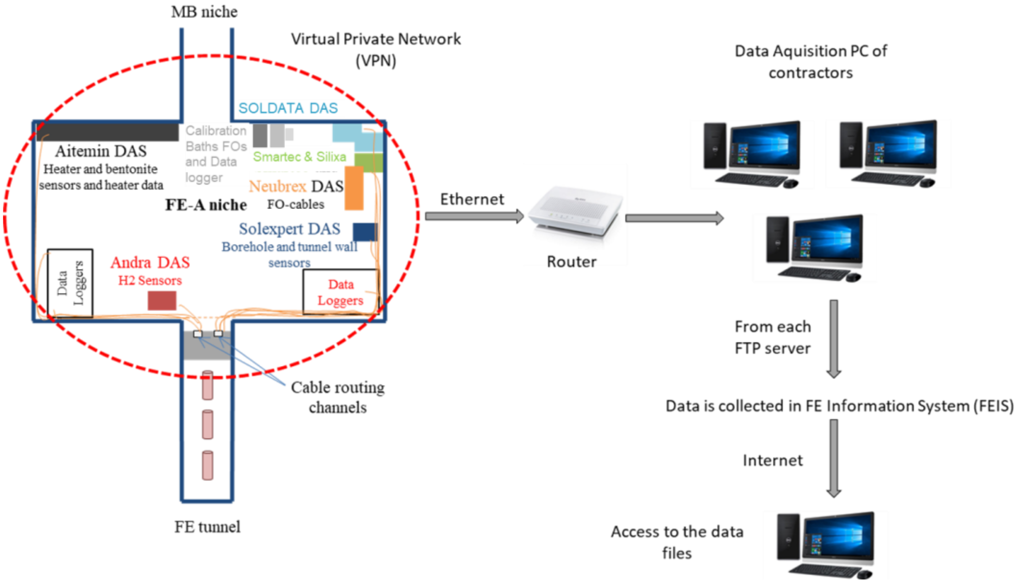


Figure 2.12 - Schematic diagram of the data acquisition and storage system in the FE experiment [46].

Figure 2.13 outlines a workflow diagram showing the steps involved in the collection of monitoring data in the Prototype Repository II experiment. The raw monitoring data (i.e. electrical signals from the sensors) were collected and stored in data loggers, and then transferred to computers, where they were converted to the parameter of interest. Following this, raw and converted data were then transferred to the database [47].

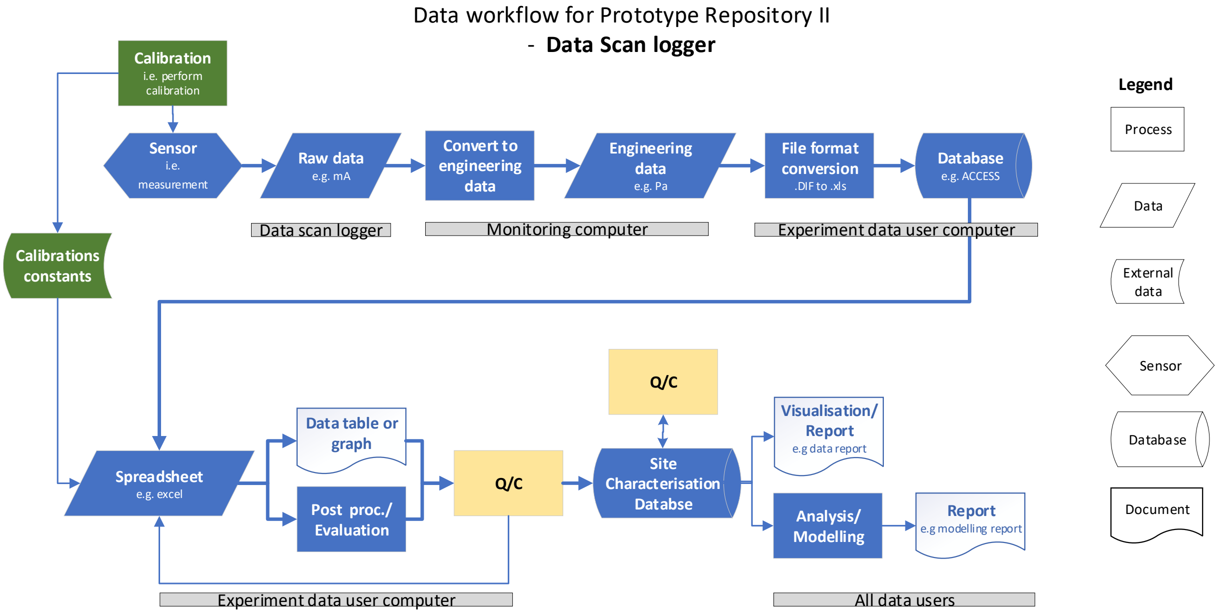


Figure 2.13 - Data workflow diagram in the Prototype Repository II [47].

Simple structured query language (SQL), PostgreSQL, MySQL, MongoDB databases or Microsoft Excel spreadsheets are used in the smaller scale surveyed experiments [e.g. 24, 30, 35]. However, bespoke systems are used in the larger experiments; for example the FEIS database or Système d'Acquisition et de Gestion des Données (geoscientific data acquisition and management system; SAGD), which is used by Andra in the ALC1605 demonstrator [3] and the ORS experiment [26]. SAGD consists of an autonomous optical fibre network with a high-speed link between the Andra URL and the Mont Terri URL, which enables data to be transferred and centralised in control rooms [3].

A range of different metadata are collected alongside the monitoring data, including information on the sensors and the events that have occurred during the experiment and may influence results. These data are either stored in the monitoring data databases or within separate databases (e.g. experiment logs). Metadata recorded in the URL experiments include [5, 15, 30]:

- Sensor identification codes.
- Sensor type and model.
- Sensor signal type.
- Sensor location, e.g. local and national coordinates, angles, photographs.
- Borehole name, location and depth (if the sensor is installed in a borehole).
- Sensor installation data, e.g. quality assurance procedures, dates, fixing process (e.g. glue, grout etc.).
- Sensor installation reports.
- Sensor calibration data, e.g. conversion / calibration formula, calibration constants (e.g. Figure 2.13), calibration certificates.
- Sensor status.
- Parameter and units.
- Expected parameter measurement range.
- Measurement time stamp.
- Type and nature of experimental (e.g. power cuts), man-made (e.g. other drilling activities) and natural events.
- Date and timing of experimental, man-made and natural events.

In the SAGD database, a hierarchal data format has been used to store and organise the data [48]. In this database, monitoring data are organised in a hierarchy by different metadata. An example of this data format in the SAGD database is displayed in Figure 2.14; the data are arranged by processes, waste type, demonstrator, demonstrator component, and then by sensor type, angle and coordinates [48].

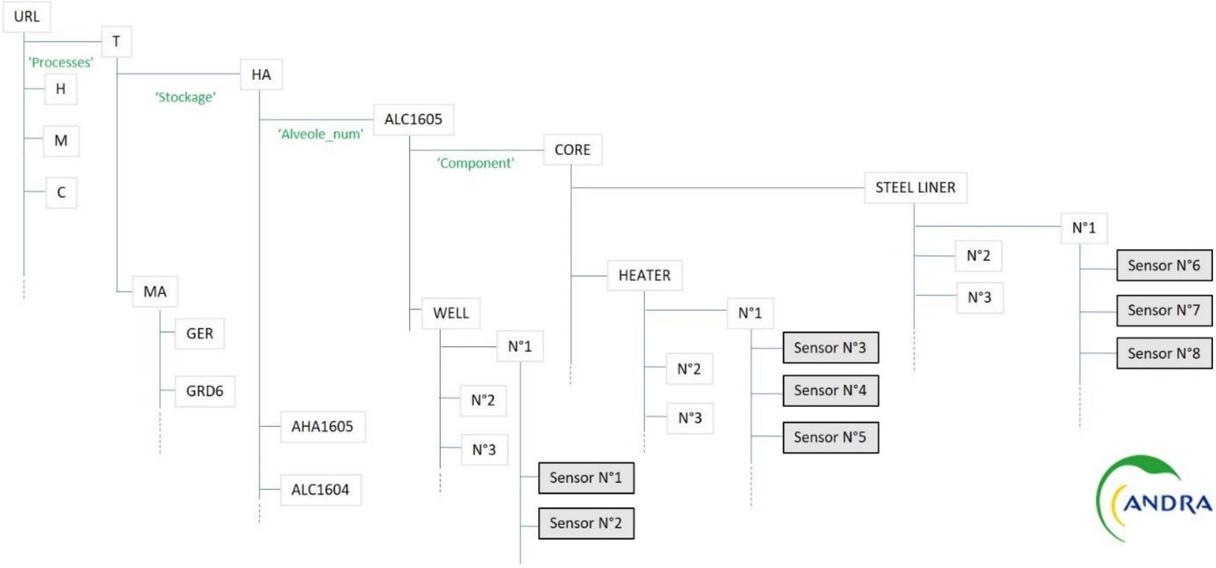


Figure 2.14 - Schematic diagram illustrating the structure of the hierarchal data format used in the SAGD database in the ALC1605 demonstrator. Figure courtesy of Andra R&D [48].

2.3.2 Monitoring Data Treatment

Invalid monitoring data are defined as data that are influenced by factors other than those described by the method[2]. They can be generated by different sensor failure modes (e.g. total or partial sensor failure, total or partial data transmission failure, failure of signal conversion), resulting in a range of different failure signals (Figure 2.15) [1 § 7.2, and references therein].

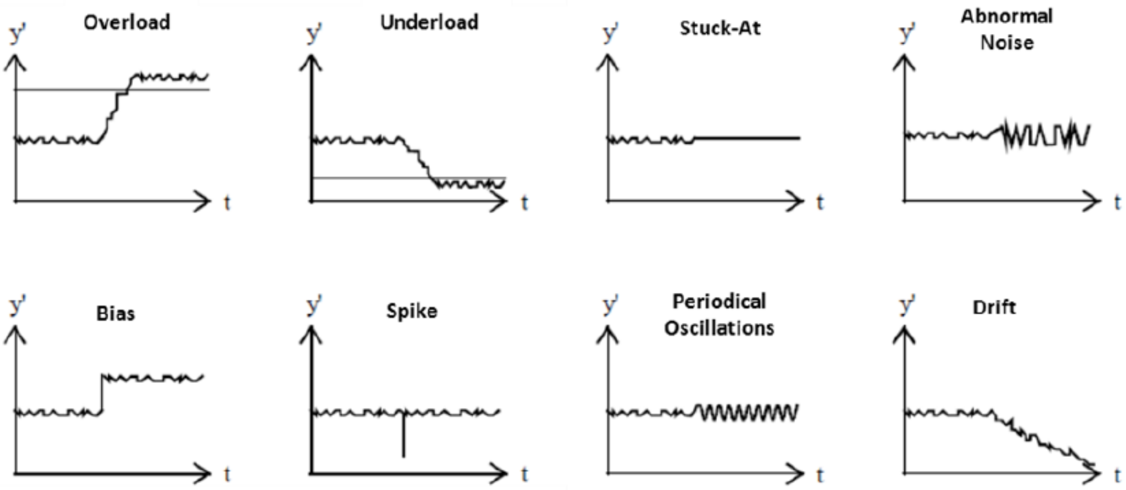


Figure 2.15 - Characteristic sensor failure signals [1 § 7.2, and references therein].

In the surveyed experiments, steps have been taken in order to minimise the acquisition of invalid monitoring data. In particular, monitoring systems have been installed using quality assured processes. Sensors have been calibrated at the time of installation and accessible sensors and equipment have been maintained according to manufacturer guidance (Section 2.2.2.1).

Once monitoring data have been acquired, data treatment methods have been used for the purposes of quality controlling the data. Data treatment methods have involved:

- Data format checks.
- Data cleansing, i.e. identifying and removing invalid data.
- Identifying and addressing outliers.
- Interpolating data gaps, as required.

In general, manual data treatment methods have been used in the surveyed experiments. For example, in the Prototype Repository II experiment, errors and outliers were visually identified, along with data gaps, by plotting the monitoring data on graphs and using expert judgement. In particular, the data were checked for overload, underload, stuck-at, abnormal noise, bias, drift (Figure 2.15) and loss of redundancy [11, 47].

Data redundancy in the monitoring system is useful to aid the identification of errors and outliers. In the CD-A experiment, a comparison of displacement values from extensometers and convergence sensors within the niches revealed outlier data that do not fit with the general trends. One example of this relates to an extensometer in the open niche, which provides higher displacement values compared to other extensometers and unlike other extensometer data, these values are not constant along the borehole axis. These outlier data are thought to relate to geological heterogeneities and, therefore, are considered to be real [32, Table 3]. In the LASGIT experiment, monitoring data QC included daily or weekly data filtering[3]. The quality-controlled data would then be subjected to 6-monthly or annual peer reviews [24].

Alarm systems are incorporated into some monitoring databases to automatically alert users to potentially invalid data when it is transferred into the database. The FEIS employs an algorithm to compare the monitoring data with the expected parameter range to identify errors and outliers. The

---

[2] Application of a technique for a specific measurement in a specific environment, including all hardware components necessary to convert sensor signals to (digital) data (wiring, connectors, converters).

[3] Data filtering is the process of selecting a subset of the data.

expected parameter ranges have been established using baseline monitoring and scoping calculations [e.g. 24, 35], although these methods are not guaranteed to capture or estimate the complete range of parameter values. The FEIS algorithm proved useful in identifying outliers during the early stages of the experiment, when it was intensely supervised, but less useful in longer term without supervision [5]. The FEIS also uses an algorithm to identify gaps in the imported data. This algorithm automatically checks for input file updates and, if possible, uploads the updated data into the database, (e.g. when the contractor has repaired the original data file) [5].

IRSN have developed an automated statistical pre-processing tool for time-series data, called MuSTAT, which will be further tested and developed using the VSEAL monitoring data. This tool is capable of standardising the acquisition time step, identifying spurious data and reconstructing time gaps [2 and 49]. Andra is developing automatic data treatment approaches using machine learning and artificial intelligence. In particular, partial least squared regression is being used to identify measurement drift and errors, while robust principal component analysis is being used to reconstruct missing monitoring data. Andra is also developing automatic approaches to simulate noise for the purposes of identifying real noise in the monitoring data [48].

2.4 Monitoring Data Analysis and Use

The ways in which monitoring data are analysed and used depends on the aims of the specific experiments. However, a common and basic step in data analysis is the visualisation of data.

2.4.1 Monitoring Data Visualisation and Analysis

Monitoring data are typically presented in graphs and data tables. In the surveyed experiments, graphical visualisations include simple time-series of a certain parameter in a given location or locations (e.g. Figure 2.16) often with basic visualisation of the sensor locations, or cross-plots of related parameters.

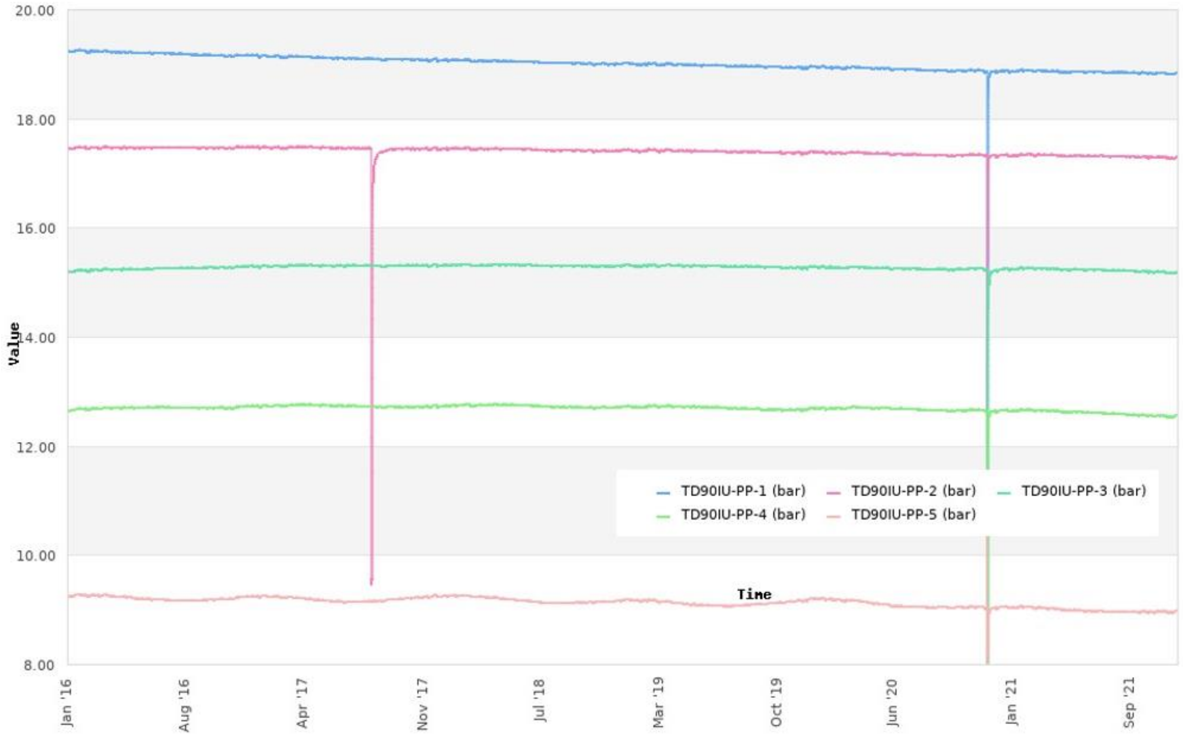


Figure 2.16 - Time-series graph of pore pressure data (measured in bars), in the five observation boreholes in the ATLAS experiment [15].

Graphs and data tables are manually created by users or accessible through database interfaces. The Geoscope web interface is used to visualise data in the ALC1605 demonstrator in real time. This interface includes time-series graphs and 2D visualisations of the sensor locations (Figure 2.17) [3].

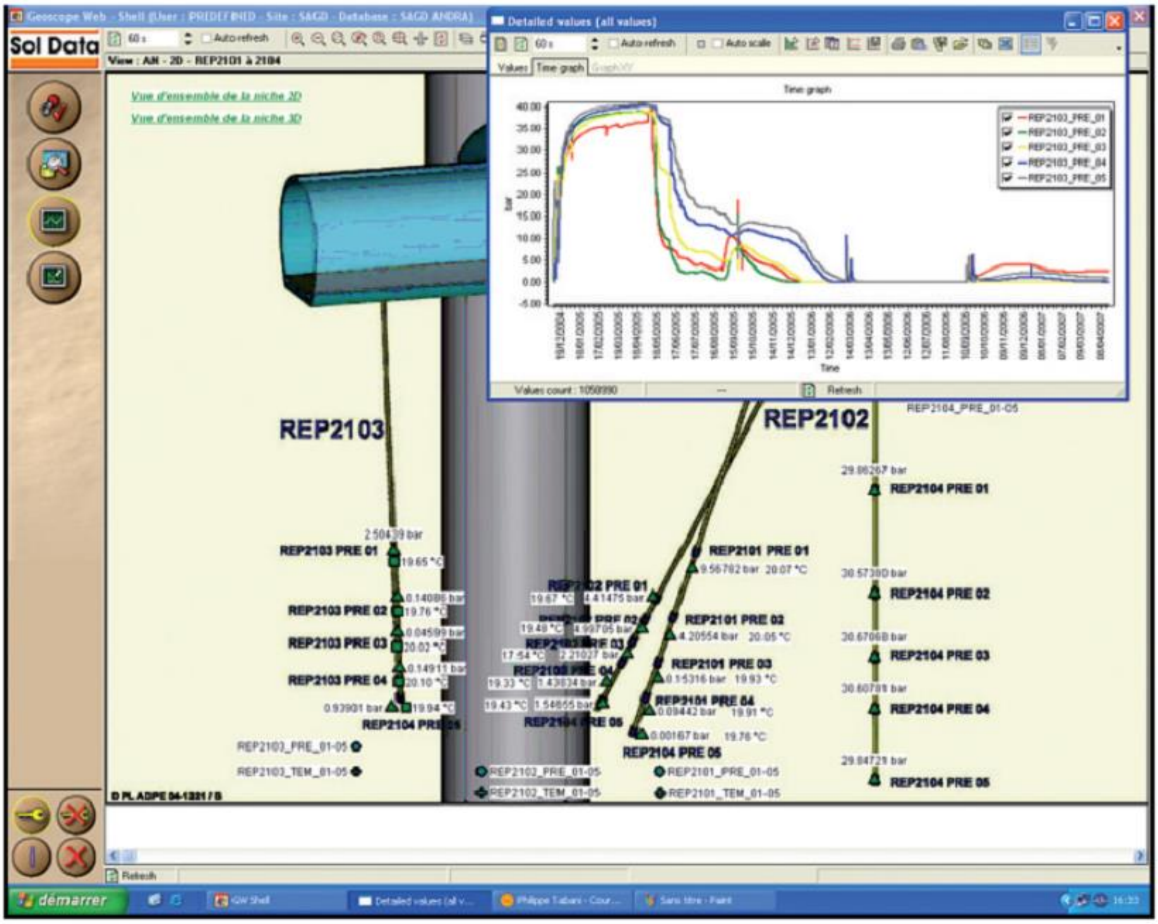
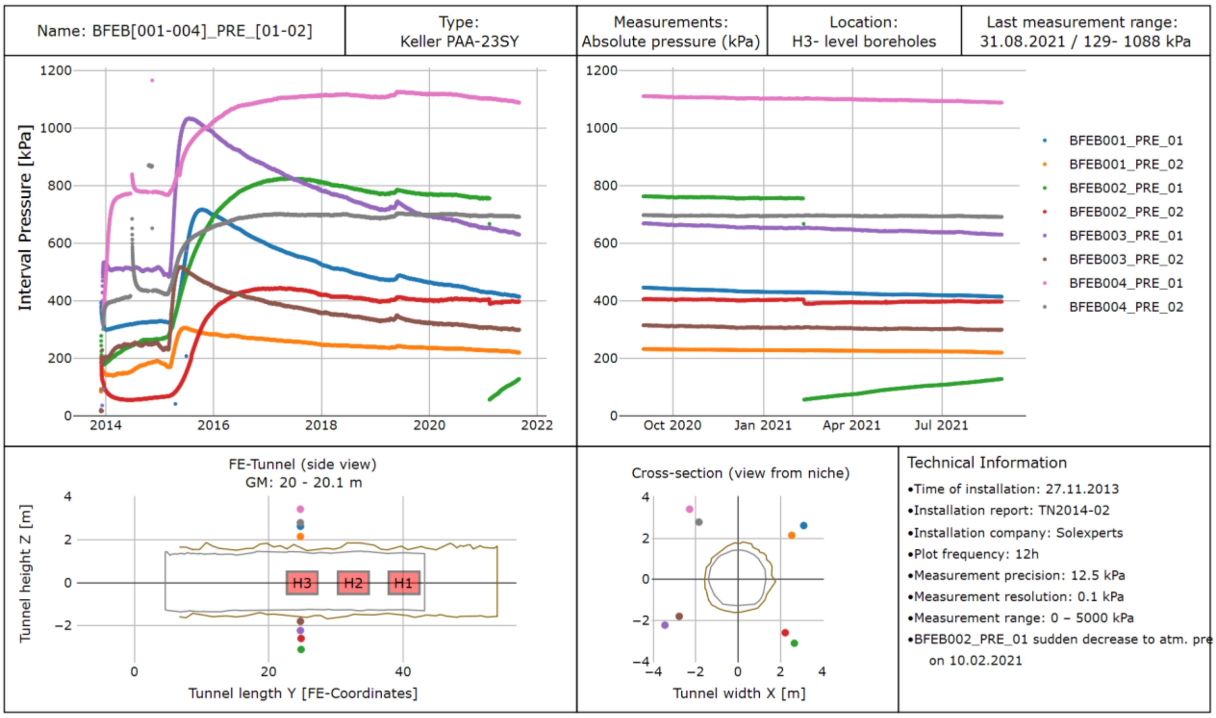


Figure 2.17 - Graph of pore pressure data over time at multiple locations, along with a visualisation of the sensor location, taken from the Geoscope web interface, used by Andra in the ALC1605 demonstrator [3].

A web-based interface is also used in the FEIS in the FE experiment [5]. This interface provides the user with near real time access to the data, which can be visualised in customisable graphs and data tables. For example, in the FEIS, graph scales can be modified, colours can be changed and labels can be added. Data tables can be arranged according to different parameters. The data are downloadable, specifically into data packages relating to given sensors; these packages incorporate time-series graphs, visualisations of the sensor locations (displayed on the coordinate graphs) and tabulated metadata, such as the measurement range, resolution and accuracy [50]. Figure 2.18 provides an example of a data package relating to pore pressure sensors. In the PRACLAY experiment, a custom interface and dashboard has been implemented. It provides functionality to automatically generate daily safety reports, and weekly and quarterly data reports [8].

In the CD-A experiment in the Mont Terri URL, a 3D representation of the Gallery 2018 has been created using laser scan data (Figure 2.19) [32, 51]. Sensor locations and geological data have been integrated into this representation, which is being used as a data visualisation tool. Similar to the other surveyed experiments, the data are displayed in time-series graphs; however they are also visualised in different formats. For example, convergence data have been colour coded according to their magnitude, paired with arrows corresponding to the convergence direction and positioned within the representation of the niches to interpret the convergence trends (Figure 2.20) [32].

The data visualisation approach employed in the CD-A experiment also aids the identification of outliers and errors (Section 2.3.2). For example, the visualisation of the dominant fault zones in the near field of the niches in the 3D model allows users to readily interrogate associated data and understand the hydraulic and mechanical processes that may explain outliers [32].



Name: BFEB[001-004]_PRE_[01-02]	Type: Keller PAA-23SY	Measurements: Absolute pressure (kPa)	Location: H3- level boreholes	Last measurement range: 31.08.2021 / 129- 1088 kPa

Technical Information

- •Time of installation: 27.11.2013
- •Installation report: TN2014-02
- •Installation company: Solexperts
- •Plot frequency: 12h
- •Measurement precision: 12.5 kPa
- •Measurement resolution: 0.1 kPa
- •Measurement range: 0 – 5000 kPa
- •BFEB002_PRE_01 sudden decrease to atm. pre on 10.02.2021

Figure 2.18 - Pore pressure data package from the FE experiment, showing pore pressure data measured boreholes in different locations surrounding heater 3 [50].

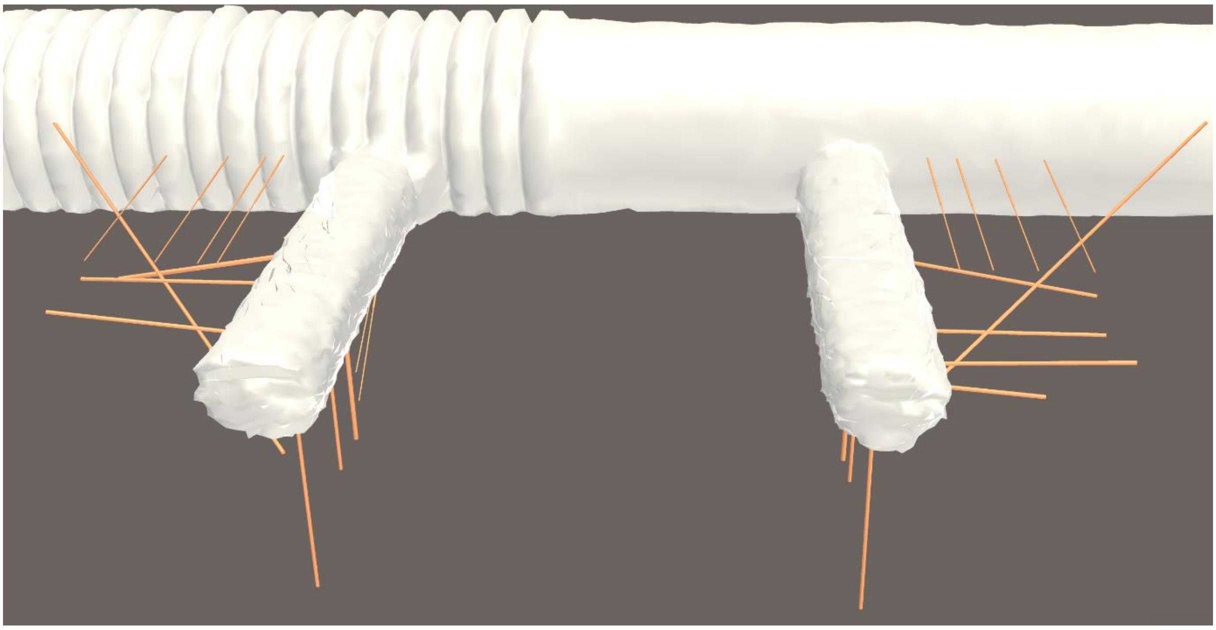


Figure 2.19 - 3D representation of Gallery 2018, which hosts the CD-A experiment, showing the gallery, niches and the location of the boreholes (in light orange) [51].

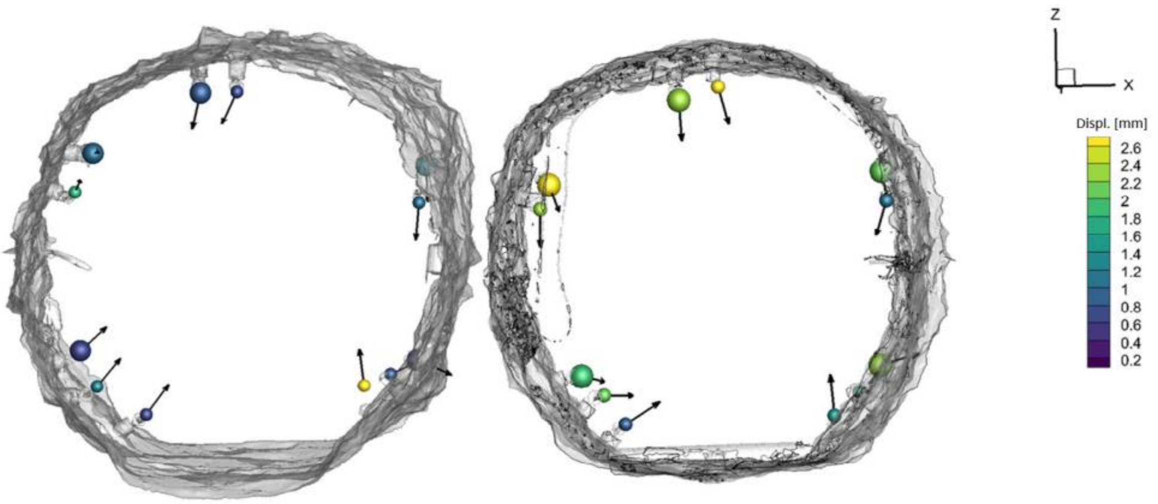


Figure 2.20 - 3D visualisation of convergence measurements (displacement) in the open (left) and closed (right) niches in the CD-A experiment [32]. Small spheres relate to data from convergence sensors anchored at a depth of 20 cm and laser scans, while the big spheres relate to data from convergence sensors anchored at a depth of 5 cm. The orientation of the arrows corresponds to the convergence direction.

2.4.2 Monitoring Data Use

The aims of experiments dictate the ways in which monitoring data are used.

One of the aims of Andra's ALC1605 demonstrator and ORS experiment is to test monitoring technologies in repository-like conditions (Sections 1.3.1.1 and 1.3.2.6). Andra is using monitoring data to inform the qualification of monitoring technologies for their implementation in the Cigéo facility. They have a four-step process to qualify technologies (Figure 2.21).

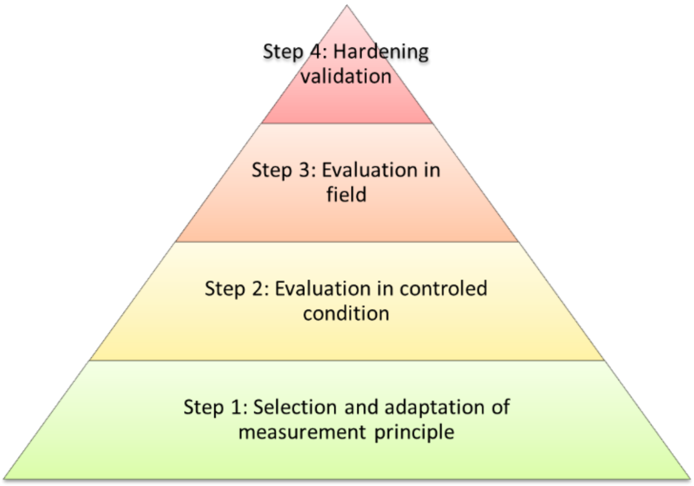


Figure 2.21 - Schematic diagram illustrating Andra's monitoring technology qualification process [3, 26].

The first step involves detailed desk-based research to select the most suitable technologies for monitoring in the geological repository (i.e. those technologies that are capable of fulfilling monitoring requirements in the repository). Steps 2, 3 and 4 encompass the testing of monitoring technologies in relevant conditions in the laboratory, in the field and in *in situ* conditions, respectively. Testing of technologies and their implementation procedures in the ALC1605 demonstrator and the ORS experiment provide data for the "hardening validation" of the THM monitoring technologies (i.e. step 4), such as Pt-1000 sensors, TDR probes, optical fibre strain and temperature distributed sensors, vibrating wire extensometer and pressure cells (Figure 2.21) [3, 26]. Even though the ALC1605 demonstrator and ORS experiment explicitly define the qualification of monitoring technologies as a key experimental aim, the experience and expertise developed from conducting URL experiments over the last 50 years can also be used for this purpose.

The majority of the surveyed URL experiments use monitoring data to further understand coupled processes. In the LASGIT experiment, monitoring data were used in a deterministic manner to inform discussions relating to safety assessments, specifically regarding high gas overpressures. In particular, the LASGIT experiment showed that high gas pressures were not generated in the bentonite buffer in the full-scale KBS-3V concept in *in situ* conditions [24].

Monitoring data have been used to attempt to validate the accuracy of coupled models by comparing monitoring data to modelling predictions. Resampling is the process of interpolating a dataset to adjust the sampling period. This process has not been required in the experiment monitoring datasets because the temporal and spatial resolutions of the THM models and the resulting modelling data are higher than the monitoring data.

In the ATLAS experiment, where the main aim was to understand THM behaviour in the Boom Clay under thermal load, models of the thermal evolution of the Boom Clay were created. These models had a higher spatial resolution than the monitoring data, and, therefore, modelling temperature data points have been directly compared to the monitoring data (Figure 2.22). These comparisons improved the confidence in the models, and provided a greater understanding of anisotropy in the Boom Clay, specifically relating to thermal conductivity and coupled HM process [15].

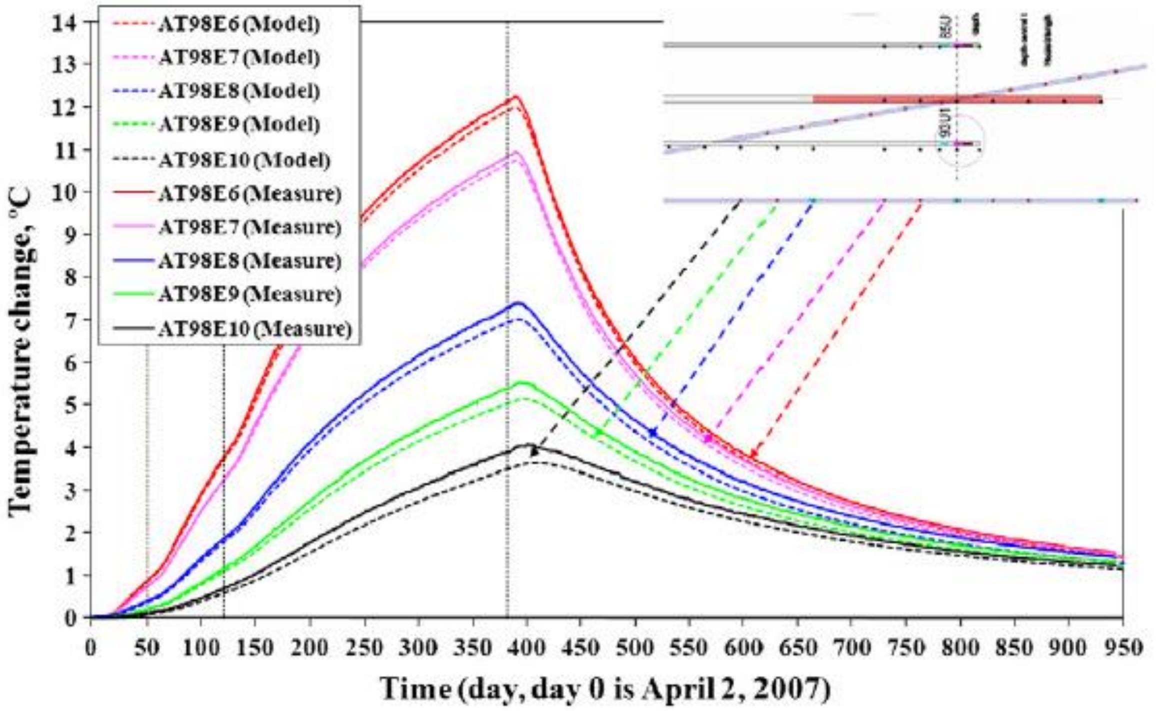


Figure 2.22 - Graph comparing monitoring and modelling temperature data in the AT98E observation borehole in the ATLAS experiment [15].

In the CLIPEX experiment, four blind pore pressure models were generated by different modelling teams using the excavation data. Similar to the ATLAS experiment, the spatial resolution of the models was greater than that of the monitoring data, therefore, the modelling and monitoring data could be readily compared by selecting modelling data at similar locations to the monitoring data. The comparisons of the different models with the monitoring data highlighted the main factors that influenced the model results; specifically, the size of mesh, the method used to integrate the constitutive law, the HM parameters and the initial boundary conditions. These comparisons provided understanding to optimise the development of future coupled models [19].

THM models were created as part of the Prototype Repository II experiment. The aims of the modelling work were to improve capabilities to predict THM processes in the backfill and buffer during saturation, and to further understand the THM processes in the rocks adjacent to the deposition holes [13 § 6]. Similar to other experiments, monitoring data were graphically compared to the modelling results to aid the fulfilment of these aims [11]. The THM model showed that the saturation of the buffer is sensitive to the hydraulic properties of the rock close to the deposition hole; however, uncertainty in the deposition hole inflow data meant that it was not possible to calibrate the model using the monitoring data and obtain predictions with a high accuracy [11]. Furthermore, modelling and monitoring temperature data were compared to understand thermal processes in the rock surrounding the deposition holes and to calibrate models. Figure 2.23 shows these comparisons.

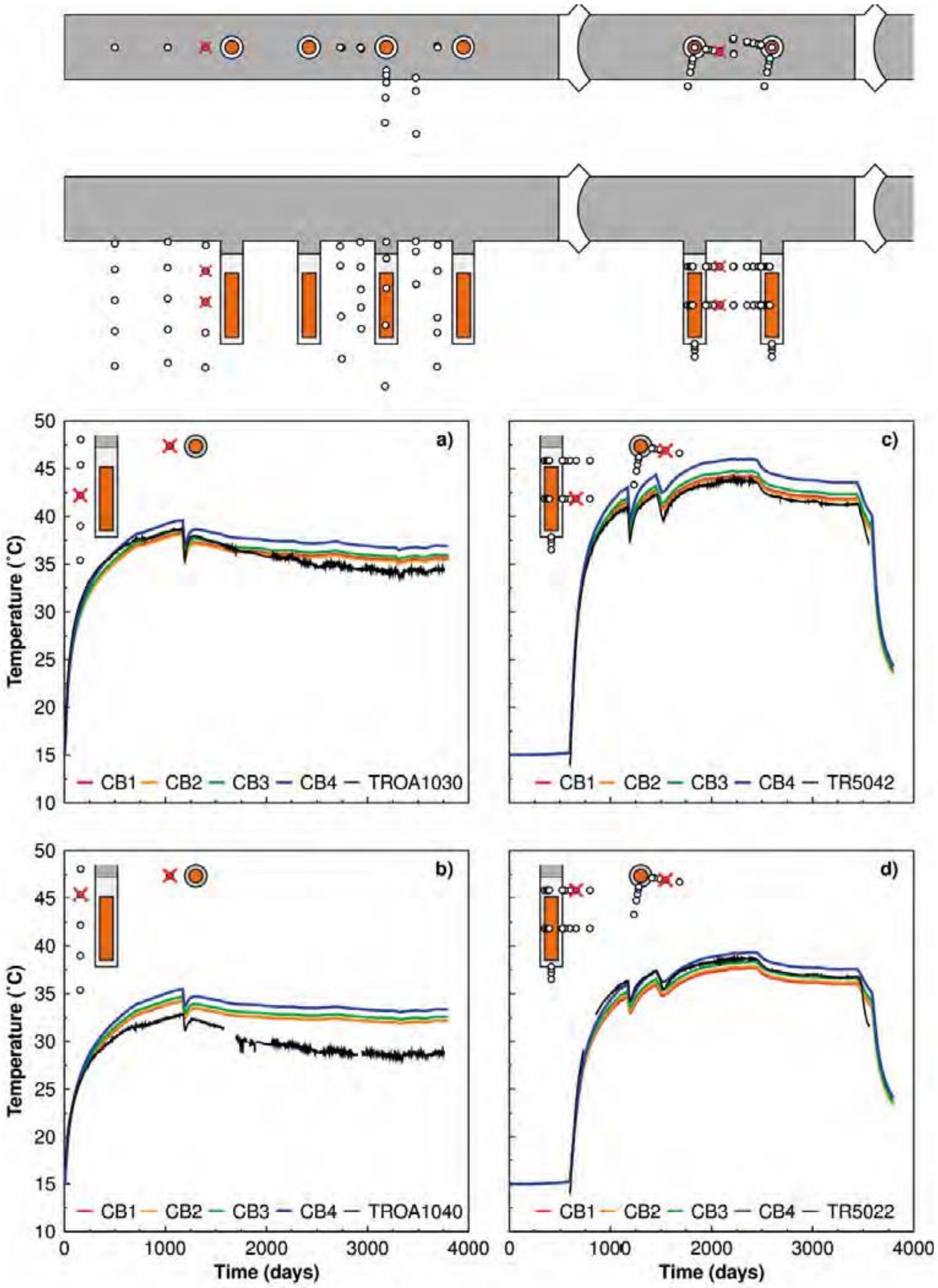


Figure 2.23 - Comparisons of monitoring data (black lines) and modelling temperature data (coloured lines) in Deposition Holes 1 (a and b) and 5 (c and d) in the Prototype Repository [13].

There is a good match between the modelled and monitoring data in Deposition Hole 5, which suggests that the thermal conductivities used in the models are representative of the *in situ* properties (Figure 2.23, graphs c and d); however, in Deposition Hole 1, the models overpredict the temperatures particularly after 1000 days (Figure 2.23, graphs a and b). These overpredictions are thought to relate to changes in drainage surrounding the deposition hole at this time that resulted in different water movements and changes to thermal conductivities in the rock [13 § 6.2.2]. The comparison of the modelling and monitoring temperature data were, therefore, used to further understand thermal processes and to build confidence in the models. Similar comparisons of mechanical modelling and monitoring data were not possible because the mechanical monitoring technologies did not provide sufficient reliable data [11].

In the FE experiment, monitoring data have been used to calibrate thermal models. Basic scoping calculations conducted in the design phase of the experiment suggested that the peak temperatures on the heater could vary considerably, depending on the thermal conductivity of the bentonite buffer, which is a function of the bentonite saturation [5].

The monitoring temperature data during the initial heating phase has been used in a prediction-evaluation study to calibrate the thermal properties of the heaters and the bentonite. This study demonstrated the impact of conceptual model uncertainty and scenario uncertainty on the evolution of temperature of the heaters and bentonite [5].

The thermal properties and ranges established for the heaters and bentonite have been combined with various uncertainties (e.g. parametric uncertainties, conceptual uncertainties, scenario uncertainties) and monitoring temperature data in near-field boreholes, to simulate the temperature in the near-field Opalinus Clay for the next 3 years. Uncertainty analysis has been undertaken to quantify the accuracy of the model predictions; it showed that the monitored temperature data are within the 95 % confidence interval of the predictions [5].

Monitoring data has, therefore, been used in the FE experiment to confirm the understanding of thermal processes and to aid the generation of numerical models that predict thermal evolution. Pore pressure monitoring data are similarly being used to build confidence in the understanding of pore pressure evolution; although this work is still in progress [5].

3. Lessons Learned for Repository Monitoring

Effective monitoring system designs and appropriate monitoring data acquisition, management and analysis procedures will provide confidence in monitoring data and the understanding it provides.

This section provides a discussion of the survey responses presented in the previous section to develop lessons for repository monitoring programmes that could enhance such confidence. These lessons relate to:

- Monitoring system designs (Section 3.1).
- Monitoring data acquisition (Section 3.2).
- Monitoring data management (Section 3.3).
- Monitoring data analysis and use (Section 3.4).

The lessons learned are highlighted in bold and summarised in Section 4.

3.1 Monitoring System Designs

3.1.1 Monitoring Parameter Selection

The aims of the experiments commonly dictate the parameters that were monitored. In the majority of experiments, temperature, pore pressure, total pressure and displacement were monitored (Table 2.2) to fulfil the aim of further understanding THM processes. For example, in the FE Experiment, key THM parameters were selected to calibrate and validate related models [5]. **Similarly, in repositories, the aims of the monitoring programme should dictate the parameters that will be monitored.**

In some experiments, parameter selection was informed by the availability of technologies with proven capabilities to accurately monitor a given parameter [e.g. 5]. **The selection of parameters is closely related to the selection of technologies.**

Based on the aims and information requirements, expert judgement has been used to select the monitoring parameters in most URL experiments. This selection process typically involved informal expert panel discussions. In some experiments, the resulting decisions have been recorded in internal memos or test plans. Andra have alternatively used a structured approach to select monitoring parameters in the AHC1605 and ORS experiments [3, 26]. This approach is based on a workflow adapted from the Modern2020 Screening Methodology.

The selection of monitoring parameters in repositories monitoring programmes are expected to be partly informed by regulations, which may require a formal structured approach to justify parameter selection. Therefore, **repository monitoring parameter selection is expected to follow a structured process**. **The Modern2020 Screening Methodology provides a structured process for parameter selection based on international consensus, which could be tailored to the needs of the specific repository monitoring programme**. **The resulting selection decisions should be justified and documented.**

3.1.2 Monitoring Technology Selection

A range of different technologies have been used in monitoring systems in URL experiments (Table 2.3), and considerable experience and knowledge of their use and capabilities has been acquired. Therefore, **a broad range of proven technologies are available for repository monitoring**.

In URL experiments, the experimental teams make the decisions regarding the selection of monitoring technologies, drawing on the knowledge and experience of technology providers. For example, in the ATLAS experiment, total pressure sensors were selected based on their compatibility with the instrumentation casing and also because they provided measurement redundancy. However, these aspects of the sensor were only possible because the technology supplier customised existing sensors. In repository monitoring programmes, **the selection of technologies is likely to involve close collaboration between technology providers and the monitoring team.**

Selection decisions in URL experiments have been based on performance requirements, defined by the experiment teams. These are requirements that the technology must be capable of fulfilling to be implemented in the experiment, and the identification of technologies that fulfil the requirements. A list of performance requirements is provided in Section 2.1.2. Scoping calculations are commonly used in the design of URL experiments to inform performance requirements, e.g. to gain a basic understanding of the evolution of relevant parameters. Similarly, **in repository monitoring programmes, the**

requirements on technology performance should be defined during the monitoring system design phase and be used to inform technology selection.

3.1.3 Monitoring System Layout

The layouts of monitoring systems in URL experiments are based on the design knowledge and practical installation experience of small-scale laboratory tests and previous URL experiments. They are also based on the existing THMCGR process understanding gained from small-scale laboratory tests, modelling and previous URL experiments. For example, the layout of the monitoring system in the VSEAL experiment was based on knowledge and experiment from a previous related experiment SEALEX, where the arrangement and location of sensors were tested [35]. **Repository monitoring system layouts are likely to be supported by knowledge of design and installation, and the processes occurring in the near-field gained, in part, from URL experiments**.

In the majority of experiments, monitoring technologies are geometrically arranged in cross-sections oriented perpendicular to parameter gradients (Section 2.1.3.2). For example, in the EPSP experiment technologies have been symmetrically arranged in cross-sections oriented perpendicular to fluid flow gradients across the plug (Figure 2.2). In other experiments, monitoring technologies are located in boreholes in the host rock, but similarly oriented perpendicular to parameter gradients (e.g. in the FE experiment; Figure 2.3). **In repositories, sensors should be arranged in cross-sections oriented perpendicular to parameter gradients**.

The density of sensors in monitoring systems in URL experiments varies considerably (Section 2.1.3.1). Some experiments implement high-density monitoring systems with considerable redundancy (e.g. FE Experiment [5] and PRACLAY [8]), while other experiments use lower density monitoring systems with less redundancy (e.g. Prototype Repository II [11]). The factors that influence decisions relating to the density of monitoring systems are discussed in detail in the next section. However, in general, they relate to information requirements. **In repository monitoring programme, sensors should be clustered in locations within cross-sections where they fulfil information requirements**. Owing to the different information requirements in URL experiments and repositories, as well as other design factors, such as the need to minimise the creation of artefacts, **monitoring systems in repositories are expected to use a lower density of sensors.**

3.1.4 Design Considerations

Monitoring system designs in the surveyed experiments considered a wide range of design factors, including (Section 2.1.3.3):

- Experimental and modelling data requirements (e.g. parameter boundary condition, temporal and spatial evolution of parameters, property anisotropy, measurement redundancy).
- Operational requirements, including the feasibility to install and operate the sensors and cables in the experiment materials, available space and experiment environmental conditions (e.g temperatures, pore pressures).
- Minimisation of the creation of artefacts relating to installed sensors and cables that could impact the processes being monitored.
- Operational safety.
- Resources (e.g. total cost and expertise for installation, maintenance and data acquisition).

For example, installation feasibility was a decisive factor in the design of the monitoring system in the PRACLAY experiment. Boreholes could only be drilled from the existing underground openings and those that were drilled had to avoid water-bearing strata, which would cause drilling failures. Owing to these installation constraints, the majority of monitoring boreholes surrounding the PRACLAY Gallery were drilled horizontally in the first experiment phase [8] (Section 2.1.3.3). Boreholes converge quickly after drilling in the Boom Clay in the HADES URL owing to the *in situ* conditions and rock properties [8, 19], therefore, the design of the monitoring systems in this geological environment must consider the ease and speed of sensor installation in the natural conditions.

Redundancy is often used in the monitoring system design in URL experiments to improve confidence in monitoring data because it can aid the identification of monitoring data errors. In particular, sensors that measure the same parameter using different principles are unlikely to be impacted by the same failure modes. **Greater confidence in repository monitoring data could be gained by using redundancy in the design, specifically in the number of sensors and types of technology for monitoring the same parameter**. However, artefacts could be created in redundancy-designed monitoring systems owing to the high number of sensors and associated cabling. These artefacts could influence the processes being monitored and affect the behaviour of the multi-barrier system. Therefore, the creation of artefacts also needs to be considered in monitoring system designs.

In the main, data management has not been considered in the design of the surveyed monitoring systems. However, repository monitoring systems will collect significant quantities of data over long periods of time and therefore, the impact of the monitoring system design on data management should be considered.

URL experiments that focus on understanding specific geological features and their evolution have not been surveyed in this research. An example of such an experiment is the Progressive Rock Mass Failure and Overbreak in Fault Zones (PF) experiment, in the Mont Terri URL, which characterises structurally controlled damage evolution in the faulted Opalinus Clay [52]. As a result, this report does not provide any learning about monitoring system designs associated with such geological features. However, it is important to recognise that geological features could impact the design of monitoring systems in repositories.

Data and operational requirements, artefact creation, operational safety, resources, data management and geological features should all be considered in the design of repository monitoring programmes.

Using these factors, heuristic approaches have often been used in the monitoring system design decision-making process in URL experiments, although some numerical approaches (e.g. modelling and data worth analyses) have also been used to aid decision making. Failure modes and effects analysis involves examining each component of a system to identify the potential failure modes and the effects of the failure modes on the operation of the system as a whole. This analysis could be used to identify the components of the monitoring system that could fail before the success of the monitoring programme will be impacted.

The processes by which design decisions will be made for repository monitoring systems should consider all design factors to provide an optimal design solution. Such processes are still under development and consideration by WMOs, although they are likely to include numerical approaches. Independent of the processes, **justification and documentation of design decisions are required for future understanding and knowledge management**.

3.1.5 Using Experience of Sensor Performance in Design

Monitoring data from URL experiments (e.g. Table 2.5), as well as information collected during the dismantling of completed experiments provide an understanding of sensor performance and failure mechanisms.

Monitoring systems in URL experiments have provided THM data for almost two decades (Section 2.1.4). For example, in the LASGIT experiment, 95 % of the installed sensors were still operating after 15.5 years [24], while in the FEBEX experiment, sensors were still providing THM data after 18 years [17]. In both of these examples, the monitoring systems were functioning beyond their design lifetimes.

Common sensor failure mechanisms are related to water ingress, heat, deformation and / or salt contamination / corrosion. A range of different examples of sensor failures are outlined in Section 2.1.4. For example, in the FEBEX experiment, some sensors were positioned in the joints between bentonite blocks, owing to the ease of installation in this location. These zones experienced significant mechanical deformation during bentonite swelling, which led to sensor damage and failures [17]. **Failure mechanisms of sensors are well understood and the learning from URL experiments can be used to mitigate the risk of sensor failure in repositories**.

3.2 Monitoring Data Acquisition

Monitoring data acquisition relates to the methods used to ensure monitoring data are effectively obtained. This includes general QA / QC procedures, as well specific procedures associated with monitoring system installation, such as calibration and other testing.

3.2.1 QA / QC

Contractors leading the monitoring system installation in URL experiments have used their own quality management systems. For example, the contractor used in the GAST experiment used its own quality assurance system. Such systems are documented in internal documents, which outline overarching quality concepts, specific internal and external processes and responsibilities [28].

Additionally, quality management systems have been implemented by experiment teams, particularly to manage quality-related documentation. For example, in the PRACLAY experiment, a quality management process is used to maintain an inventory of the monitoring system equipment [8].

In repository monitoring programmes, quality management systems will be implemented to ensure, as much as possible, the quality and effectiveness of the installed monitoring systems and, therefore, confidence in the acquired monitoring data. These systems will include the generation and management of a variety of quality-related documentation.

QA / QC approaches in URL experiments provide some learning. However, different systems, processes and documentation have been used in the experiments. Furthermore, the QA / QC approaches in repository monitoring need to consider the long monitoring timescales and the inaccessibility and hence inability to maintain some sensors in repository monitoring systems. **Standardised QA / QC approaches tailored to repository monitoring would be beneficial to demonstrate consistent good practices and to build further confidence in the monitoring data**.

3.2.2 Monitoring System Installation

Technical drawings and 3D models of the monitoring systems have been developed prior to their installation in experiments. For example, in the FE experiment, a 3D model of the FE Tunnel was created showing the locations of boreholes and the positions of sensors within these boreholes. This model was used to aid the drilling of boreholes and the installation of sensors (Section 2.2.2) [5]. **Detailed technical drawings or 3D models of the monitoring systems should be developed to support the monitoring system installation in the repository**.

Following the installation of monitoring systems in URL experiments, the precise location of sensors and other components were documented in as-built surveys (Section 2.2.2). The as-built surveys used laser and optical techniques to measure local coordinates relative to the experiment and URL and, in some experiments, national coordinates. This information has been recorded in quality-related documentation (e.g. in instrumentation emplacement QA sheets in GAST; Figure 2.10 [28]) and has been used as metadata to aid data visualisation and analysis (Sections 2.3.1 and 2.4). **In the repository**, **the location of installed sensors should be measured and stored as metadata to aid data visualisation and analysis**.

Some experiments have implemented systematic sensor naming conventions that include the sensor type and location information. In the HotBENT experiment, sensors were named according to the sensor type and its relative position relative to the HotBENT cavern. For example, TP_5000_090_114 refers to a total pressure sensor, which is positioned 5000 cm from the gallery entrance, at an angle of 90 ° from the top of the cavern and 114 cm from the centre of the cavern [33] (Section 2.2.2). **Good practice for sensor naming conventions is to include the sensor type and location in the name**.

Depending of the parameter and the monitoring location, the timing of sensor installation relative to start of monitoring varies in URL experiments. In some instances, monitoring begins directly following installation of the monitoring system, while in others, the onset of monitoring can be significantly later owing to technical or operational reasons. For example, in the Boom Clay, six to nine months are generally required after the installation of piezometers in boreholes to obtain porewater pressure values that are representative of the environment prior to borehole drilling [8]. Furthermore, monitoring in the PRACLAY Gallery could not begin until the gallery seal installation work was complete because the cabling associated with sensors in the gallery was disturbed by the seal installation work (Section 2.2.2) [8]. **In repository monitoring programmes, considerable periods may exist between monitoring system installation and the start of repository monitoring**. **The management of these periods should be detailed in operational plans**.

3.2.3 Calibration and Other Testing

In general, calibration involves the comparison of a sensor measurement value to a known reference value. It is used to ensure the accuracy of sensor signals (Section 2.2.2.1). In the surveyed experiments, sensors have been calibrated in the factory or laboratory by the manufacturer. They have not been calibrated *in situ* following installation.

Manufacturers use a range of different procedures to calibrate sensors. In some instances, calibration involves the comparison of one measurement value to a known value, while in others it can involve multiple measurements across a wide range of values and at different temperatures.

Typically, experiment teams have not been involved or inputted into the calibration of sensors. The only exception is in the FE experiment, where the experiment team stipulated that temperature sensors should be calibrated across the complete range of expected temperatures in the experiment [5].

Calibration certificates document the calibration procedures and the results (i.e. accuracy of the sensor signal). In the majority of experiments, calibration certificates have been issued for all sensors and are stored as part of the quality management system.

Additionally, functionality tests have been undertaken on sensors, cables and DASs once they have been installed in some experiments (e.g. VSEAL [35], HotBENT [33], GAST [28]). In the GAST experiment, the functionality of the data acquisition system was tested after its installation, including under elevated temperatures and pressures. The results of these functionality tests were recorded in QA documentation [28].

In repository monitoring programmes, **rigorous and standardised approaches to monitoring system calibration and testing are required to build confidence in monitoring data**. These approaches must include clear documentation of all calibration and testing procedures and the associated results.

To account for measurement drift, accessible sensors are regularly recalibrated after installation. For example, in the PRACLAY experiment, pore pressure sensors installed in the instrumentation casing within boreholes are regularly accessed to perform recalibration [8]. **Accessible sensors should be recalibrated through the lifecycle of the repository monitoring programme**.

Recalibration of inaccessible sensors is, in the main, not possible following installation. The only exception is optical fibre distributed temperature sensors, which are regularly recalibrated using temperature baths in the FE and HotBENT experiments (Figure 2.11). Such *in situ* recalibration systems could impact the behaviour of the multi-barrier system. ***In situ* recalibration systems could be used to recalibrate inaccessible sensors in the repository**. However, it must be demonstrated that they can be implemented and operated without unacceptably impacting the behaviour of the multi-barrier system. Additionally or alternatively, it may be possible to install “control” sensors in environments where conditions are similar to that of the repository. These control sensors can be recalibrated at suitable intervals, and be used as a benchmark for the performance of inaccessible sensors in the repository.

In the surveyed experiments that have been completed and dismantled, inaccessible sensors have been removed and analysed in laboratory. Data from these analyses, along with the monitoring data, have been integrated to understand the performance of the monitoring systems, specifically, to quantify measurement drift. For example, in the Prototype Repository II, during the dismantling of Section 2 (Figure 1.4), total pressure sensors were carefully removed from the buffer and backfill. Their functionality and performance were tested in the laboratory. The results of these analyses showed that minimal operational deviations had occurred and that all the total pressure sensors had provided reliable data [11]. **Testing of sensors after dismantling of experiments has modified data, but has not changed the fundamental understanding of THM processes**. Coupled with the learning on the operational longevity of sensors in URL experiments (Section 3.1.5), this suggests that **in repository-like conditions, monitoring systems are capable of providing accurate and reliable THM data for in excess of two decades**.

3.3 Monitoring Data Management

3.3.1 Monitoring Data Storage

In long-running experiments that operated through multiple phases with different monitoring technologies and different experimental teams, significant quantities of data were collected and stored in a range of formats and in different databases. Organising these data into standardised formats and in centralised and harmonised databases for future use, proved to be a time-consuming and difficult task.

Repository monitoring programmes will collect significant quantities of data over long periods. These data will be acquired from different sensors in different locations and in a range of different formats. **Effective data management plans should be developed during the design of repository**

monitoring systems to ensure data are traceable and readily accessible for use as required in the future.

In the experiments, monitoring data are stored in databases that range from simple Excel spreadsheets to large, bespoke databases, such as the FEIS or SAGD (Section 2.3.1). These databases can automatically apply conversion formulae to convert the raw data to the parameter of interest. Typically, they store the raw data, as well as the parameter data and the associated metadata (e.g. conversion formulae). They also store a range of other metadata, including information relating to the sensors (e.g. types, models and locations) and information associated with experimental, man-made and natural events (Section 2.3.1).

In the SAGD database, which is used to store data from the ALC1605 demonstrator, monitoring data are hierarchically organised according to relevant metadata, such as the process that is being monitored, the demonstrator component it is monitored in, the sensor type and its location (e.g. coordinates) (Figure 2.14).

In repository monitoring programmes, **raw monitoring data should be stored, alongside metadata**, for the purposes of knowledge management and data traceability. Data should be appropriately organised to ensure they can be accessed and analysed, as needed. **Good practice for monitoring data storage is to structure and organise databases around different aspects of the monitoring system, e.g. the process and / or component being monitored**.

3.3.2 Monitoring Data Treatment

Once acquired, experimental monitoring data have undergone data treatment to ensure data quality (Section 2.3.2). This has involved:

- Data format checks.
- Data cleansing, i.e. identifying and removing invalid data.
- Identifying and addressing outliers.
- Interpolating data gaps, as required.

In the majority of experiments, manual graphical data treatment methods have been used, particularly to identify erroneous data and outliers. For example, erroneous data and outliers were visually identified in the Prototype Repository II experiment by plotting the monitoring data on graphs and using expert judgement [47].

Data redundancy through monitoring system design has been used to aid the identification of errors and outliers. In the CD-A experiment, a comparison of displacement values from different types of sensors revealed outlier data, which do not fit with the general displacement trends [32].

Information related to experimental and natural events, as well as man-made events associated with the construction and operation of the experiments, which are key metadata (Section 2.3.1), can be used to aid the identification of outliers.

Some automated data treatment processes are used in some experiments (Section 2.3.1). Alarm systems are incorporated into some monitoring databases to automatically alert users to potentially invalid data when it is transferred into the database. For example, the FEIS employs an algorithm to compare monitoring parameters with the expected parameter ranges to identify errors and outliers [5]. It is also possible to compare monitoring parameters to related parameters, and check that the relationship between the two parameters is consistent with the expected relationship. The FEIS also uses an algorithm to identify gaps in the imported data [5]. Furthermore, Andra and IRSN are developing and testing automated data treatment tools to perform data cleansing, to identify outliers and to interpolate data gaps [48, 49]. Further developments will be needed to implement these algorithms and tools into repository monitoring databases.

Data cleansing processes should be used to ensure, as much as possible, data quality. Considering the large amounts of data that are expected to be collected during repository monitoring (Section 2.3), **automated data cleansing processes would be beneficial in repository monitoring databases**.

3.4 Monitoring Data Analysis and Use

3.4.1 Monitoring Data Visualisation and Analysis

Monitoring data are summarised in data tables and visualised in simple time-series graphs in the surveyed experiments (Section 2.4.1). These graphs commonly plot a given parameter in a specific location, often with a basic visualisation of the location (e.g. Figure 2.17 and Figure 2.18). **Repository monitoring data are expected to be visualised and analysed using graphical approaches.**

Some databases used in the experiments provide functionality to interactively plot and visualise monitoring data in space and time (e.g. FEIS and SAGD). This functionality can be provided in web-based interfaces with near real time or real time monitoring data [3, 5]. Visualisations in space and time provide general context that allow data to be easily interrogated and interpreted. **In repository monitoring programmes, databases should include functionality to interactively visualise monitoring parameter data in space and time**. Experimental monitoring databases also provide the functionality to generate data reports over different periods of time (e.g. in PRACLAY [8]). **Repository monitoring databases should be capable of generating data reports, as required**.

Building information modelling (BIM) data and geological modelling data have been used to create a 3D representation of the Mont Terri URL (Figure 2.19) [32]. Monitoring data and relevant metadata have been integrated into this representation to provide a data visualisation tool in the CD-A experiment. This tool is capable of displaying monitoring data in time-series graphs, but it can also integrate a variety of different metadata to create 2D and 3D visualisations of monitoring data in a given location (e.g. Figure 2.20 [32]). **Metadata should be used to aid repository monitoring data visualisation and analysis**.

Such visualisations could be used as tools to aid the interpretation of monitoring data to build understanding for multiple purposes depending on stakeholder needs, including:

- To identify monitoring data errors and outliers.
- To fulfil the aims of the repository monitoring programme.
- To communicate understanding to civil society.

3.4.2 Monitoring Data Use

In the surveyed experiments, monitoring data have been used to understand THMCGR processes (Section 2.4.2). In particular, monitoring data have been analysed to build understanding for the purposes of informing safety arguments for repository safety cases. They have been compared to THM modelling data at the same temporal scales and in the same locations, using simple graphical methods (e.g. Figure 2.22 and Figure 2.23), to aid the understanding of processes. For example, in the Prototype Repository II, monitoring data were used to understand the THM processes in the rocks adjacent to the deposition holes [11]. Monitoring data have also been summarised into representative statistics and used to calibrate input parameters to build further confidence in THM models. In the FE experiment, for example, temperature data have been used to calibrate thermal models [5].

Additionally, monitoring data have been used to understand monitoring system performance in repository-like conditions. In particular, Andra is using the monitoring data from the ALC1605 to inform the qualification of monitoring technologies for their implementation in the Cigéo facility (Section 2.4.2).

Repository monitoring programmes will have different aims to experimental monitoring programmes and the methods that will be used to analyse monitoring data will be different. Repository monitoring data are likely to be used to aid decision making, as well as in optimisation and engagement. These topics have not been addressed in the URL experiment survey and therefore, no lessons relating to monitoring data use in repositories have been identified.

4. Conclusions and Gaps

In repository monitoring programmes, monitoring data will be used to aid decision making and to build further confidence in the safety case. Significant quantities of data will be acquired, managed and analysed for these purposes.

This section outlines the lessons learned from URL experiments relating to the designs of monitoring systems and the acquisition, management, analysis and use of monitoring data for repository monitoring. These lessons are discussed in detail in the previous section, where they are linked to information from the URL survey. This section also highlights specific gaps in understanding relating to these aspects of the monitoring.

4.1 Monitoring System Design

Lessons learned for the design of repository monitoring systems identified from the survey relate to the selection of monitoring parameters and technologies, system layouts, design considerations and system performance.

Monitoring Parameter Selection

- The aims of the repository monitoring programme should dictate the parameters that will be monitored.
- The selection of parameters is closely related to the selection of technologies.
- The selection of monitoring parameters should follow a structured process and the resulting decisions should be justified and documented.
- The Modern2020 screening methodology provides a structured process for parameter selection based on international consensus, which could be tailored to the needs of the specific repository monitoring programme.

Monitoring Technology Selection

- A broad range of technologies are available for repository monitoring, with considerable experience and knowledge of their use and capabilities.
- The selection of technologies is likely to involve close collaboration between technology providers and the monitoring team.
- Detailed requirements on technology performance should be defined during the monitoring system design phase and be used to inform technology selection.

Monitoring System Layout

- Repository monitoring system layouts are likely to be supported by knowledge of design and installation, and the processes occurring in the near-field gained, in part, from URL experiments.
- Sensors should be arranged in cross-sections oriented perpendicular to parameter gradients.
- Sensors should be clustered in locations within cross-sections where they fulfil information requirements.
- Repository monitoring systems are expected to use a lower density of sensors compared to URL experiments.

Design Considerations

- Greater confidence in repository monitoring data could be gained by using redundancy in the design, specifically in the number of sensors and types of technology for monitoring the same parameter.
- Repository monitoring system designs should consider several factors, such as data requirements, installation and operational feasibility, creation of artefacts, operational safety, cost, data management and geological features.
- There needs to be justification and documentation of design decisions for future understanding and knowledge management.
- Failure mechanisms of sensors are well understood and the learning from URL experiments can be used to mitigate the risk of sensor failures in repositories.

Monitoring System Performance

- Monitoring systems are capable of providing accurate and reliable THM data for in excess of two decades, in specific environments.

4.2 Monitoring Data Acquisition

Data acquisition lessons for repository monitoring are associated with the QA / QC of monitoring systems, particularly in relation to installation, calibration and other testing.

QA / QC

- Standardised QA / QC approaches tailored to repository monitoring would be beneficial to demonstrate consistent good practices and to build further confidence in the monitoring data.

Installation

- Detailed technical drawings or 3D models of the monitoring systems should be developed to support the installation of monitoring systems in repositories.
- Installed sensor locations should be measured and stored as metadata to aid data visualisation and analysis.
- Good practice for sensor naming conventions is to include the sensor type and location in the name.
- Considerable periods may exist between monitoring system installation and the start of repository monitoring. The management of these periods should be detailed in operational plans.

Calibration and Other Testing

- Rigorous and standardised approaches to monitoring system calibration and testing should be used to build confidence in monitoring data.
- Accessible sensors should be recalibrated through the lifecycle of the repository monitoring programmes.
- *In situ* recalibration systems could be used to recalibrate inaccessible sensors.
  - However, it must be demonstrated that they can be implemented and operated without unacceptably impacting the behaviour of the multi-barrier system.
- Testing of sensors after dismantling of experiments has modified data, but has not changed the fundamental understanding of THM processes.

Further research is required to evaluate QA / QC approaches and to provide guidance documentation outlining the best QA / QC practices. Research in MODATS Task 2 will aim to address this collective gap in understanding (D17.4: Guidance on Quality Assurance Project Plans (QAPPs)).

4.3 Monitoring Data Management

The survey provides lessons relating data storage and treatment for repository monitoring programmes.

Monitoring Data Storage

- Effective data management plans should be developed during the design of repository monitoring systems to ensure data are traceable and readily accessible for use as required in the future.
- Raw monitoring data should be stored, alongside metadata.
- Good practice for monitoring data storage is to structure and organise databases around different aspects of the monitoring system, e.g. the process being monitored, the component the process is being monitored in.

Monitoring Data Treatment

- Data cleansing processes should be used to ensure, as much as possible, data quality, including the removal of null values and obvious errors.
- Repository monitoring would benefit from automated data cleansing processes, owing to the large amounts of data that are expected to be collected over the lifetime of the programme.

Research and development is required to advance repository monitoring data management methods. In particular, further research is needed to develop semi-automated and automated data cleansing tools. Planned data management research in MODATS Task 2 aims to partly address this collective gap in understanding.

4.4 Monitoring Data Analysis and Use

The survey provides monitoring data visualisation and analysis lessons for repository monitoring programmes. However, it does not provide insight into the ways monitoring data will be used in repositories because the aims of repository monitoring are expected to be different to aims of experimental monitoring.

Monitoring Data Visualisation and Analysis

- Repository monitoring data are expected to be visualised and analysed using graphical approaches.
- Databases should include functionality to interactively visualise monitoring parameter data in space and time. They should also include functionality to automatically generate monitoring data reports, as required.
- Metadata should be used to aid graphical data visualisation and analysis.

Use of Monitoring Data in Repository Programmes

Repository monitoring data are likely to be used to aid decision making, as well as in optimisation and engagement, but these topics have not been addressed in the URL experiment survey.

In URL experiments, monitoring data have been used to calibrate and build further confidence in numerical models, specifically thermal models. Further work is required to use monitoring data to further confidence hydraulic and mechanical models, as well as coupled process models, owing to the complexity of these processes in the multi-barrier system. Research on modelling procedures, as well as the approaches to integrate monitoring data into process models is planned in the MODATS WP.

Additionally, it is necessary to define the modelling approaches that will be used in repositories. It is also necessary to understand the monitoring data that will be required (i.e. information and data requirements), and the methods by which it will be used in these models. It is possible that digital representations of components of the multi-barrier could be built, i.e. digital twins, but it is unclear how monitoring data will be integrated and used in these systems. Ongoing research in the MODATS WP addresses the integration of monitoring and modelling data and the development of digital twins.

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References

1. M. Jobmann. Case Study Report. MoDeRn Deliverable D-4.1, 2013.
2. T. Haines and M. White. Survey of URL Experiments: Workshop Minutes. MODATS Task 2, 13 January 2022.
3. J. Bertrand. ALC1605 URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
4. R. Farhoud, F. Martinot and J. Bertrand. Development of HA monitoring plan. Modern 2020, Work Package 4, Deliverable 4.2. 2019.
5. T. Vogt. FE Experiment URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
6. H. Müller, H. Weber, S. Köhler, T. Vogt and T. Vietor. The full-scale Emplacement (FE) Experiment at the Mont Terri URL. Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, 5th International Conference, Montpellier, France, 2012.
7. E. Holt and P. Koho. DOPAS 4.5: POPLU Experimental Summary Report. Deliverable No. 4.5, 2016.
8. J. Verstricht. PRACLAY URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2022.
9. EIG EURIDICE. GIE. PRACLAY Experiment. www.euridice.be, 2022.
10. Ph. Van Marcke, X.L. Li, W. Bastiaens, J. Verstricht, G. Chen, J. Leysen and J. Rypens. The design and installation of the PRACLAY In-Situ Experiment. EURIDICE Report 13-129, 2013.
11. M. Morosini and R. Geza. Prototype Repository II URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
12. A. Ledesma and G. Chen. T-H-M Modelling of the Prototype Experiment at Äspö HRL (Sweden). In Elsevier Geo-Engineering Book Series, Edited by O. Stephanson. Volume 2, Pages 377-382, 2004.
13. C. Svemar, L.-E. Johannesson, P. Grahm, D. Svensson, O. Kristensson, M. Lönnqvist and U. Nilsson. Prototype Repository Opening and retrieval of outer section of Prototype Repository at Äspö Hard Rock Laboratory: Summary report. SKB Technical Report, TR-13-22, 2016.
14. L.-E. Johannesson, D. Gunnarsson, T. Sandén, L. Börgesson and R. Karlzén. Prototype Repository Installation of buffer, canisters, backfill, plug and instruments in Section ll. SKB International Progress Report, IPR-04-13, 2004.
15. J. Verstricht. ATLAS URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
16. ESV Euridice GIE. ATLAS Test Summary. www.euridice.be, 2017.
17. J.-L. García-Siñeriz. FEBEX URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
18. M. V. Villar, R. J. Iglesias and J.-L. García-Siñeriz. State of the in situ Febex test (GTS, Switzerland) after 18 years: a heterogeneous bentonite barrier. Environmental Geotechnics. Volume 7, Issue 2, Pages 147-159, 2020.
19. J. Verstricht. CLIPEX URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
20. F. Bernier, X. L. Li, J. Verstricht, J. D. Barnichon, V. Labiouse, W. Bastiaens, J. M. Palut, J. K. Ben Slimane, M. Ghoreychi, J. Gaombalet and F. Huertas. CLIPEX: Clay instrumentation programme for the extension of an underground research laboratory. Final Report, EUR, 20619, 2003.
21. ESV Euridice GIE. CLIPEX Overview. www.euridice.be, 2022.

22. J.-L. García-Siñeriz. EB URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
23. B. Palacios, M. Rey, J.-L. García-Siñeriz, M. V. Villar, J. C. Mayor and M. Velasco. Engineered Barrier Emplacement Experiment in Opalinus Clay: "EB" Experiment, As-Built of Dismantling Operation. Long-term Performance of Engineered Barrier Systems (PEBS), Deliverable 2.1-4, 2013.
24. R. J. Cuss and P. Sellin. LASGIT URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
25. R. J. Cuss, J. F. Harrington, D. J. Noy and C. C. Graham. Final Report of FORGE WP3.1.1: The large scale gas injection test (Lasgit) performed at the Äspö Hard Rock Laboratory. British Geological Survey Commissioned Report CR/12/141. Pages 31, 2012.
26. J. Bertrand. ORS URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
27. R. Farhoud, J. Bertrand, S. Buschaert, S. Delepine-Lesoille and G. Hermand. Full scale in situ monitoring section test in the Andra's Underground Research Laboratory. Technical Innovation in Nuclear Civil Engineering (TINCE), Paris, France, 2013.
28. A. Reinicke. GAST URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
29. Grimsel Test Site. The GAST Experiment. www.grimsel.com, 2021.
30. J. Svoboda. EPSP URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
31. G. Ziefle, P. Bossart, S. Costabel, O. Czaikowski, M. Furche, B. Graupner, J. Hesser, J., D. Jaeggi, K. Jantschik, O. Kolditz, F. Königer, H. Kunz, J. Maßmann, C. Nicaty, D. Rebscher, K. Rink, R. Schuhmann and K. Wieczorek. Mont Terri Project. CD-A Experiment: Installation report. Technical Report 2020-41, 2021.
32. G. Ziefle, T. Cajuhi, N. Graebling, D. Jaeggi, O. Kolditz, H. Kunz, J. Maßmann and K. Rink. Multi-disciplinary investigation of the hydraulic-mechanically driven convergence behavior: CD-A twin niches in the Mont Terri Rock Laboratory during the first year. Geomechanics for Energy and the Environment, 2022.
33. E. Manukyan. HotBENT URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
34. Grimsel Test Site. The HotBENT Experiment. www.grimsel.com, 2021.
35. J.-M. Matray. VSEAL URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
36. A. M. Alcantara, N. Mokni, E. Romero and S. Olivella. Modelling of oedometer tests on pellet-powder bentonite mixtures to support mock-up test analysis. E3S Web of Conferences, 195, 04004, 2020.
37. V. Montoya. DR-C URL Survey Response. EURAD Work Package 17: MODATS. Final Version, 2021.
38. J. Svoboda, R. Vašíček, J. Smutek, J. Šťástka, D. Nádherná, D. Pacovská, M. Dvorakova, I. Hanusova and L. Belickova. DOPAS 3.2: EPSP plug test installation report. Deliverable No. 3.2, 2016.
39. M. White and S. Scourfield. Modern2020 Project Synthesis Repository Monitoring: Strategies, Technologies and Implementation. Work Package 6, Deliverable No D6.5, 2019.
40. J. Farrow, M. White, S. Scourfield, A. Chabiron, M. Jobmann, R. Gazul, B. Frieg, J. Hart, E. Rosca-Bocancea, T. Schröder, A. Wildenborg, T. Karvonen, T. Pere, J. Hansen, H. Reijonen, M. Morosini, D. Luterkort and A. Vokal. Modern2020 Monitoring Parameter Screening: Test Cases. Work Package 2, Deliverable No D2.2, 2019.

41. L. Börgesson and T. Sandén. Äspö Hard Rock Laboratory: Prototype Repository Instrumentation of buffer and backfill in Section II. SKB International Progress Report, IPR-03-21, 2003.

42. F. Huertas, J. L. Fuentes-Cantillana, F. Jullien, R Rivas, J. Linares, P. Farina, M. Ghoreychi, N. Jockwer, W. Kickmaier, M. A. Martinez, J. Samper, E. Alonso and R. J. Elorza. Full-scale engineered barriers experiment for a deep geological repository for high-level radioactive waste in crystalline host rock (FEBEX project). Euratom, Nuclear Science and Technology Project Report, EUR 19147, 2000.

43. Grimsel Test Site. The FEBEX-DP Experiment. www.grimsel.com, 2021.

44. B. Firat Lüthi, A. Reinicke and B. Frieg. Overview of installed sensors of the Full-Scale Emplacement Experiment (FE) at Mt. Terri Rock Laboratory. Nagra Project Report, NPB 21-02, 2021.

45. M. Schoenball. Data Management in Global Seismology. MODATS Task 2, Workshop 2, February 2022.

46. B. Firat Lüthi. FE Experiment: Data Trend Report: Data from excavation and during 6 years of heating (01.01.2012 – 31.08.2021), Nagra Work Report, NAB 21-031, 2021.

47. M. Morosini and R. Goudarzi. Prototype Repository II Experiment: Datasets, Selection and Workflow. MODATS Task 2, Workshop 2, February 2022.

48. J. Cotton. ALC1605: Towards a Digital Twin, Data Overview and Processing Examples. MODATS Task 2, Workshop 2, February 2022.

49. D. Bailly, J.-M. Matray and R. Ababou. Statistical analyses of meteorological, crack aperture and water content time series measured at the Tournemire Underground Research Laboratory: The MuStat algorithm: Tools, methods and applications. IRSN, 2012.

50. B. Firat Lüthi, H. Müller, T. Vogt and A. Reinicke. Full-scale emplacement Experiment. MODATS Task 2, Workshop 2, February 2022.

51. N. Graebling. Mont Terri URL: Digital Twin of the CD-A Experiment. MODATS Task 2, Workshop 2, February 2022.

52. M. Ziegler, Q. Lei, C. Zhao, O. Moradian, A. Obermann, M. Furche, T. Beilecke and S. Loew. Mont Terri PF Experiment: Progressive Failure of Structurally Controlled Overbreaks, Status update 2021. Swiss Federal Nuclear Safety Inspectorate, Research and Experience Report, 2021.

Appendix A. URL Survey

MODATS Task 2.1 URL Survey **Lessons for Repository Monitoring Design and the Implications for Safety Case Development**	
Organisation	
Name of the Experiment	
Name of Person Completing the Survey	
Role of Person Completing the Survey in the Experiment	
Date of Completion	
Version	
Experiment and Programme Context	

Question C.1: Please provide an overview of the experiment.

Where is/has the experiment been undertaken?

Please provide a brief summary of the geological environment in which the experiment is being/was undertaken, including details relevant to experiment, such as hydrogeological details in a sealing experiment.

What organisations are/were involved in the experiment?

What is the WMO programme status? Is the disposal programme in the generic, site-specific or implementation phase?

What is/was the experiment schedule? (e.g., the key phases, such as installation, operation, decommissioning, and their dates)

What are/were the objectives and scope of the experiment?

If the objectives are/were to test a specific disposal concept, or component of the disposal concept, please briefly summarise the disposal concept and/or the relevant components. Please state the waste types the disposal concept is designed for.

Question C.2: Please describe the experiment design.

Please describe the engineered components used in the experiment, their construction materials and the experiment dimensions. Diagrams of the experiment design would be useful, if available.

Did/does the experiment test safety functions, if so, please describe the safety functions.

What safety case requirements, if any, were placed on the engineered structures?

MODATS Task 2.1 URL Survey

Lessons for Repository Monitoring Design and the Implications for Safety Case Development

1. Monitoring Parameters

Question 1.1: What processes and parameters are/were monitored in the experiment?

Please include the measurement units of the selected parameters.

Question 1.2: Please describe the processes by which the parameters were selected and incorporated into the monitoring programme of the experiment.

Please describe any structured processes used to select the parameters? (i.e., a formalised evaluation of the relevance of the proposed parameters to the safety case)

How were decisions regarding monitoring parameter selection documented?

Was a monitoring plan developed that identified the parameters to be monitored and outlined the intended use of the resulting monitoring data?

How do the selected parameters relate to the objectives of the experiment?

Were the selected parameters related to safety functions associated with multi-barrier components in the experiment?

Were numerical modelling data used to support the selection of monitoring parameters?

Were any processes monitored using different approaches? (e.g., in situ monitoring using sensors and remote monitoring using geophysical techniques)

Were there any parameters considered that were not selected? If so, why were they not selected?

MODATS Task 2.1 URL Survey

Lessons for Repository Monitoring Design and the Implications for Safety Case Development

2. Monitoring Technologies

Question 2.1: What monitoring technologies and sensors are/were used in the experiment?

Please describe the monitoring technologies used and the parameters provided by those technologies.

Do/did the technologies and/or sensors measure the selected parameters named in Question 1.1 or does/did the basic measurement need to be converted to the selected parameters using known mathematical relationships?

What uncertainties are associated with such conversions?

Question 2.2: What processes were used to select monitoring technologies and sensors?

Who selected the monitoring techniques and sensors? For example, the experiment lead, the experiment team, other internal customers, such as a modelling group or a safety case group, or contractors responsible for monitoring.

If they were proposed by contractors, what oversights or inputs into selection did the experiment lead/team or other internal customers have?

What were the performance requirements for the selection of the sensors? (e.g., measurement range, accuracy or resolution)

Were numerical modelling data used to support the selection of the monitoring technologies and sensors? For example, did numerical modelling results quantify the expected parameter ranges?

Did the selection process include consideration of monitoring sensor performance, particularly with respect to the environmental conditions of the experiment? If so, how were they considered?

Did the selection process include consideration of monitoring sensor longevity and cable protection, particularly with respect to the environmental conditions of the experiment? If so, how were they considered?

Were the technologies and sensors used to monitor a selected parameter all the same type, or were different types of technologies and sensors used for the same parameter (e.g., redundancy or different ranges)? Why were single or multiple monitoring sensor/probe types selected?

3. Design of the Monitoring Sensor System (sensor and associated cables)

Question 3.1: How many monitoring sensors/probes are/were used to monitor the selected parameters in the experiment?

Quote numbers relative to a volume, e.g., 2 per m^3.

Explain why this number of sensors/probes was selected.

Did the selected sensors/probes provide measurement redundancy? If so, how many sensors/probes provided measurement redundancy?

Question 3.2: What are/were the geometrical arrangements of the monitoring sensors/probes in the experiment?

Explain why this geometrical arrangement of sensors/probes was selected.

For example, were monitoring cross-sections used and, if so, how were these defined?

Question 3.3: How were the monitoring sensors/probes installed?

MODATS Task 2.1 URL Survey **Lessons for Repository Monitoring Design and the Implications for Safety Case Development**
Please describe the practical implementation of the placing/installation of the sensors. *How was the spatial location of the sensors recorded? Was a local reference coordinate system used? If so, how was it realised in practice?* *Was an as-build survey conducted to verify the sensor position/location?*
Question 3.4: What was the process used to select the number and location of the monitoring sensors/probes? *Were numerical modelling data used to support the decision on the layout of the monitoring sensors?* *Were data management considerations factored into the decision on the number of monitoring sensors/probes? Data management considerations include the number of data points, their storage, analysis and visualisation.* *Was monitoring redundancy in-built into the sensor/probe arrangement? If so, were the same or different monitoring sensors/probes used for the purposes of redundancy?* *How was it confirmed that the in-built redundancy related to meaningful differences in the parameter, rather than differences associated the location of the sensor/probe?*
Question 3.5: How did the design of monitoring sensor system account for the practicalities of its installation? *Please describe the practical constraints for implementing the monitoring sensor system.* *Did monitoring sensor/probe cable routing influence the decisions on the number and locations of sensors/probes?* *How did the monitoring sensor/probe installation impact experiment activities?*

MODATS Task 2.1 URL Survey

Lessons for Repository Monitoring Design and the Implications for Safety Case Development

4. Lifecycle Quality Assurance and Quality Control

Question 4.1: Please provide the definition, scope and objective of 1) quality assurance and 2) quality control with respect to the installation, operation and decommissioning of the monitoring sensor system.

Outline the difference between quality assurance and quality control with respect to monitoring systems.

Question 4.2: What are/were the quality assurance and quality control arrangements for the experiment?

Was a Quality Plan or an equivalent document developed. If so, please provide, if available.

Who is/was responsible for quality assurance and quality control?

Please describe how the environmental conditions and parameter values of the experiment were determined at the start of the monitoring period.

Please explain how sensor/probe calibration was performed.

Was the calibration procedure performed on all monitoring sensors/probes, or a selected few? Please explain the calibration strategy.

Did the same monitoring sensors/probes require different calibrations depending on their location and the associated environment conditions (e.g., sensors located in zones with varying water saturation).

How is/was the monitoring data quality assured during the experiment operation?

Is/was there a data error detection method?

Question 4.3: Please describe any problems that were encountered during the installation of monitoring sensors/probes.

Did installation take longer than expected/planned?

Did the monitoring method fail during installation? If so, why?

> The monitoring method is defined as the application of a technique for a specific measurement in a specific environment, including all hardware components necessary to convert sensor signals to (digital) data (wiring, connectors, converters) [1].

Quantify the survival rate of sensors/probes (e.g., after the installation, after 1 year of the experiment and after 5 years of the experiment)?

Question 4.4: What was learnt about the monitoring method performance during operations and decommissioning?

Was the monitoring method successful throughout the entire experiment, or did it fail? Please outline which sensors/probes were operational throughout the experiment lifecycle and which sensors/probes/components failed. For example, did a particular sensor/probe type fail or did sensors/probes in a given location fail.

> The monitoring method is defined as the application of a technique for a specific measurement in a specific environment, including all hardware components necessary to convert sensor signals to (digital) data (wiring, connectors, converters) [1].

If the monitoring method failed, for what reasons did it fail?

What factors influenced the sensor/probe performance?

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Did the sensors/probes interact with the host medium and fluids it contains? For example, did the sensors/probes corrode? *Did the sensors/probes or associated cables modify the properties of the experimental materials? If so, how?* *Did the operation of monitoring sensors/probes have an impact on the results of the experiment? For example, did cables provide water flow pathways or did sensors reduce the density of bentonite?*
5. Data Management and Interpretation
Question 5.1: Please describe the data acquisition system. *Where is the monitoring data stored? For example, in a datalogger or via transmission to a PC.* *How much data is stored in terms of the number of data points and the monitoring period?*
Question 5.2: Please describe the data management system, including the database. *Please provide your definition of metadata.* *What metadata were collected as part of the experimental monitoring?* *What are the strengths and weaknesses of the database?* *Are/were monitoring data accessible in real or near real time?* *How is data visualised?*
Question 5.3: What processes are/were used to treat the data? *Who is responsible/owns the data treatment process?* *Are/were algorithms applied to the stored data to correct for noise, errors and anomalies? If so, please detail how these algorithms operated.*

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Question 5.4: How are/were the monitoring data compared to numerical models?

How are/were modelling data interpolated from point values to 3D/4D parameter distributions?

Are/were the temporal and spatial resolutions of the monitoring data the same as the numerical models? If not, how were the monitoring data up-scaled and what was the confidence in the up-scaling?

Question 5.5: How are/were monitoring data used to update numerical models of the processes investigated in the experiment?

How were monitoring data selected for comparison to the modelling data?

Were all of the monitoring data used in revising the understanding of the processes being monitored? Or in practice, were the data from only a few sensors used?

Did the monitoring data change or confirm the understanding of processes occurring in the experiment? Did they change or confirm the fundamental understanding of the processes, or did they refine the mathematical relationships underpinning the numerical models? For example, the revision of co-efficients.

Was confidence in the understanding of processes occurring in the experiment increased through the acquisition and interpretation of monitoring data? If such confidence was increased, how was the confidence increased and could such confidence be applied wider than the experiment?

6. Lessons Learned

Question 6.1: Please summarise any significant lessons that you have learned in this experiment concerning monitoring data acquisition, treatment, management and analysis and how they can be used to ensure confidence in repository monitoring.

References

1. Jobmann, M. Case Studies: Final Report, MoDeRn EC Deliverable D-4.1, 2013.

Appendix B. Organisations Involved in the URL Experiments

AITEMIN:	Asociación para Investigación y el Desarrollo Industrial de los Recursos Naturales, Spain.
Andra:	Agence Nationale pour la Gestion des Déchets Radioactifs, France.
ASC:	Applied Seismology Consulting, United Kingdom.
BASE:	Federal Office for the Safety of Nuclear Waste Management, Germany.
BGE:	Bundesgesellschaft für Endlagerung, Germany.
BGR:	Federal Institute for Geosciences and Natural Resources, Germany.
BGS:	British Geological Survey, UK.
BMWi:	Bundesministerium für Wirtschaft und Klimaschutz, Germany.
DBE Technology:	DBE Technology GmbH, Germany
CIEMAT:	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, Spain.
CIMNE:	Centre Internacional de Métodes Numèrics en Enginyeria, Spain.
CSIC-Zaidin:	Estación Experimental del Zaidín, Consejo Superior de Investigaciones Científicas, Spain.
CTU:	Czech Technical University, Czech Republic.
ENSI:	Swiss Federal Nuclear Safety Inspectorate, Switzerland.
Euridice:	European Underground Research Infrastructure for Disposal of nuclear waste in a Clay Environment, Belgium.
Enresa:	Empresa Nacional de Residuos Radiactivos, Spain.
FANC:	Federal Agency for Nuclear Control, Belgium.
Forschungszentrum Jülich, Germany.	
GEOCONTROL:	GEOCONTROL S.A., Spain.
G.3S:	École Polytechnique, France.
GRS:	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany.
IRSN:	Institut de Radioprotection et de Sûreté Nucléaire, France.
KAERI:	Korea Atomic Energy Research Institute, South Korea.
KIT:	Karlsruhe Institute of Technology, Germany.
KORAD:	Korea Radioactive Waste Agency, South Korea.
Nagra:	National Cooperative for the Disposal of Radioactive Waste, Switzerland.
NUMO:	Nuclear Waste Management Organisation, Japan.
NWMO:	Nuclear Waste Management Organisation, Canada.
Obayashi Corporation, Japan.	
ONDRAF/NIRAS:	Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies, Belgium.
Posiva:	Posiva Oy, Finland.
RWM:	Radioactive Waste Management, United Kingdom.
SCK CEN:	Belgium Nuclear Research Centre, Belgium.
SKB:	Swedish Nuclear Fuel and Waste Management Company, Sweden.
SÚRAO:	Správa Úložišť Radioaktivních Oodpadů, Czech Republic.
Swisstopo:	Federal Office of Topography, Switzerland.
UFZ:	Helmholtz Centre for Environmental Research, Germany.
US DoE LBNL:	U.S. Department of Energy / Lawrence Berkeley National Laboratory, USA.
ÚJV Řež, Czech Republic.	
ULC:	Universidad de La Coruña, Spain.
UPM:	Universidad Politécnica de Madrid, Spain.

Table B.1 - List of the organisations involved in the experiments that are included in this report. Full organisation names are listed above.

Experiment	Organisations
ATLAS	Euridice, SCK CEN and ONDRAF/NIRAS.
FEBEX	Enresa, Nagra, CIEMAT, AITEMIN, CIMNE, ULC, CSIC-Zaidin, UPM, Andra, G.3S, GRS, BGR, KAERI, Obayashi, ONDRAF/NIRAS, RWM, Posiva, SKB, SÚRAO and US DoE LBNL.
CLIPEX	Euridice, Andra, Enresa, G.3S, GEOCONTROL, UPM and ONDRAF/NIRAS.
EB	Enresa, BGR, Nagra, AITEMIN and CIMNE.
Prototype Repository II	SKB, Posiva, RWM, Andra, NUMO, BMWi, NWMO, Nagra, GRS and ASC.
LASGIT	SKB, BGS, Posiva, Andra, BGR, RWM and NWMO.
ORS	Andra.
GAST	Nagra, Andra, NWMO, KORAD.
FE Experiment	Nagra, Andra, US DoE LBNL, NWMO, GRS, FANC and BGR.
PRACLAY Heater Test	Euridice, NIRAS/ONDRAF and SCK CEN.
EPSP	CTU, SÚRAO and ÚJV Řež.
POPLU	Posiva, SKB, VTT and DBE Technology.
CD-A	BGE, BGR, ENSI, GRS, UFZ and Swisstopo.
HotBENT	Nagra, RWM, NUMO, NWMO, SÚRAO, US DoE LBNL, BGE, BGR, Enresa and Obayashi.
VSEAL	IRSN.
ALC1605	Andra.

Experiment	**Organisations**
DR-C	FANC, UFZ, KIT, Andra, ENSI, BASE and Forschungszentrum Jülich.