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Work Package 6

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RE	Restricted to a group specified by the partners of the Modern2020 project	
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Reviewed by:

This report has been reviewed according to the Modern2020 Quality Plan and the Deliverables Review Procedure therein. Review has been undertaken by Johan Bertrand (Andra), Bernd Frieg (Nagra), Johanna Hansen (Posiva), and Assen Simeonov and Mansueto Morosini (SKB) during a review meeting held at Andra's offices in Paris on 26 June 2019. The version 2 has bee obtained after the review by F. Plas (Andra).

Approved by:

This report has been approved by Johan Bertrand, Modern2020 Project Co-ordinator, 09/09/2019

Preface

This report has been prepared by the editors (Matt White and Sally Scourfield, Galson Sciences Limited) using inputs from project partners and through involvement in aspects of the work over the course of the project. All project partners have been given the opportunity to review, comment and contribute to the report, and the views of work package and task leaders have taken precedence in final editing.

Executive Summary

The European Commission (EC) Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project was initiated to further develop the capability to implement repository monitoring during the operational phase to support the post-closure safety case. It aimed to provide the means for developing and implementing an effective and efficient repository monitoring programme, taking into account the requirements of specific waste management programmes. The main focus of the work was monitoring of the engineered barrier system (EBS) and near-field rock during the operational period to support decision making and to build further confidence in the post-closure safety case.

Activities sought to achieve these aims by:

- Developing strategies for selecting and maintaining a list of monitoring parameters and for responding to monitoring results that are applicable to different repository concepts and national contexts.
- Conducting research and development (R&D) on monitoring technologies with the aim of making them suitable for repository monitoring purposes.
- Conducting *in situ* demonstrations of the implementation of repository monitoring.
- Developing methods for engaging with local citizen stakeholders to gain a broader understanding of their views, and to find ways of enabling them to engage earlier with the development of monitoring strategies and technology research, development and demonstration (RD&D).

This document is the synthesis of the Modern2020 Project. The objective of the synthesis is to summarise the work conducted, to present the key messages and results, and to provide signposts to underpinning reports that describe the results in more detail.

Strategies and parameters

A generic iterative workflow for developing and undertaking a repository monitoring programme had been developed in the preceding EC Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) Project. However, it was recognised that monitoring during the operational phase to build further confidence in the post-closure safety case required greater consideration of, and integration of the repository monitoring programme in, the safety case programme of work; such monitoring should be regarded as an integral part of a the post-closure safety case. Analysis of the post-closure safety case can provide a set of possible processes to monitor based on, for example:

- Evaluation of safety functions.
- Evaluation of features, events and processes (FEPs).
- Evaluation of safety assessment parameters.
- Evaluation of thermal, hydraulic, mechanical and chemical (THMC) processes.

However, any list of processes has to be assessed for technical feasibility, to ensure that monitoring the processes would provide value to ongoing operations, and to ensure that the overall monitoring programme was sufficient and appropriate given the operational limitations.

Therefore, in the Modern2020 Project, a method for selecting monitoring parameters was developed, based on consideration of the post-closure safety case and on information gathered from test cases focusing on seven specific programmes. This methodology, the Modern2020 Screening Methodology, is a generic process for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. It provides an overview of the steps that a waste management organisation may take in identifying and managing a list of parameters, linked to processes, and repository monitoring strategies and technologies. The application of a preliminary version in the seven test cases resulted in a revised Methodology and identified how it can be implemented in specific waste management programmes.

The Modern2020 Project also developed a set of recommendations and guidance on planning for evaluating and responding to monitoring results. Most significantly, the work recognised that responding to monitoring results must be flexible in order to respond to unexpected repository evolutions, and, therefore, specific actions and response plans cannot be defined ahead of the acquisition of monitoring data. Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the entire dataset. A set of generic responses that could be invoked in response to monitoring results has been identified in the Project. The strategic developments in the Modern2020 Project have been incorporated in a new version of the generic iterative workflow, which is referred to as the Modern2020 Monitoring Workflow (Figure E.1).

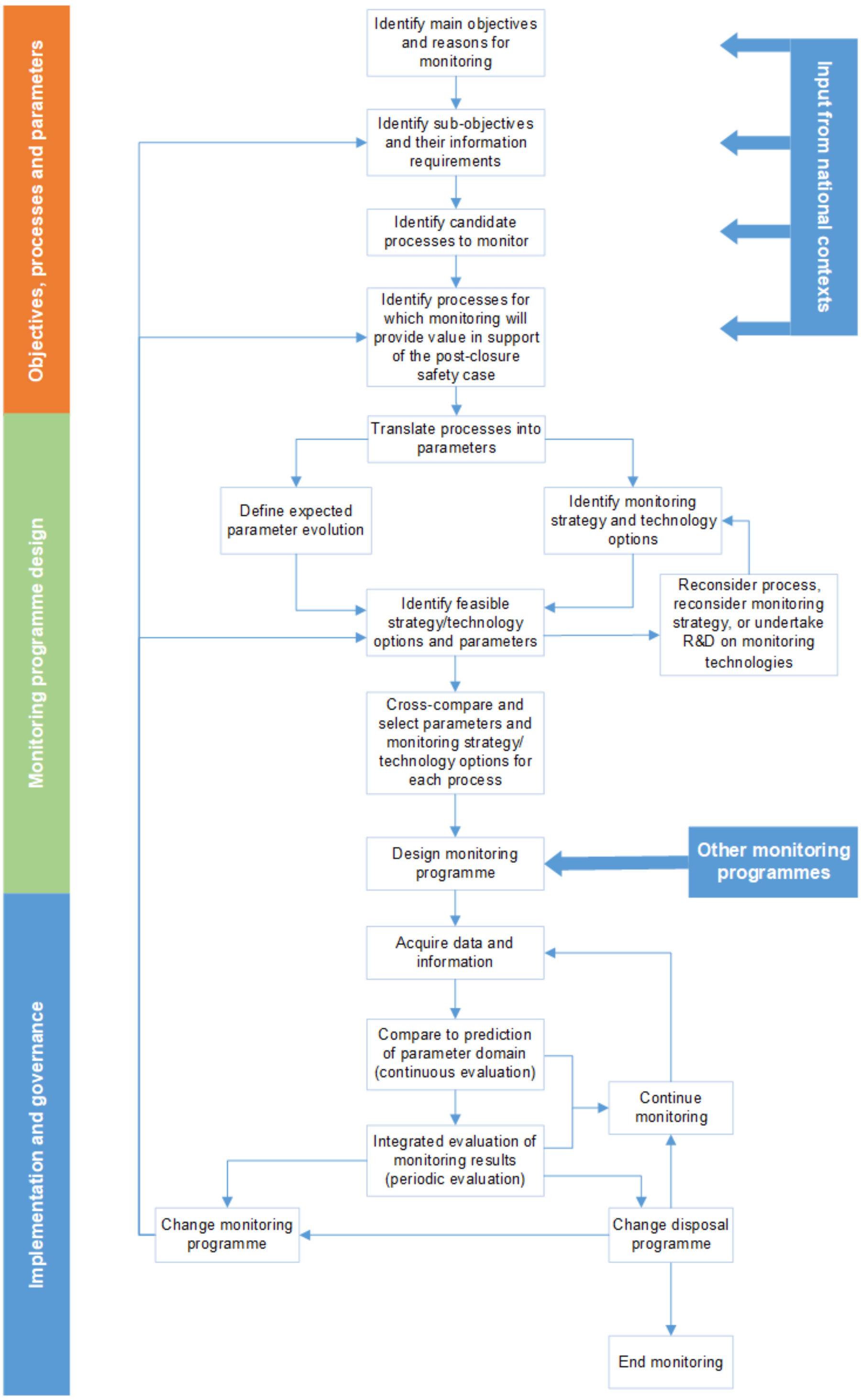

Figure E.1: The Modern2020 Monitoring Workflow.

Monitoring technologies

Monitoring the evolution of the EBS and near-field rock during the operational period requires sensors that can operate reliably in a potentially harsh environment, over long periods (many decades), and with the appropriate accuracy and precision. In the Modern2020 Project, technology R&D, driven by the needs of different repository programmes, focused on development of monitoring technologies to provide a toolbox of solutions that can be utilised whilst respecting the passive safety of the repository:

- **Wireless Data Transmission:** Significant advances were made in understanding, designing and demonstrating solutions allowing wireless data transmission through components of the EBS and geological barrier. Different technological solutions covering transmission distances between 0.5 m and 275 m have been developed and tested under realistic conditions. Versatile solutions for short-range wireless data transmission were developed based on medium-frequency and low-frequency systems. For data transmission over long ranges, the wireless transmission of data through 275 m of rock using a single-stage very-low-frequency system was demonstrated, and a method using multi-stage relay devices was also developed. Technical integration of short-range wireless solutions with sensors or long-range wireless solutions has also been devised and shown to be feasible for a range of settings. Sufficient understanding was gained to allow their deployment after additional engineering and site-specific testing, which requires limited additional efforts to bring them into practical industrial use.

- **Long-Term Power Supply:** The current state-of-the-art in battery lifetime is insufficient for repository monitoring without replacement of the batteries. Therefore, alternative solutions for providing power were investigated, with the main driver being the ambition to use wireless data transmission systems in some monitoring programmes. Alternative solutions include *in situ* power generation (use of thermoelectric generators, i.e. generation of electric power from the transfer of heat away from waste packages, or radioisotope sources), and wireless transmission of energy through EBS components or the host rock to wireless sensor units. Energy-sourcing technologies were concluded to be a relevant and a feasible means of powering repository monitoring systems. Interim energy storage solutions are required in combination with the studied alternative power solutions and their performance is critical with respect to their application in repository monitoring. A review of the options concluded that there are technical approaches which are sufficient for the purposes of repository monitoring. Continued research to further develop and verify the energy sourcing technologies and integrate them into a realistic monitoring system is still required.

- **Optical Fibre Sensors (OFS):** Several new sensors and measurement systems based on OFS technology were developed. Sensors were developed which could be used to monitor water content, water chemistry, pH and irradiation. Optoelectric sensing chains were developed to provide distributed measurements of strain and temperature. A distributed OFS solution for measuring thermal conductivity, density and water content in the EBS was developed using heatable fibre-optic cables. Advancement was also made on the development of fibre-optic pressure cells for boreholes. Further work is mainly required to ensure these technologies can withstand repository conditions.

- **New Sensors:** Other new sensors have been developed for monitoring water chemistry using ion-selective electrodes, relative humidity using the dew point method, and temperature, pressure and relative humidity in a single integrated sensor. These sensors require testing in conditions similar to those expected in a repository. In addition, preliminary research into monitoring displacement using short-range non-contact methods has been undertaken.

- **Geophysical Techniques:** A range of geophysical techniques were improved for specific repository environments. Seismic full waveform inversion algorithms were improved by extending the inversion algorithms to include a model of density and, thereby, to account for anisotropy in the seismic velocity of the rock, and an automatic anomaly detection algorithm was developed. Differential tomography algorithms were established which allow consistent and precise identification of differential changes of physical parameters. Electrical resistivity and induced polarisation tomography algorithms were tested and shown to be a suitable method of monitoring changes in temperature and moisture content. Further research in these areas is required to validate the methods and algorithms.

- **Monitoring System Qualification Methodology:** A multi-stage qualification methodology was developed that is applicable to all components of a repository monitoring system. The methodology includes four steps: selection of components; laboratory tests; mock-up tests (this step is optional); and on-site tests. The methodology needs to be applied systematically in order to ascertain its validity and to make improvements, if required.

In summary, the technological work of the Modern2020 Project has made substantial advances in developing new, or adapting existing, technologies such that their readiness for use in a repository monitoring context has been raised. Fundamental research into new methods of measurement of relevance to repository monitoring needs has also been conducted with success. However, further research is required to fully bring these technologies into practical use in an industrial setting. In particular, this requires specifications for monitoring sensors to be developed based on strategic planning for monitoring programmes and on preliminary design of monitoring systems. Methods of assessing the impact of monitoring sensors on post-closure performance will need to be developed and applied in order to demonstrate that monitoring of the EBS and near-field can be undertaken without significantly affecting post-closure safety.

In situ demonstrations

Within the Modern2020 Project, four *in situ* monitoring demonstrations were performed, one in a crystalline rock setting and three in clay rock settings. These demonstrations provided the opportunity to test multiple components of monitoring systems or strategies in a realistic setting, collect information about how sensors and other monitoring equipment withstand repository conditions (including monitoring equipment developed in the Modern2020 Project), and allow practical aspects of implementing monitoring to be assessed. In addition, these demonstrators provided a platform for application of some of the methods and workflows developed in the strategic work undertaken in the Modern2020 Project.

The *in situ* demonstrations undertaken were:

- The development of an EBS monitoring plan for ONKALO® [1] in Finland was carried out as a desk-based study. The work aimed to demonstrate the applicability of a monitoring plan which focused on showing compliance with the safety case and primarily covered long-term monitoring aspects.
- Development and qualification of a monitoring programme was conducted through practical demonstrations inside the AHA programme at the Bure underground research laboratory (URL), in France. Parameters for monitoring were selected, and evaluation of the monitoring system for a vitrified waste (HLW) disposal cell was conducted during experiments in two demonstrators. These experiments provided useful information on the practicalities of installing a monitoring system.
- Demonstration of monitoring in the Long-Term Rock Buffer Monitoring (LTRBM) demonstrator in the Tournemire URL in France, has focused on the *in situ* testing of new monitoring technologies developed within the Modern2020 Project. Additionally, demonstration of wireless data transmission from the LTRBM borehole to the ground surface (a distance of 275 m through rock) was successfully demonstrated. The LTRBM is fully operational and work is still ongoing.
- The Full-Scale Emplacement (FE) Experiment at Mont Terri URL in Switzerland was used to demonstrate the implementation of monitoring. In the FE Experiment, which was conducted outside of the Modern2020 Project, the construction, emplacement, backfilling, and post-closure

[1] ONKALO® is a registered trademark of Posiva Oy.

THM evolution of a spent fuel and HLW repository tunnel was simulated in a realistic manner, and the induced THM effects in the host rock and EBS were investigated through a full-scale multiple heater test. The test demonstrates monitoring of the THM evolution of the EBS and the host rock. Information on sensor performance and reliability was also gathered.

These demonstrations show the feasibility of conducting integrated monitoring programmes consistent with the strategies and parameters identified in the strategic work of the Modern2020 Project and applying the technologies considered in the technology R&D. However, there is significant more work to be undertaken in refining the proposed monitoring approaches, linking the approaches to the safety cases to which they will contribute, and understanding the limitations and practical challenges in implementing monitoring during ongoing operations.

Citizen stakeholder engagement

Citizen stakeholder engagement research focused on ways of involving local citizen stakeholders (e.g. people in potential repository host communities, and people in communities hosting a URL) in repository monitoring RD&D. The driver was identification of inclusive two-way processes from the early stages of repository implementation and design of monitoring programmes. In order to better understand the views and expectations held by local stakeholders regarding repository monitoring, several engagement activities were conducted, involving local stakeholders from Belgium, Finland, France and Sweden. Representatives from these communities were invited to several Modern2020 Project meetings to establish direct interaction between researchers from the technical work packages and the local stakeholders. Additional workshops (or "home engagement sessions") were set up in the home communities giving a broader group the opportunity to share and discuss their opinions about repository monitoring with social scientists and technical experts (with expertise in various specific subjects) in their own language. All sessions were arranged, documented and analysed by social scientists working as part of Modern2020. The same local stakeholders were also offered the opportunity to share their experiences by taking part in an online survey, to which all Modern2020 partners were also invited to participate.

A Stakeholders' Guide to monitoring in geological disposal and public participation was developed collaboratively by social scientists, technical experts and local citizen stakeholders. The Guide was envisaged as a way to communicate the state-of-the-art on geological disposal and repository monitoring to a non-scientific audience, and, through this, facilitate dialogue between scientists and public groups (for example, citizens, policy-makers and journalists) about technological and social concerns. Through the joint writing process, the nature of the Stakeholders' Guide evolved from being focused on the technical details of repository monitoring to giving a broader view on monitoring in the context of repository governance and the role of public participation. The production of the Stakeholders' Guide was itself a valuable exercise in stakeholder participation, which helped to clarify the different social perspectives, interests and concerns of citizen stakeholders and technical experts surrounding repository monitoring.

The main conclusions from the interactions with citizen stakeholders were as follows:

- Citizen stakeholders felt that their role in the project was not to influence the course of the technical research, but to understand what it was for and how it could affect the national waste management programmes.
- Citizen stakeholder participants were not prepared to legitimise research outcomes, but wanted to ask critical questions in order to increase understanding and give feedback.
- Citizen stakeholders indicated that they want to be engaged from an early stage in research processes and technology development. They indicated that they did not want to participate in the research itself, but they wanted to enhance their own understanding of the research and the process by which it proceeds, to broaden the thinking of the researchers, and to ensure that local stakeholders' views are taken into account.
- Many local stakeholders involved in the Modern2020 Project were already quite trusting towards their particular waste management organisation and the work undertaken by them.

Being able to participate in this project, in close contact with an international group of researchers, further enhanced this trust. This was not because this group spoke to them in one voice, but precisely because being part of "science in action" unveiled differences between countries and repository programmes, and showed knowledge as well as remaining knowledge gaps.

- Focusing on reaching an international consensus on a standard monitoring strategy and route for that to be obtained, risks concealing national differences, and political interests, which may become disguised as technical issues.
- Co-production of the Stakeholder Guide helped local citizen stakeholders increase their understanding of repository monitoring.

Modern2020 Project Conclusions

The Modern2020 Project has enhanced our ability to implement, both strategically and technically, repository monitoring during the operational phase to build further confidence in the post-closure safety case and to develop a common understanding of how monitoring during the operational phase in support of building further confidence in the post-closure safety case would be beneficial. The challenges of monitoring have been explicitly recognised, whilst, at the same time, building broad agreement that such monitoring is of value and should be undertaken.

The integrated strategic, technical and sociological work undertaken provides the platform for developing site-specific repository monitoring programmes. In programmes close to licensing, specific monitoring programmes for the operational phase are required in the next few years. Some aspects of these monitoring programmes are already developed. The results of the Modern2020 Project provide a broad set of tools, methods and guidance, and innovative technological approaches that can underpin the further development of these monitoring programmes.

In addition, the information from Modern2020 will also support programmes at earlier stages of licensing. For example, understanding the approach to monitoring may allow designs that specifically take account of monitoring requirements at an early stage to be developed. All programmes have challenges in public acceptance, although developing trust and acceptance by the public may be more challenging for programmes in the earlier stages of licensing. For these programmes, being able to explain general plans for monitoring and expectations for monitoring during the operational phase might play a role in developing trust and acceptance.

The strategic work in the Modern2020 Project has evaluated the role of repository monitoring within the safety case. In particular, the test cases focused on the selection of monitoring parameters have explicitly looked at the safety case and identified instances where specific monitoring may provide additional value to the ongoing implementation of geological disposal.

As each monitoring programme must respond to the national context (consisting of the relevant regulations, the waste characteristics, the geological environment, the disposal concept and repository design, and the socio-political environment), the next step is for specific waste management programmes to progress specific monitoring programmes.

Although there have been significant advances in the strategic, technological and sociological aspects of repository monitoring within the Modern2020 Project, international collaborative efforts should continue so that there are adequate resources available for technological development and so that the learning gained from practical application of the guidance, tools and approaches developed in the Project can be shared on an international basis and each programme can benefit from the lessons learned elsewhere.

The Modern2020 Project was undertaken by a wide range of organisations with expertise in geological disposal of radioactive waste and the post-closure safety case, monitoring technologies, and stakeholder engagement related to geological disposal. This group met frequently throughout the Project, sometimes in small group meetings and workshops, and also in Project-wide events such as the General Assemblies, the international conference and the training school. Many of the participants in the Modern2020 Project had previously been involved in the MoDeRn Project or were responsible for the development of specific repository monitoring programmes. This allowed the outcomes of the MoDeRn Project to be communicated to a broader audience and for an extension of knowledge and competence on repository monitoring. Hence, the Modern2020 Project has been successful in maintaining and enhancing knowledge and competence with respect to repository monitoring, and continued collaboration is encouraged.

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List of Acronyms

DTS:	Distributed temperature sensing
EBS:	Engineered barrier system
EDZ:	Excavation Damaged Zone
EF4:	4th IGD-TP Exchange Forum
ERT:	Electrical resistivity tomography
ETN:	European Thematic Network
FE:	Full-Scale emplacement
FEIS:	Full-scale emplacement information system
FWI:	Full-waveform inversion
GBM:	Granular bentonite material
GPR:	Ground penetrating radar
GTS:	Grimsel Test Site
HA:	Highly-Active
HLW:	High-level waste
IAEA:	International Atomic Energy Agency
IGD-TP:	Implementing Geological Disposal of Radioactive Waste Technology Platform
IL-LLW:	Long-lived intermediate-level waste
IPT:	Induced polarisation tomography
LVDT:	Linear variable differential transformer
LTRBM:	Long-Term Rock Buffer Monitoring
MB:	Main horizontal borehole
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure (see MoDeRn Project documentation e.g. MoDeRn (2013a))
Modern2020:	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal – Horizon2020
NEA:	Nuclear Energy Agency
OFS:	Optical fibre sensor
R&D:	Research and development
RD&D:	Research, development and demonstration
SSG:	Specific Safety Guide
SSR:	Specific Safety Requirements
TDR:	Time-domain reflectometry
THM:	Thermal, hydraulic and mechanical
THMC:	Thermal, hydraulic, mechanical and/or chemical
TRL:	Technology readiness level
TSO:	Technical support organisation

URL:	Underground research laboratory
VLF:	Very low frequency
WMO:	Waste management organisation
WP:	Work package
WTB:	Wireless Test Bench

List of Modern2020 Project Partners

The partners in the Modern2020 Project are listed below. In the remainder of this report each partner is referred to by their short name:

Partner name	Short name	Country
Agence Nationale pour la Gestion des Dechets Radioactifs	Andra	France
AITEMIN (until 30/09/2016)	AITEMIN	Spain
Amberg Infraestructuras (from 01/10/2016)	Amberg	Spain
Arquimea (from 01/10/2016)	Arquimea	Spain
BGE Technology GmbH (former DBETEC)	BGETEC	Germany
CeskeVysoke Uceni Technicke v Praze	CTU	Czech Republic
Electicite de France	EDF	France
Agenzia Nazionale per le Nuove Tecnologie, L'Energia e lo Sviluppo Economico Sostenibile	ENEA	Italy
Empresa Nacional de Residuos Radiactivos S.A.	ENRESA	Spain
Eidgenoessische Technische Hochschule Zuerich	ETH Zurich	Switzerland
European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment	EURIDICE	Belgium
Galson Sciences Limited	GSL	UK
Institut de Radioprotection et de Surete Nucleaire	IRSN	France
Nationale Genossenschaft für die Lagerung radioaktiver Abfälle	Nagra	Switzerland
Nidia SRL	Nidia SRL	Italy
Nuclear Research and consultancy Group	NRG	The Netherlands
Nationale Instelling voor Radioactief Afval en Verrijkte Splijstoffen	ONDRAF/NIRAS	Belgium
Orano	Orano	France
Posiva Oy	Posiva	Finland
Radioactive Waste Management Limited	RWM	UK
Radioactive Waste Management Funding and Research Center	RWMC	Japan
Svensk Karnbranslehantering AB	SKB	Sweden
Radioactive Waste Repository Authority	RAWRA/SURAO	Czech Republic
Technicka Univerzita v Liberci	TUL	Czech Republic
Universiteit Antwerpen	UAntwerpen	Belgium
Goeteborgs Universitet	UGot	Sweden
Universite de Mons	UMons	Belgium
Universite de Limoges	ULim	France
University of Strathclyde	UStrath	UK
Teknologian tutkimuskeskus VTT Oy	VTT	Finland

1 Introduction

1.1 Background to repository monitoring and implementation of geological disposal

Geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste (HLW) and spent fuel considered as waste (Official Journal of the European Union, 2011). Implementation of radioactive waste disposal should address both technical and societal needs, and monitoring has the potential to contribute to both of these aspects. Monitoring can form part of a repository safety strategy; it can contribute to public and stakeholder understanding of processes occurring in the repository, and hence, it can respond to public concerns and be used to build confidence in geological disposal. Monitoring could therefore play a role in enabling waste management organisations (WMOs) to work towards the safe and accepted implementation of geological disposal.

Significant international collaborative work on the reasons for, and principles of, repository monitoring has been on-going for decades. The key purposes of monitoring of repository systems are seen to be (IAEA, 2001):

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure.
- To strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects.
- To provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence, for as long as society requires, that the repository is having no undesirable impacts on human health and the environment.
- To accumulate an environmental database on the repository site and its surroundings that may be of use to future decision makers.
- To address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste.
- For operational reasons:
    - To determine any radiological impacts of the operational disposal system (as with a nuclear installation, like a power plant) on the personnel and on the general population, in order to comply with statutory and regulatory requirements.
    - To determine non-radiological impacts on the environment surrounding the repository, to comply with environmental regulatory requirements (e.g. impacts of excavation and surface construction on local water supply rates and water quality).
    - To ensure compliance with non-nuclear industrial safety requirements for an underground facility (e.g. dust, gas and noise).

Work has been undertaken under the auspices of the International Atomic Energy Authority (IAEA), the Nuclear Energy Agency (NEA) and the European Commission (EC). It has included analysis of strategy and decision-making processes; research and development of new and novel technologies specifically suited to repository monitoring; *in situ* testing of sensors and monitoring systems in repository-like conditions; and research into the role stakeholder involvement may play in overall geological waste disposal.

Some of the key activities include:

- Production of an IAEA TECDOC on monitoring of geological repositories for high-level waste (IAEA, 2001).

- A European Thematic Network (ETN) on the role of monitoring in a phased approach to geological disposal of radioactive waste (EC, 2004).
- The EC Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) Project (MoDeRn, 2013a).
- A study into the technical and societal aspects of repository monitoring (NEA, 2014).

In parallel with international collaboration on monitoring, the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) was launched on 12 November 2009 (IGD-TP, 2011). The vision ("Vision 2025") of the IGD-TP is that "*by 2025, the first geological disposal facilities for spent fuel, HLW and other long-lived radioactive waste will be operating safely in Europe (IGD-TP, 2009). The IGD-TP's activities are driven by this vision that, and its commitment to:*

- *Build confidence in the safety of geological disposal solutions among European citizens and decision-makers.*
- *Encourage the establishment of waste management programmes that integrate geological disposal as the accepted option for the safe long-term management of long-lived and/or HLW.*
- *Facilitate access to expertise and technology and maintain competences in the field of geological disposal for the benefit of Member States.*"

Following the publication of the IGD-TP vision, good progress has been made in implementing geological disposal of radioactive waste in geological repositories in European waste management programmes. A construction licence has been granted to Posiva for a spent fuel repository in Olkiluoto, Finland. In Sweden, SKB has submitted a licence application for construction of a spent fuel repository in Forsmark and an encapsulation plant in Oskarshamn, and a Government decision on the application is expected in 2020. In France, Andra expects to submit a licence application for construction of a geological repository for HLW and long-lived intermediate-level waste (IL-LLW) in 2020. In Switzerland, deep borehole investigations commenced in 2019 in three siting regions as part of the third and final stage of the site selection process.

Progress has also been made by programmes that are at earlier stages of implementation. In Belgium, work is progressing on a first iteration of a Safety and Feasibility Case (ONDRAF/NIRAS, 2013). An update to the reference project for a deep geological repository in the Czech Republic was published in 2012 (Pospíšková *et al*., 2012) and the experimental phase of the Bukov underground research facility started in 2017. In Germany, the Commission on Storage of High-Level Radioactive Waste has published conclusions regarding the site selection procedure for a repository (German Commission on the Storage of High-Level Radioactive Waste, 2016). In the Netherlands, COVRA has published the OPERA Safety Case for a geological disposal facility (GDF) in the Boom Clay (Verhoef *et al*., 2017). In the UK, RWM has published a generic Disposal System Safety Case (RWM, 2016) and a siting process was launched in 2018 (RWM, 2018).

Monitoring was recognised as a priority topic by the IGD-TP in its Strategic Research Agenda (SRA) (IGD-TP, 2011). Key Topic 6 of the SRA points to the need for *"practical monitoring strategies including techniques for implementation"* and *"monitoring of progress in relevant scientific and technological areas"*. In addition, Key Topic 7 of the IGD-TP SRA focuses on *"governance and stakeholder involvement" with the objectives to "develop guidance for communicating to decision makers and stakeholders the results of research that underpin the development of safety cases and environmental assessments"*.

Following the completion of the MoDeRn Project in 2013 (MoDeRn, 2013a), the need for future international collaborative research into monitoring was discussed at the 4th IGD-TP Exchange Forum (EF4). The meeting recognised the IGD-TP view that further work on monitoring was required, with four areas to be considered: strategy aspects; technology development; practical implementation; and communication and stakeholder dialogue (IGD-TP, 2013).

In recognition of the priorities of the IGD-TP, topic NFRP 6 of the Euratom Research and Training Programme (2014-18), entitled *"Supporting the implementation of the first-of-the-kind geological repositories"*, called for research to *"improve the knowledge base for the safety case including the development of monitoring strategies, also taking into account stakeholder's concerns"*.

The Modern2020 Project was launched in response to this call.

1.2 Background to the Modern2020 Project

1.2.1 Scope and objectives of the Modern2020 Project

The overall objective of the Modern2020 Project was to provide the means for developing and implementing an effective and efficient repository monitoring programme, which takes into account the requirements of specific repository programmes. The project focused on monitoring of the near field[2] during repository operations, and, in particular, monitoring of the EBS to provide further confidence in the post-closure safety case (see discussion in Section 2.2). The Project focused on this aspect of monitoring because this is where the greatest challenges lie in terms of strategy, technology and public stakeholder engagement. It was intended that the work carried out within the project would provide the means for advanced radioactive waste disposal programmes to design monitoring systems suitable for deployment when repositories start operating in the next decade. The results of the project are also expected to support less-developed programmes and other stakeholders by illustrating how the national context can be taken into account in designing monitoring programmes.

The objectives of the Modern2020 Project were based on the recommendations arising from the recent international collaborative efforts described in Section 1.1. Consistent with the outcomes of EF4, objectives were split into four categories, which focused on monitoring plan strategy, repository monitoring technology, demonstration and practical implementation of strategies and technologies, and the role of stakeholder involvement in repository monitoring.

The objectives of work on **Strategy** in Modern2020 were:

- To understand the needs of specific types of repository programme and to provide the methodology for translating these needs into a monitoring programme design basis, by developing understanding of the link between the post-closure safety case and monitoring and by developing and testing traceable and transparent methods for identifying parameters to be monitored.
- To develop recommendations and guidance on responding to monitoring results.

The objectives of work on repository monitoring **Technology** were:

- To improve wireless monitoring technology including the integration of short-range and long-range systems.
- To research alternatives power supplies for autonomous, wireless monitoring nodes.
- To develop new sensors, including those based on optical fibre technology to monitor water content, water chemistry, pH and irradiation.

[2] The near field is defined as "The excavated area of a disposal facility near or in contact with the waste packages, including filling or sealing materials, and those parts of the host medium/rock whose characteristics have been or could be altered by the disposal facility or its contents". (IAEA 2018).

- To refine and further improve the most promising geophysical methods for repository monitoring (such as seismic full-waveform inversion (FWI) and electrical resistivity tomography (ERT)).
- Establish a common methodology for qualifying the components of the monitoring system.

The objectives of work on **Demonstration and Practical Implementation** were:

- To demonstrate new technology developments under *in situ* conditions.
- To demonstrate the development of a monitoring system design utilising multiple technologies and linked to a specific safety case.
- To utilise existing experience in near-field monitoring to provide guidance on monitoring system design, e.g. by examining whether existing monitoring technologies can provide information on the required parameters, at the required frequency and accuracy.

The objectives of the work on **Stakeholder Involvement** were:

- To engage local citizen stakeholders in national and international repository monitoring research, development and demonstration (RD&D), and to analyse the impact this has on both the participating stakeholders' and the project partners' understanding of, and expectations regarding, repository monitoring.
- To define more specific ways for integrating public stakeholder concerns and expectations into national repository monitoring programmes.
- To learn how local stakeholder groups could be engaged effectively with RD&D programs and projects at an EU level.

These project-level objectives were translated into task-specific objectives as described in more detail throughout this report.

1.2.2 Structure of the Modern2020 Project

The Modern2020 Project was divided into six Work Packages (WPs):

- **WP1: Coordination and Management of the Consortium**. This WP focused on delivery of the Modern2020 Project.
- **WP2: Monitoring Programme Design Basis, Monitoring Strategies and Decision Making**. This work package aimed to define the requirements on monitoring systems in terms of the identification of parameters to be monitored in monitoring programmes with explicit links to the long-term safety case and the wider scientific programme. This included consideration of decision-making requirements, monitoring strategies, screening of monitoring parameters, and responding to monitoring results. A key aspect of this work was to research how the design basis of practical, feasible, efficient and effective monitoring programmes can be established.
- **WP3: Research and Development of Relevant Monitoring Technologies**. In WP3, research and development (R&D) was undertaken on wireless data transmission systems, power supplies, new sensors, and geophysical methods. WP3 also assessed the readiness levels of relevant technologies, and established a common methodology for qualifying the elements of the monitoring system intended for repository use.
- **WP4: Demonstration of Monitoring Implementation in Repository-Like Conditions**. In WP4, a series of demonstrator studies were undertaken, each addressing a range of monitoring-related objectives. The demonstrators were the Engineered Barrier System (EBS) Monitoring Plan in Finland, the Highly-Active (HA) Industrial Pilot Experiment in France, the Long-Term Rock Buffer Monitoring (LTRBM) Experiment in France, and the Full-Scale Emplacement (FE) Experiment in

Switzerland. An assessment and synthesis of several other tests and demonstrators was also undertaken, including consideration of the reliability of monitoring results.

- **WP5: Effectively Engaging Local Citizen Stakeholders in RD&D on Monitoring for Geological Disposal**. In WP5, research was undertaken into the involvement of citizen stakeholders in RD&D and planning for monitoring of geological repositories. The work included participation of citizen stakeholders in technical meetings, dedicated stakeholder meetings, literature review and web-based surveys. In addition, a "Stakeholders' Guide" was developed to inform stakeholders of the background to repository monitoring. The work also contributed to understanding of how stakeholders can participate in the early stages of repository RD&D.
- **WP6: Communication and Dissemination**. The activities in WP6 included an international conference, a training school, the production of a video and this report, the Modern2020 Synthesis. The conference included 33 oral presentations and 31 poster presentations, which were spread across nine plenary conference sessions (Modern2020 Consortium, 2019c). The training school was attended by 26 advanced PhD students, and early-career scientists and engineers (Modern2020 Consortium, 2019d).

Published reports from the Modern2020 Project are listed in Table 1.1.

Table 1.1: Public deliverables produced during the Modern2020 Project.

Deliverable Number	Deliverable Title	Reference
	Work Package 2	
D2.1	Repository Monitoring Strategies and Screening Methodologies	White *et al.* (2017)
D2.2	Monitoring Parameter Screening: Test Cases	Farrow and White (2019)
D2.3	Responding to Monitoring Results	White *et al. (*2019)
	Work Package 3	
D3.1	Synthesis Report on Relevant Monitoring Technologies for Repository	Amberg *et al. (2019)*
D3.2	Wireless Data Transmission Systems for Repository Monitoring	Schröder *et al*. (2019)
D3.3	Long-Term Power Supply Sources for Repository Monitoring	Strömmer *et al*. (2019)
D3.4	New Sensors for Repository Monitoring	Bertrand *et al*. (2019)
D3.5	Geophysical Methods for Repository Monitoring	ETH *et al. (*2019)
D3.6	Reliability and Qualification of Components	IRSN *et al.* (2018)
	Work Package 4	
D4.1	EBS Monitoring Plan	VTT *et al. (*2019)
D4.2	Development of HA Monitoring Plan	Andra and EDF (2019)
D4.3	The LTRBM Experiment in the Tournemire URL, France	Dick *et al*. (2019)
D4.4	The Full-Scale Emplacement (FE) Experiment, Mont Terri (Switzerland) – Field Realisation	Fisch *et al*. (2019)

Deliverable Number	Deliverable Title	Reference
D4.4	Evolution of TEM experiment at the Grimsel test Site (GTS) during the timeframe of Modern2020 project	Tunon Valladares *et al.* (2019)
Work Package 5		
D5.1	Monitoring the Underground: What Role for Repository Monitoring in the Governance of Geological Disposal for Nuclear Waste?	Lagerlöf *et al*. (2017)
D5.2	Monitoring in Geological Disposal and Public Participation: A Stakeholder Guide	Meyermans *et al. (*2019)
D5.3	Repository Monitoring in the Context of Repository Governance	Bergmans *et al*. (2019)
Work Package 6		
D6.1	Plan for the Dissemination and Exploitation of the Project's Results	Modern2020 Consortium (2019a)
D6.2	Modern2020 Website	Modern2020 Consortium (2019b)
D6.3	Modern2020 Final Conference Proceedings: Second International Conference on Monitoring in Geological Disposal of Radioactive Waste: Strategies, Technologies, Decision Making and Public Involvement	Modern2020 Consortium (2019c)
D6.4	Modern2020 Training School 2019	Modern2020 Consortium (2019d)
D6.5	Modern2020 Project Synthesis Repository Monitoring: Strategies, Technologies and Implementation	This report

1.3 Introduction to the Modern2020 Synthesis

1.3.1 Objectives and scope

The objective of this report is to summarise the work conducted as part of the Modern2020 Project, to present the key messages and results from this work, and to provide signposts to underpinning reports that describe the results in more detail. The extent to which objectives of the Project have been met and the extent to which the expected impacts have been realised are also discussed. As such, the report provides conclusions regarding the state-of-the-art in repository monitoring, the extent to which WMOs are ready to develop detailed monitoring programmes and to commence monitoring of the near field during the operational phase in support of building further confidence in the post-closure safety case, and future work requirements.

This report is focused on the technical and social outcomes from the Modern2020 Project, so does not discuss the work of WP1 (management) and WP6 (communication and dissemination).

1.3.2 Main audiences for this report

The Modern2020 Project recognises that different stakeholders may be interested in, or have a specific role to play with respect to, the development, implementation, and use of monitoring. Therefore, the report is intended to be informative to a wide range of stakeholders, including:

- WMOs and supporting research entities, to whom the report can provide guidance on how to develop, implement and use monitoring in support of decision making. In particular, the content of this report is expected to be relevant to WMO staff responsible for developing and implementing repository monitoring programmes.
- Safety authorities who may place requirements on the monitoring approach and who may impose some monitoring as part of license conditions, and the technical support organisations (TSOs) carrying out activities aimed at providing the scientific and technical basis for supporting the decisions made by safety authorities.
- Designated advisory boards likely to inform national decision makers on waste management issues.

However, owing to the technical context for much of the Modern2020 Project work, a good understanding of geological disposal of radioactive waste is assumed, including a general understanding of the development of post-closure safety cases. Although other audiences may be interested in this Synthesis and find it informative, for example policy makers, local citizen stakeholders and those responsible for monitoring in other industries, the report has not been specifically tailored to other audiences. Other documents may provide more suitable introductions to repository monitoring for other audiences, for example, the Stakeholder Guide (Modern2020 Project Deliverable D5.2; Meyermans *et al.*, 2019) is more focused on the needs of citizen stakeholders.

1.3.3 Structure

The structure of this report is aligned to the Modern2020 Project structure. For each WP, we describe the understanding at the start of the project, the work undertaken in the Modern2020 Project, the results of the work undertaken, and identify gaps and future research requirements. The content of each chapter of the report is as follows:

- Chapter 2 describes the work undertaken, key results and conclusions of WP2.
- Chapter 3 describes the work undertaken, key results and conclusions of WP3.
- Chapter 4 describes the work undertaken, key results and conclusions of WP4.
- Chapter 5 describes the work undertaken, key results and conclusions of WP5.
- Chapter 6 provides the key conclusions from the Project and recommendations for further work.

2 Modern2020 WP2: Monitoring Strategies, Parameters and Responding to Results

This chapter provides a summary of the work undertaken, key results and conclusions of the Modern2020 Project WP2 work on the strategic aspects of repository monitoring. This included consideration of the strategies and parameters that could be used to provide further confidence in the post-closure safety case by monitoring of the near field during the operational phase:

- Section 2.1 outlines the understanding of strategic aspects of monitoring prior to the start of the Modern2020 Project.
- Section 2.2 outlines the role of repository monitoring in the post-closure safety case.
- Section 2.3 summarises seven test cases used to consider what parameters might be monitored during the operational phase to build further confidence in the post-closure safety case, and draws conclusions on strategies and parameters.
- Section 2.4 presents the Modern2020 Screening Methodology which was developed using generic considerations, and the information and experience gained from the test cases.
- Section 2.5 discusses the possible responses to monitoring data, with particular focus on how the information acquired through monitoring can influence decision making.
- Section 2.6 presents the conclusions from WP2.

The information presented in this chapter is presented in more detail in the three WP2 task reports:

- Deliverable D2.1 (White *et al*., 2017) summarises the outcomes from Task 2.1, which addressed the link between repository monitoring programmes and the post-closure safety case, and developed a preliminary version of the Modern2020 Screening Methodology.
- Deliverable D2.2 (Farrow *et al*., 2019) describes the outcomes from Task 2.2, including the seven test cases and feedback from the test cases to the Modern2020 Screening Methodology.
- Deliverable D2.3 (White *et al*., 2019) describes the outcomes of Task 2.3, which considered evaluation of monitoring results, development of response plans and decision-making processes.

2.1 Understanding of monitoring strategies prior to the Modern2020 Project

2.1.1 International guidance and collaborative research

A significant body of work has been undertaken by the international community related to monitoring strategies. The most significant progress and the resulting position at the start of the Modern2020 Project is discussed below.

In 2001, the IAEA published a Technical Document (TECDOC) on monitoring of geological repositories (IAEA, 2001). The key purposes of monitoring were listed as being: to provide information for making management decisions; to strengthen system understanding; to provide society with information; to accumulate an environmental database; to address the requirement to maintain nuclear safeguards; and for operational reasons. A suggested monitoring methodology was outlined and typical monitoring parameters listed. The document provides a good discussion on the various issues associated with monitoring to build further confidence in the post-closure safety case. However, the impact of monitoring on passive safety is not discussed, monitoring parameters are not linked to a monitoring strategy or to safety case drivers, and the technical feasibility of monitoring the proposed parameters is not evaluated.

The IAEA monitoring TECDOC forms an underpinning reference to the IAEA Specific Safety Requirements (SSR-5) (IAEA, 2011a), which establishes requirements concerning monitoring programmes, and Specific Safety Guide 14 (SSG-14) (IAEA, 2011b), SSG-23 (IAEA, 2012) and SSG-31 (IAEA, 2014), which provide guidance on these requirements. In SSR-5, Requirement 21 states that "Monitoring shall … be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure", and includes the principle that a repository should be designed to be intrinsically and passively safe, such that long-term safety does not require action from future generations and does not rely on monitoring after closure. Despite this, the importance of baseline monitoring and contingency plans to address system behaviour outside the performance bounds addressed in the safety case is emphasised. The IAEA also recognises the importance of monitoring through all steps in repository development, reflecting the significance that many WMOs place on monitoring within their programmes.

The ETN was established to assess the role of monitoring in the phased approach to geological disposal of radioactive waste, and identify how monitoring could contribute to decision making, operational and post-closure safety, and confidence in repository behaviour (EC, 2004). A main conclusion was that existing and newly developing technology offered promising potential for achieving a level of monitoring appropriate for, and of benefit to, stepwise repository implementation. However, the ETN also concluded that the actual extent of monitoring would have to be determined by specific programmes. No common method for determining the extent of monitoring, i.e. selecting the parameters to be monitored, was developed within the ETN.

The MoDeRn Project was a collaborative research project that ran from 2009 to 2013. Its aim was to further develop collective understanding of the role of monitoring in the staged implementation of geological disposal and to provide guidance and recommendations to WMOs; outcomes of the Project are presented in MoDeRn (2013a). As part of this project, work was undertaken relating to strategy and decision making in repository monitoring, the main result of which was the MoDeRn Monitoring Workflow. The Workflow represents a structured approach to the development, implementation and operation of a repository monitoring programme. The MoDeRn Monitoring Workflow has been updated in the Modern2020 Project, as discussed in this section and as illustrated in Figure 2.9.

As part of a wider project on the preservation of records, knowledge and memory across generations, the NEA published a report in 2014 (NEA, 2014a) which summarised general objectives, practices and approaches to monitoring of radioactive waste disposal facilities, covering both technical and societal aspects. The NEA (2014a) made the following comments on selection of monitoring parameters, which are particularly relevant to the work undertaken in WP2 of the Modern2020 Project:

> *"The current, and justifiable, tendency is to measure as many parameters as possible so as to contribute in the most comprehensive way towards both the compilation of a complex description of the disposal system and the understanding of its performance under real conditions. With the transition from the repository development stage to implementation, it becomes necessary to optimise the selection of the parameters to be monitored which is motivated by practical reasons since it would be difficult to install and operate such a large number of monitoring systems over long time periods in the final disposal system. Thus, the identification of those parameters which would sufficiently demonstrate the attainment or approach to the passive safety status of the disposal system would be of substantial benefit."*

2.1.2 Existing monitoring programmes

In addition to the theoretical and experimental work described above, lessons can be learned from reviewing the development, implementation and management of monitoring programmes for existing radioactive waste disposal facilities. These include operating geological repositories, near-surface disposal facilities and repositories under construction. Two of the examples that were considered in the Modern2020 Project are summarised below to provide a real-world context to the discussions in this chapter. Further information on these monitoring programmes is available in Appendix B of White *et al.* (2017).

The Waste Isolation Pilot Plant

The Waste Isolation Pilot Plant (WIPP) is a repository for transuranic waste constructed in bedded salt in New Mexico, USA. The licensing criteria for the WIPP Facility includes a requirement to develop a performance confirmation plan. Performance confirmation is a formal testing and monitoring programme focused on the essential elements of a license basis, and is set up for the purpose of demonstrating that the bases of the safety case are substantiated. The WIPP monitoring programme is part of the performance confirmation plan. Development of the monitoring programme included a multi-stage process to identify a relatively small list of compliance monitoring parameters for monitoring during the operational phase as part of the performance confirmation plan. The process used the following criteria to assess potential monitoring parameters:

- Addresses significant disposal system parameters defined by their: (i) effect on the system's ability to contain waste; or (ii) effect on the ability to verify predictions about the performance of the disposal system.
- Addresses an important disposal system concern.
- Obtains meaningful data in a short period.
- Will not violate disposal system integrity.
- Complements other existing environmental monitoring programmes.

Ten parameters, relating to human activities in the surrounding area, hydrogeology, geotechnical performance, waste activity and overburden subsidence, met the criteria3:

- Creep closure and stresses: the closure rate of the mined openings.
- Extent of deformation: fracture propagation in rock surrounding drifts.
- Initiation of brittle deformation: qualitative parameter related to rock behaviour.
- Displacement of deformation features: lateral displacement of drift boreholes.
- Groundwater compositions: relates to flow, transport and solubility assumptions.
- Change in groundwater flow: relates to the transmissivity model and the groundwater basin model.
- Drilling rate: exploratory drilling, a parameter related to human activity used in safety assessment calculations.
- Probability of encountering a brine reservoir, a parameter used to assess possible consequences from future human activities
- Subsidence: ground movement in response to repository construction and operation.
- Waste activity: Curies of ten significant radionuclides.

Dounreay disposal facility for low-level waste, UK

A surface disposal facility for low-level waste developed at Dounreay, UK, under a similar regulatory regime as a geological repository would be developed. The monitoring programme demonstrates a strong link to the safety case prepared against similar requirements for authorisation as will be used for geological repositories, and also illustrates how a consolidated

[3] Some of these parameters were also identified as part of other monitoring plans, in addition to the monitoring plan linked to performance confirmation.

monitoring programme can be developed and managed starting from the consideration of a number of different monitoring objectives. The monitoring programme covers four objectives: (i) long-term safety case; (ii) operational safety case; (iii) environmental impact assessment; and (iv) other objectives (e.g. the regulatory framework and public reassurance).

For each objective or set of objectives, the monitoring programme defined the information requirements in terms of monitoring parameters, with suggested techniques for undertaking the monitoring of the parameters. A risk-based approach was used for identifying selecting important monitoring concerns related to the long-term safety case, as advocated by regulatory guidance. Parameters selected were those that were significant to long-term performance and/or building confidence in long-term performance, and were also suitable for monitoring. The monitoring parameters for each objective were then grouped into monitoring programmes, each concerned with a set of related parameters (e.g., groundwater monitoring covers hydrogeological parameters and groundwater chemistry parameters). The duration of each monitoring programme was defined in terms of the stages of development of the facilities, as set out in UK regulatory guidance: (i) pre-construction; (ii) construction; (iii) operations (in parallel with phased construction); (iv) closure (in parallel with phased operations); and (v) post-closure.

A set of parameter-related monitoring sub-programmes was then derived by considering overlaps between the lists of monitoring parameters, and the timescales for their determination for each objective. The final result was a consolidated list of 24 monitoring sub-programmes.

2.1.3 The need for further work in Modern2020

At the start of the Modern2020 Project, the general principles and role of monitoring within a geological disposal programme had been defined. Illustrations of how monitoring might be implemented had been developed, and an overall reference framework for monitoring established (MoDeRn, 2013a). However, several generic issues remained; further development of generic monitoring guidance was required, which explicitly considered the links between monitoring and the safety case and how a practical and feasible list of monitoring parameters could be defined.

In particular, although the MoDeRn Monitoring Workflow had been used by several WMOs in progressing monitoring plans (e.g. Posiva, 2012), there was a need for thorough testing of it against multiple different national contexts, with particular scrutiny of its more detailed aspects. Furthermore, the MoDeRn Project case studies focused on developing preliminary parameter lists - no screening was applied. As identified by the NEA (2014a), development and implementation of effective and efficient monitoring programmes requires detailed and structured descriptions for screening of monitoring parameters.

Although work prior to the Modern2020 Project had concluded that monitoring can support decision making, how this might occur has not been explicitly described. Therefore, there was also a need for the Modern2020 Project to consider how a WMO might plan for responding to monitoring results.

2.2 The post-closure safety case and retrievability context for monitoring

2.2.1 The post-closure safety case

A post-closure safety case is the synthesis of evidence, arguments and analyses that quantify and substantiate a claim that a disposal facility will be safe after closure and beyond the time when active control of the facility can be relied on (NEA, 2004). It is an integrated methodology using multiple lines of reasoning, including both qualitative arguments and scientific evidence, and quantitative arguments based on performance assessment and safety assessment. The safety case includes a statement of confidence in these arguments. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages. It will be updated periodically throughout the lifetime of a repository, including both before and after an operational licence is granted.

2.2.2 Retrievability

The French 2006 Programme Act (Loi, 2006) mandates that geological disposal shall be reversible for a period of no less than one century. Prior to closure, therefore, the repository must be managed according to reversibility as governance according to the progressive development of the repository, with different tolls, in particular the ability to retrieve waste disposal packages from disposal cells (not in accidental situation). Therefore, in the French programme, monitoring is contributing to the management of the retrievability, and this has a significant impact on the selection of parameters for the monitoring programme.

2.2.3 Monitoring

In the Modern2020 Project, the role of monitoring in the safety case was considered through analysis of guidance documents, existing monitoring programmes (e.g. the programmes discussed in Section 2.1.2), and through workshop discussions. The outcome is discussed in detail in White *et al.* (2017).

For a monitoring programme focused on the post-closure safety case during the operational period, the context is set by the permit under which the emplacement of waste is regulated (see discussion of monitoring programme national contexts in Farrow *et al.*, 2019). To receive a permit to operate, the safety case will have demonstrated confidence in safety. Therefore, further monitoring during the operational period, might be used to build *further* confidence. What constitutes further confidence is a programme-specific issue, but might include monitoring to demonstrate compliance (as in the WIPP case discussed in Section 2.1.2); monitoring of a suite of thermal, hydraulic, mechanical and/or chemical processes (THMC) in the EBS (for example in a pilot repository or in a few selected waste emplacement locations) to increase process understanding and/or to check if any significant unknown processes are affecting system evolution; or monitoring to feed into ongoing design consideration (this is the expectation in Germany). These different sub-objectives have implications for the strategies applied and the parameters that will be monitored (as discussed in the test cases undertaken in Modern2020, see Section 2.3).

2.2.4 Modelling

Extensive modelling in support of the post-closure safety case will have been undertaken prior to licensing, including consideration of variant scenarios. This will include modelling of the THMC processes occurring throughout the multi-barrier system, and the testing and verification of this modelling against underground research laboratory (URL) experiments, site-specific rock characterisation facilities and commissioning tests. Such understanding will include estimation of the range of responses that would be expected owing to variations in boundary conditions (such as temporal and spatial variability in groundwater flow into repository excavations). Modelling will also include safety assessment calculations to estimate doses or risks from the repository system. Modelling in support of the safety case will continue to be undertaken during the operational period, to demonstrate that any new information is consistent with the safety case.

Understanding from modelling and the wider RD&D programme will inform the identification of monitoring parameters, and development of a prediction of parameter values over the monitoring period. A prediction of parameter values, considering uncertainty, is required at a relatively early stage in the development of the monitoring programme in order to check the technical feasibility of monitoring a candidate parameter and as a basis for monitoring programme design (i.e. as a basis on which to select sensors, to develop their specification and to determine their location within the repository). The prediction of monitoring parameter values is not necessarily the same as the values assumed in the safety case, as the safety case typically uses conservative values to account for uncertainty (see discussion in White *et al.*, 2017). The range of values used in the safety case is therefore expected to be greater than the range of predicted parameter values used in the monitoring programme.

2.2.5 Monitoring system and repository performance

Therefore, monitoring can be used to check certain features of the repository evolution to provide additional confidence in performance. However, the IAEA principle that monitoring should not significantly affect system performance must always be considered when selecting monitoring parameters. Monitoring could affect the performance of the repository multi-barrier system. An outstanding issue is the extent of monitoring that will be undertaken to build further confidence in the post-closure safety case during the operational phase. For each disposal programme, a decision needs to be made whether extensive monitoring will be undertaken to know in detail what is happening, and accept a decrease in the performance of the barrier[4], or to undertake more limited monitoring in order to gain a general understanding of system evolution. The extent to which monitoring affects performance is, in part, addressed by the high-level strategy that a WMO takes to monitoring. High-level strategies are discussed in Section 2.3.

Overall, deciding what to monitor is largely a process of expert judgement, based on the perceived value to the safety case and what would provide further confidence for the specific programme in question. Such judgement will involve comparing and contrasting the benefits and disbenefits of any proposed monitoring activity, and considering the potential benefits to the safety case, especially the periodic update of the safety case during the operational period and in support of closure. Monitoring can be undertaken to increase confidence in the safety case further and to check concerns of third parties (award of an operational licence requires confidence in repository safety on behalf of both the implementer and the regulator).

The expert judgement involved in deciding on monitoring parameters is a central theme of the Modern2020 Screening Methodology. A draft of this methodology was prepared ahead of the running of the test cases reported in the next section (Section 2.3) and used as a common basis under which they were taken. A final Methodology was developed in response to the test cases and is presented in Section 2.4.

2.3 Parameter selection test cases

The development of monitoring programmes which fulfil the criteria discussed in Section 2.1 and Section 2.2 require the identification of monitoring parameters suitable for this purpose, i.e. parameters which provide information about relevant processes, offer value in support of the post-closure safety case, are technically feasible to monitor, and are appropriate in the context of other parameters proposed for monitoring. In the Modern2020 Project, seven test cases were undertaken to examine how WMOs could identify parameters to build further confidence in the post-closure safety case. The test cases are described in detail in Farrow and White (2019), and are summarised in Section 2.3.1. The integrated conclusions from the test cases are discussed in Section 2.3.2.

The test cases undertaken were as follows:

- Cigéo: The safety assessment , the planned repository for HLW and IL-LLW in the Callovo-Oxfordian Clay layer in France, based on the Safety Options Report 2016 (Andra, 2016).
- ANSICHT: The new safety assessment concept developed for a repository sited in clay in Germany (Jobmann *et al.*, 2017).
- Opalinus Clay: Demonstration of disposal feasibility for spent fuel, HLW and ILW-LL in a clay host rock in Switzerland (Nagra, 2002a; 2002b).

[4] Any decrease in performance must be insignificant with respect to safety, and not jeopardise the safety case.

- OPERA: An evaluation of the technical feasibility and safety performance of a repository for low and intermediate-level waste (L/ILW) and HLW in the Boom Clay, in the Netherlands (Verhoef and Schröder, 2011).
- TURVA 2012: Posiva's 2012 safety case for disposal of spent fuel in crystalline rock in Olkiluoto, Finland (Posiva, 2012).
- SR-Site: Long-term safety for the final repository for spent nuclear fuel at Forsmark, Sweden (SKB, 2011).
- Reference Project 2011: Update of the reference project of a deep geological repository in granite at a hypothetical locality, Czech Republic (Pospíšková *et al.*, 2012).

Note that, with the exception of the ANSICHT test case, the results from the test cases relate to this exercise only, and do not represent fully underpinned decisions on parameters that would or would not be monitored in monitoring programmes implemented by WMOs in the future. The ANISICHT test case represents a preliminary iteration of the monitoring programme that could be implemented in a geological repository programme in Germany. Some project like Cigeo will consider the results obtained as a useful inputs to determine the monitoring parameters.

2.3.1 Test case summaries

Brief descriptions of each test case are given in this section; full details of each test case can be found in the Appendices of the Modern2020 deliverable D2.2 (Farrow and White, 2019).

Cigéo test case

The geological disposal facility of Cigéo is operated by Andra and lies within the Callovo-Oxfordian Clay layer of the Paris Basin. The design of the facility envisages that HLW disposal packages will be emplaced in small-diameter tunnels referred to as disposal cells (Figure 2.1). The disposal cells will be lined with a low-carbon steel sleeve to allow the emplacement process and retrievability of the waste if so desired during the operating period, at least one century (Andra, 2016).

The objectives of Andra's monitoring programme are to check that the installations perform as expected and as defined in the safety analysis; to assess the ability to retrieve waste packages; and to confirm that post-closure safety develops as expected, by tracking the normal evolution of the repository system during the operational period, and increasing confidence in the understanding of processes affecting long-term safety. Monitoring program will begin during the first phase of repository operation, called the Industrial Pilot Phase, that should contain some disposal cells heavily instrumented to monitor selected parameters.

Andra has developed a structured process for identification of monitoring parameters, which starts with the identification of the post-closure safety functions of each component of the repository and of the retrievability function of concerned components, followed by identification of phenomenological processes that may potentially affect these functions. The methodology used by Andra for monitoring parameter identification was extended for the purposes of the test case, and fourteen phenomenological processes which could occur in the disposal cell and surrounding rock were identified for screening. Following screening and the identification of parameters to monitor process evolution, eight monitoring parameters were identified that could provide value to the post-closure safety case or to considerations of retrievability (Table 2.1).

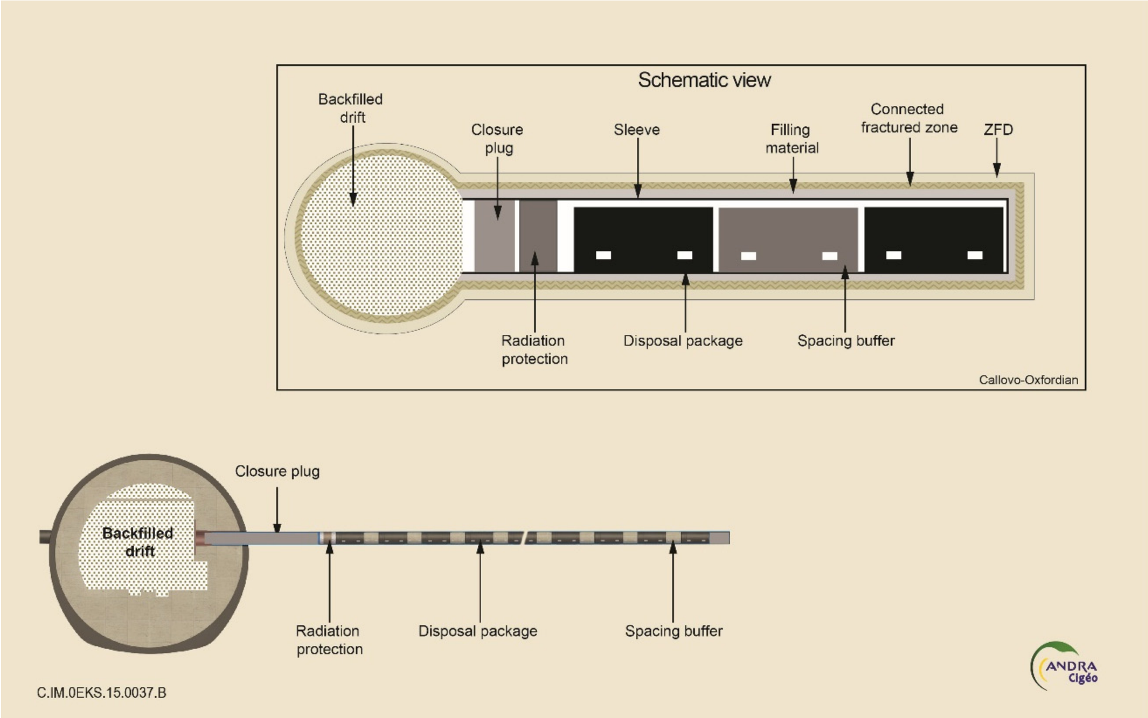


Figure 2.1: Illustration of the HLW disposal cell design. ZFD is the French acronym for the discrete fracture zone, part of the excavation damage zone. From Farrow *et al*. (2019).

Table 2.1: Parameters identified in the Cigéo test case.

Parameter	Element	Strategy and Technology	Justification
Temperature	Disposal cell and surrounding near-field rock	Monitored directly in some disposal cells using platinum probe and/or optical fibre sensors.	Long-term safety: Temperature inside the host rock has to be below 90°C in order to keep the properties of the clay rock.
Pore-water pressure	Near-field rock	Monitored directly in some disposal cells using vibrating wire or optical fibre piezometers.	Long-term safety: As opposed to the temperatures and due to the slow resaturation process, the expected hydraulic pressures will increase with time for argillaceous rocks during a transient period. Even if the thermal load is each cell is control and the temperature monitor, the measurement of the pore-water pressure in the near field (between two cells, for example) is a parameter to confirm that the properties of the rock remain the same.
Confining pressure	Total pressure on disposal cell sleeve	Monitored directly in some disposal cells, using optical fibre sensors.	Retrievability: in the French concept, the condition of retrievability has to be confirmed during the operational monitoring period. Information about the mechanical load on the metallic liner of the HLW cell will provide inputs to determine the possible deformation of the liner/tube.
Diameter	Disposal Cell sleeve	Monitored directly in some cells using optical fibre sensors. Evolution of the sleeve will also be measured directly by 3D scanning.	Retrievability: The direct measurement of the diameter of the tube is a direct way to check that the diameter (and the shape) of the tube remain in the operational range.

Parameter	Element	Strategy and Technology	Justification
Strain	Disposal cell sleeve	Monitored directly in some disposal cells, using optical fibre sensors.	Retrievability: Strain is an indirect measurement in redundancy of the diameter measurement to monitor the deformation of the sleeve.
Hydrogen concentration	Disposal cell atmosphere	Monitored directly in some cells using LiDAR and/or thermal gas conductivity and/or gas density and viscosity measurements.	Retrievability: Hydrogen concentration is monitored in order to check the atmosphere of the disposal cell for safe retrievability.
Oxygen concentration	Disposal cell atmosphere	Monitored in some cells using sensors based on luminescence.	Retrievability: Oxygen concentration is monitored in order to check the atmosphere of the disposal cell as indicator to corrosion and for safe retrievability
Relative humidity	Disposal cell atmosphere	Monitored in some disposal cells using capacitive sensors (based on an electrical capacitor).	Retrievability: Relative humidity measurement is an indicator to corrosion.

ANSICHT test case

The ANSICHT Project developed a safety assessment methodology for two clay repository concepts in Germany - one in the country's North and the other in the South. The Northern Germany repository concept was considered for this test case. It is situated in Barremian-Hauterivian clay and envisages disposal of canisters containing spent fuel and HLW in vertical boreholes (Figure 2.2). The aim of repository monitoring is to systematically monitor the properties of the geological sequence, hydrogeological conditions, the waste itself, and the impact of the repository on the environment.

The monitoring strategy involves monitoring of waste and dummy canisters in the repository emplacement area, with a focus on monitoring specific emplacement fields and boreholes, and specific seals (i.e. the borehole plug and abutment). In order to benefit from the experience gained in previous monitoring activities, monitoring will start with the first emplacement field in which waste will be emplaced. Monitoring in a further five emplacement fields is envisaged in the test case in order to address potential spatial variability within the repository footprint.

The ANSICHT test case focused on monitoring of the emplacement borehole seal, i.e. the clay borehole plug and the concrete borehole abutment. Therefore, monitoring in the repository is likely to include more parameters than identified in the test case (Table 2.2). A review of an existing catalogue of features, events and processes relevant to the Barremian-Hauterivian clay identified ten processes for potential monitoring; these formed the starting point for the screening process which followed the preliminary Modern2020 Screening Methodology.

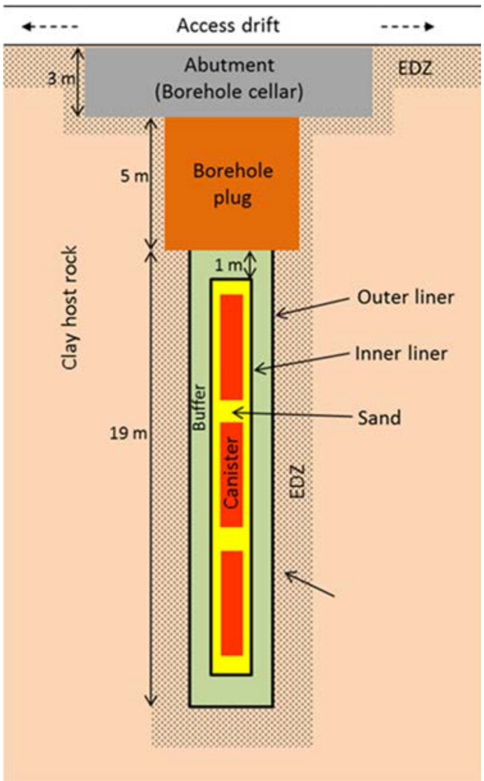


Figure 2.2: Illustration of the disposal concept for the northern Germany site considered in the ANSICHT test case. The borehole plug would be constructed from bentonite and the abutment would be constructed from cementitious materials. From Farrow *et al*. (2019).

Table 2.2: Parameters identified in the ANSICHT test case.

Parameter	Element	Strategy and Technology	Justification
Temperature	Deposition hole seal (bentonite plug and concrete abutment)	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using resistance temperature detector (RTD) or fibre optic-based systems.	Provides information about heat flow and temperature evolution in the seal, which is relevant to the performance target that the bentonite element shall be free from tensile stresses. Monitoring could provide confidence that the repository is behaving as expected.
Porewater pressure	Deposition hole seal (bentonite plug and concrete abutment)	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using vibrating wire and/or fibre optic sensors.	Provides information about fluid pressure from below (due to thermal expansion and gas generation), which is relevant to the overall safety function of the seal and to the related performance target that the bentonite element shall be free of tensile stresses. Monitoring could reduce uncertainty and/or increase knowledge beyond that gained from the wider RD&D programme and/or provide confidence that the repository is behaving as expected and/or support repository design improvements and/or feed into periodic safety case updates.

Parameter	Element	Strategy and Technology	Justification
Permeability/ groundwater flow velocity	Deposition hole seal (bentonite plug and concrete abutment)	Monitored by an indirect method using pressure sensors at different monitoring levels in dummy boreholes as well as in monitoring boreholes.	Provides information about fluid flow through the deposition hole seal, both into and out of the borehole. These are processes that are directly relevant to the overall safety function of the seal and to the related performance targets on permeability and swelling pressure of the bentonite element, and have an impact on modelled system performance. Monitoring could reduce uncertainty, increase knowledge beyond that gained from the wider RD&D programme, provide confidence that the repository is behaving as expected, support design improvements, and/or feed into periodic safety case updates.
Confining pressure	Deposition hole seal (concrete abutment)	Monitored directly in monitoring deposition boreholes at a number of “monitoring levels”, e.g. using vibrating wire and/or fibre optic sensors.	Provides information about the mechanical load on the abutment from above (including backfill mass and, later, rock pressure), which is relevant to the performance target on the expansion of the bentonite element (increase in plug length). Monitoring could support design improvements.
Swelling pressure	Deposition hole seal (bentonite plug and concrete abutment)	Monitored directly in monitoring deposition boreholes at a number of “monitoring levels”, e.g. using vibrating wire and/or fibre optic sensors.	Provides information about the swelling pressure evolution of the bentonite plug, which is relevant to the performance target on the swelling pressure of the bentonite element, and has an impact on modelled system performance. Monitoring could reduce uncertainty beyond the knowledge that gained from the wider RD&D programme, provide confidence that the repository is behaving as expected, and/or support repository design improvements.
Displacement	Deposition hole seal (vertical displacement of concrete abutment)	Monitored directly in monitoring deposition boreholes at a number of “monitoring levels”, e.g. using specific displacement sensors.	Provides information about the displacement of the concrete abutment in the direction of the drift above, which is relevant to the performance target on the expansion of the bentonite element (increase in plug length). Monitoring could reduce uncertainty beyond the knowledge that gained from the wider RD&D programme, provide confidence that the repository is behaving as expected, and/or support repository design improvements.
Water content/ saturation	Deposition hole seal (bentonite plug)	Monitored directly in monitoring deposition boreholes at a number of “monitoring levels”, e.g. using azimuthal deep resistivity (ADR) or ThetaProbes.	Provides information about the saturation evolution of the bentonite plug, which is relevant to the overall safety function of the seal and to the related performance targets on permeability and swelling pressure of the bentonite element, and has an impact on modelled system performance. Monitoring could reduce uncertainty beyond the knowledge that gained from the wider RD&D programme, provide confidence that the repository is behaving as expected, and/or support repository design improvements.

Opalinus Clay test case

The Swiss disposal concept envisages that spent fuel and HLW disposal canisters would be emplaced horizontally in a centred position on bentonite block pedestals in narrow tunnels excavated in the Opalinus Clay of northern Switzerland (Nagra, 2016) (Figure 2.3). The Opalinus Clay test case is based on this set-up, further details of which can be found in Nagra (2002a, 2002b, 2002c). Nagra’s disposal strategy is based on the concept of monitored long-term geological disposal. This concept envisages an extended period of monitoring, during which time the retrieval of waste is relatively easy, and a representative fraction of the waste is emplaced in a pilot facility. The objectives of the pilot facility are to:

- Demonstrate the emplacement process.
- Gather information about the barrier system to check predictive models and allow the early detection of undesirable system evolution
- Provide input for decisions regarding the closure of the facility.

In addition to monitoring of the pilot facility, the disposal rooms of the main facility and the access tunnels can be monitored. Furthermore, a test facility, or facility for underground geological investigations, will provide additional information in support of decision making, and some of this information can be classified as monitoring.

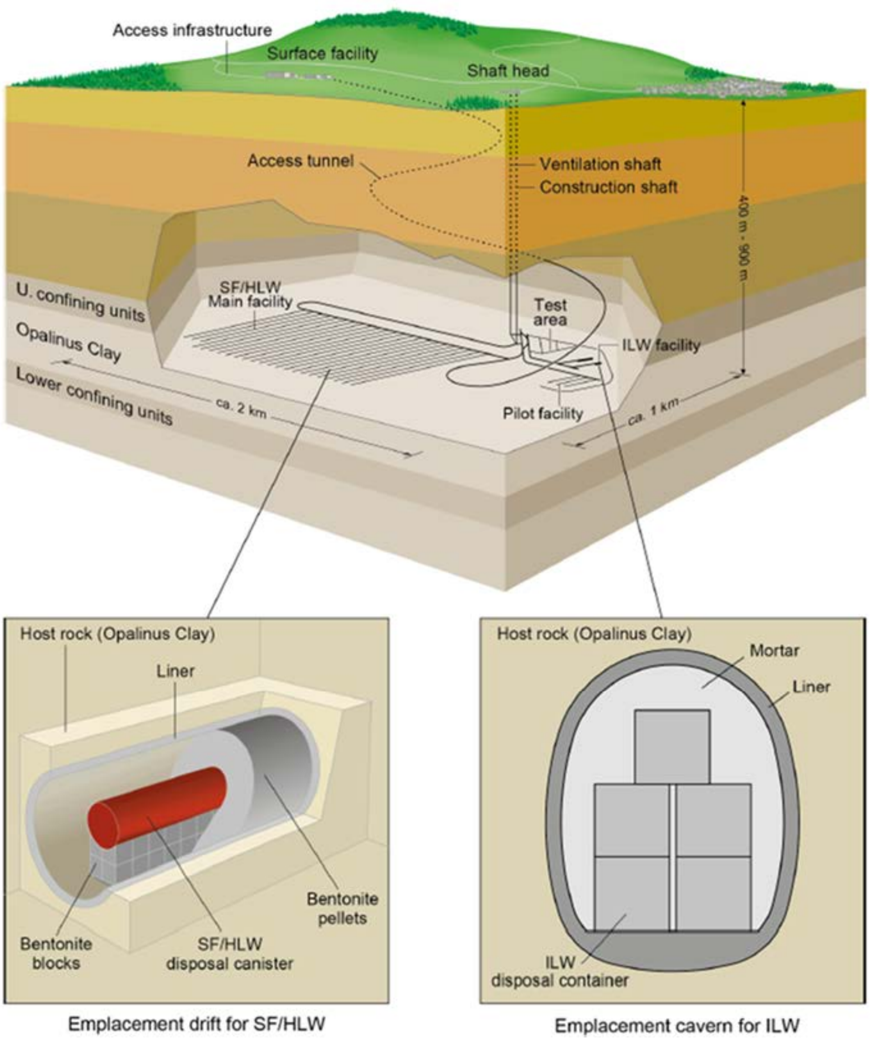


Figure 2.3: Possible layout for a deep geological repository for spent fuel, HLW and long-lived ILW in the Opalinus Clay, Switzerland. From Nagra (2016).

Nagra developed and applied its own methodology for identifying and screening parameters rather than using the preliminary Modern2020 Screening Methodology. However, the two approaches are based on the same ideas and contain equivalent steps. Nagra's methodology included five main steps: (i) identification of key safety-relevant parameters; (ii) consideration of whether monitoring is of interest; (iii) consideration of the practicability of monitoring; (iv) considerations of models and criteria for parameters; (v) overall assessment of monitoring rationale.

At the end of these steps, Nagra identified two parameters that may be useful to monitor (**Table 2.3**). In the test case, it was concluded that monitoring of these parameters during the operational phase could reduce uncertainty in meeting specific criteria.

Table 2.3: Parameters identified in the Opalinus Clay test case.

Parameter	Element	Strategy and Technology	Justification
Temperature	Near-field host rock	Monitored in pilot facility (before and after sealing) using wired fibre-optic distributed temperature sensors and/or wired or wireless thermocouples.	A criterion has been set for host rock temperature that it should remain below the maximum palaeotemperature experienced by the host rock (if met, thermally-induced mineralogical changes can be excluded). Based on modelling, there is some uncertainty as to the extent to which the criterion will be satisfied within the monitoring timeframe, so it is deemed useful to monitor.
Porewater pressure	Near-field host rock	Monitored in on-site test facility and/or pilot facility with classical sensors in combination with wireless technology if needed or alternative distributed pore pressure sensing with wired fibre-optic (under development).	A criterion has been set for host rock porewater pressure that it should remain below lithostatic pressure at repository depth (if met, the possibility that preferential release pathways will be generated by hydraulic fracturing can be excluded). Based on modelling, there is reasonable confidence that this criterion will be met within the monitoring timeframe but less confidence thereafter; therefore, monitoring may be useful to check the ability of the models to accurately predict later evolution.

OPERA test case

OPERA, a national research programme conducted in the Netherlands from 2011 to 2019, consisted of research into development of a generic safety case for geological disposal of spent fuel, HLW, ILW, LLW and depleted uranium. The OPERA safety case envisaged disposal of spent fuel and HLW in small-diameter tunnels, with the waste overpacked in concrete supercontainers (Figure 2.4).

The topic of repository monitoring is currently being addressed in the Netherlands in a generic fashion, and no guidance or specific requirements on the repository monitoring programme are available. Therefore, more specific objectives for the OPERA test case were defined, focusing on the initial identification of processes and parameters for all repository components, increasing understanding of the role of monitoring within the post-closure safety case in the Dutch programme, and the identification of uncertainties and knowledge gaps. The OPERA test case followed a two-stage approach, consisting of first deriving a preliminary parameter list, then undertaking a test screening of this list using the preliminary Modern2020 Screening Methodology.

The screening of the preliminary parameter list focused on the supercontainer only, and the approach followed the preliminary Modern2020 Screening Methodology. Following application of the preliminary Methodology, six parameters were identified for monitoring of the supercontainer during the operational period that could provide value to the post-closure safety case (Table 2.4). For all parameters, it was judged that monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme or could provide confidence that the system had been implemented as designed.

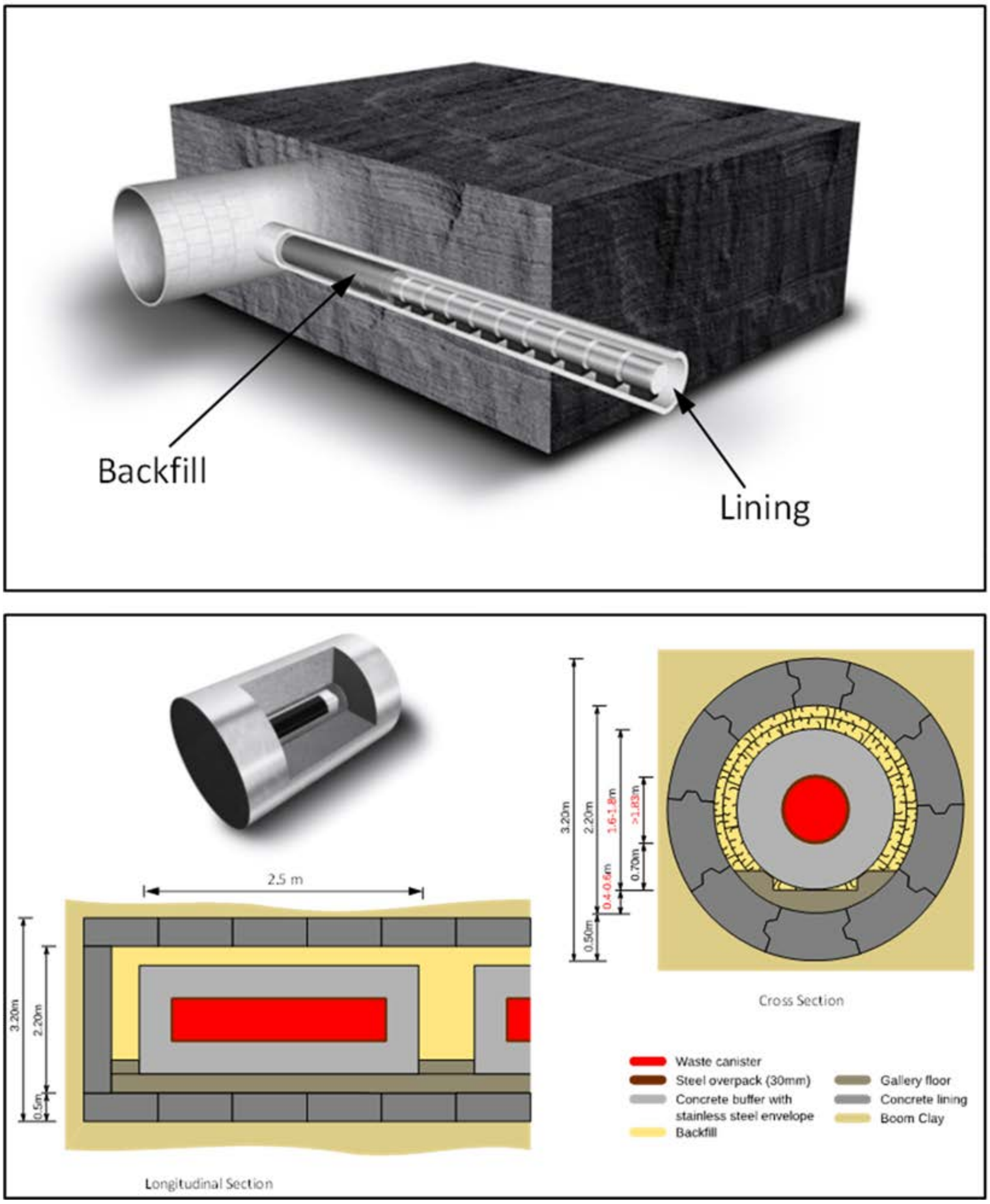


Figure 2.4: Illustration of the disposal concept considered in the OPERA safety case for the Boom Clay. Top figure shows the configuration of the disposal tunnels and bottom figure shows cross-sections and 3D image of the supercontainer. From Farrow *et al*. (2019).

Table 2.4: Parameters identified in the OPERA test case. For the OPERA test case, strategy and technology options were not defined.

Parameter	Element	Justification
Confining pressure	Supercontainer – carbon steel overpack	Provides information about mechanical disturbance to the overpack due to corrosion, cold cracking or welding, which is directly relevant to the supercontainer safety function of preventing contaminant release in the facility abandonment and poor sealing alternative evolution scenarios.
	Supercontainer – concrete buffer	Provides information about mechanical load (from external forces) on the buffer, which is indirectly relevant to the supercontainer safety function of preventing contaminant release and in the abandonment of facility and poor sealing alternative evolution scenarios.
	Supercontainer – steel envelope	Provides information about mechanical load (from external forces) on the envelope, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
Displacement	Supercontainer – carbon steel overpack	Provides information about mechanical disturbance to the overpack due to corrosion, cold cracking or welding, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
	Supercontainer – concrete buffer	Provides information about mechanical load (from external forces) on the buffer, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
	Supercontainer – steel envelope	Provides information about mechanical load (from external forces) on the envelope, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
Hydrogen concentration	Supercontainer – carbon steel overpack	Provides information about steel corrosion of the overpack following water ingress, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
	Supercontainer – steel envelope	Provides information about steel corrosion of the envelope due to interaction with Boom Clay porewater, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
Porewater pH	Supercontainer – concrete buffer	Provides information about geochemical evolution due to porewater/concrete interaction, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
Porewater / groundwater chemistry	Supercontainer – concrete buffer	Provides information about geochemical evolution due to porewater/concrete interaction, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
Redox potential	Supercontainer – carbon steel overpack	Provides information about steel corrosion of the overpack following water ingress, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
	Supercontainer – concrete buffer	Provides information about geochemical evolution due to porewater/concrete interaction, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.
	Supercontainer – steel envelope	Provides information about steel corrosion of the envelope due to interaction with Boom Clay porewater, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios.

TURVA 2012 test case

In Finland, Posiva's safety concept for the geological disposal of spent nuclear fuel is based on the KBS-3V design (Figure 2.5) and the characteristics of the Olkiluoto site in which the repository is under construction (Figure 2.6). In the KBS-3V design, the spent nuclear fuel assemblies will be placed into copper canisters with cast iron load-bearing inserts, and the canisters will be emplaced vertically in individual deposition holes bored in the floor of deposition tunnels excavated in crystalline host rock. The canisters will be surrounded by a swelling bentonite clay buffer material that will separate them from the bedrock.

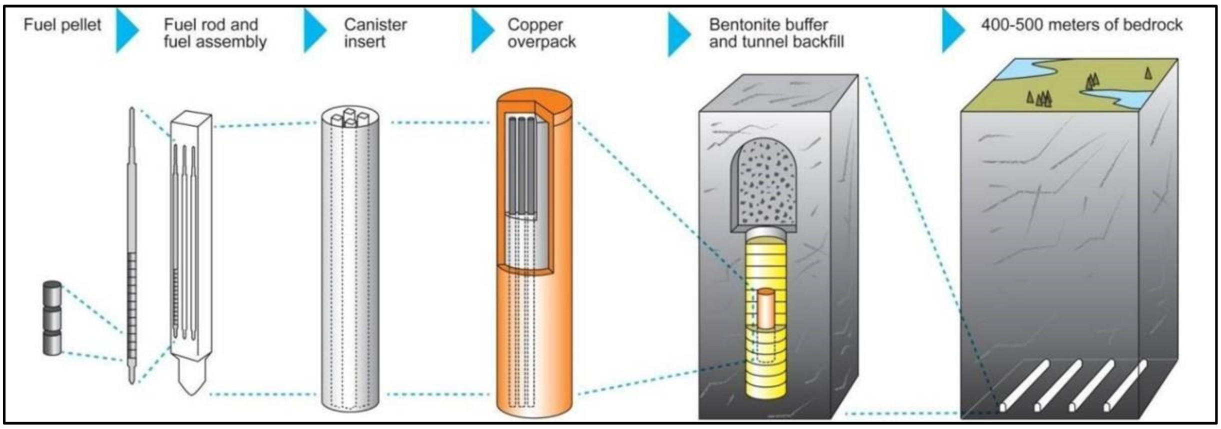


Figure 2.5: Illustration of the KBS-3V concept for disposal of spent fuel.

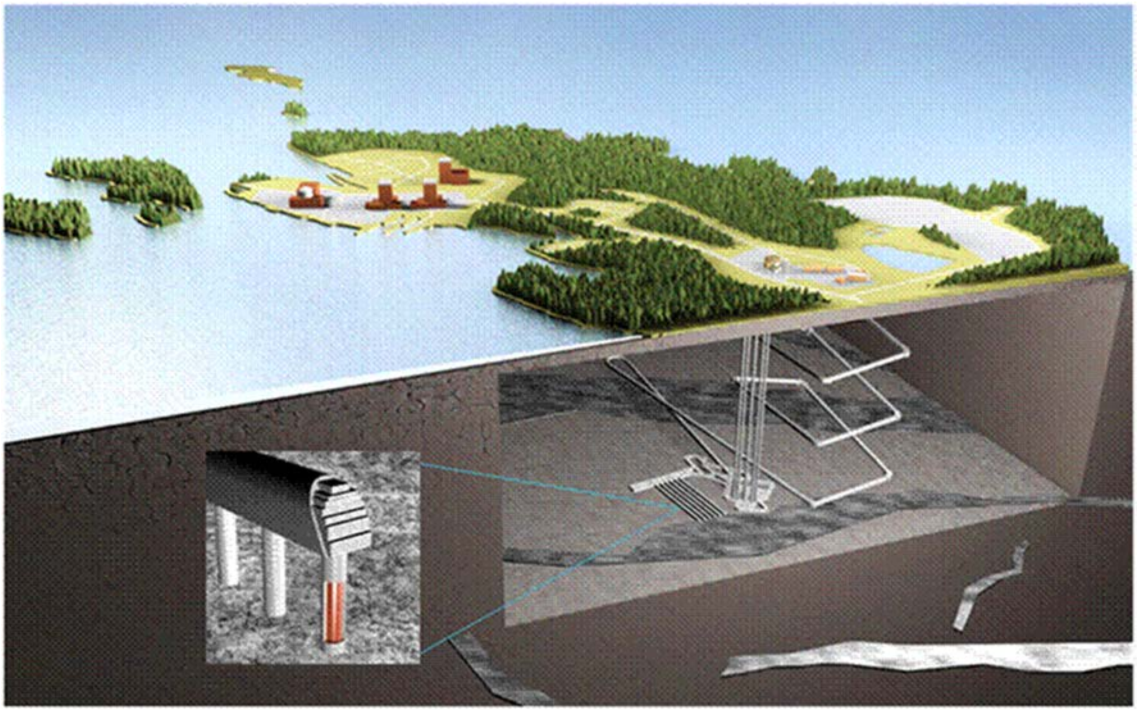


Figure 2.6: Illustration of the Olkiluoto repository considered in the TURVA 2012 test case. From Farrow *et al.* (2019).

Posiva has an existing monitoring programme which consists of five sub-programmes which deal with hydrogeochemistry, rock mechanics, surface environment, hydrology and hydrogeology, and EBS monitoring. Performance targets set for each component of the EBS within Posiva's requirements management system have been defined such that, if they are met, the safety functions will be fulfilled. These performance targets formed the starting point for the screening process. For each performance target (and relevant EBS component) one or more process with relevance to post-closure safety identified. Parameters that could be used to monitor these processes were then identified, along with its qualitative expected evolution. The technical feasibility of monitoring these parameters was assessed and an appropriate monitoring method proposed. Through overall assessment, whether or not the parameter should be monitored was then determined, together with identification of key uncertainties and how they could be resolved.

Application of this process led to the identification of twelve parameters (**Table 2.5**). In the test case, it was assumed that all of these parameters would be investigated through quality control, full-scale demonstrators and *in situ* tests (i.e. no direct operational monitoring).

Table 2.5: Parameters identified in the TURVA 2012 test case.

Parameter	Element	Strategy and Technology	Justification
Temperature	Canister, but measured in access tunnels	Monitored indirectly from tunnels (not directly related to a specific requirement on the canister).	Related to the performance target that the canister should not impair the safety functions of other barriers, hence relevant to post-closure safety, although primarily verified through design, dimensioning and QC (limited value in monitoring).
Permeability/ groundwater flow velocity	Tunnels and host rock around repository	Monitored directly from tunnels (away from deposition holes). Deposition tunnel plugs monitored visually while accessible.	Indirectly related to canister, buffer and backfill as these elements are designed to perform within specific boundary conditions. If these conditions are maintained in the geosphere then there is confidence that the canister, buffer and backfill will perform as designed, so they are considered useful to monitor. May include "light" monitoring of flow through deposition tunnel plugs.
	Deposition tunnel plug	Monitored directly during operations until tunnels backfilled, using a weir.	Provides information about piping/erosion in the buffer, since flow through the plug is related to flow through unsaturated deposition holes and could therefore indicate piping. This process is directly related to the safety function for the buffer to limit advective mass transfer. There is value in monitoring during the early development of the repository.
Swelling pressure	Buffer	Monitored in full-scale and/or *in situ* test, using sensors.	Directly relevant to several buffer performance targets, e.g. isostatic load from the buffer swelling pressure should be <10 MPa in the lower part of the buffer; swelling pressure should be less than the yield strength of copper canister and Olkiluoto host rock.
	Backfill	Monitored in full-scale and/or *in situ* test, using sensors.	Directly relevant to several backfill performance targets, e.g. swelling pressure at all points in the deposition tunnel >0.1 MPa in fully saturated state; backfill shall contribute to the mechanical stability of the deposition tunnels.
Geometry	Canister	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Directly relevant to several canister performance targets: canister must remain intact, copper shell must remain >0mm, should withstand asymmetric buffer swelling pressure loads of 3-10 MPa, which are relevant to overall safety function of preventing radionuclide release.
	Buffer	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Provides information about buffer water uptake, related to performance targets that buffer displacement should be limited, diffusion should be the dominant transport mechanism, and limits on isostatic load from buffer swelling. The process takes a long time, however, *in situ* tests could provide performance model validation.

Parameter	Element	Strategy and Technology	Justification
	Backfill	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Provides information about backfill water uptake, related to performance targets on backfill hydraulic conductivity, swelling pressure, limited deformation and requirement to contribute to mechanical stability of tunnels. The process takes a long time, however, *in situ* tests could provide performance model validation.
Displacement	Access tunnels and host rock around the repository	Indirect, regional monitoring. Also addressed through the RSC methodology.	Seismicity, including potential rock displacements, are indirectly related to the canister, buffer and backfill (e.g. related to performance targets for canister to remain intact and for copper shell to remain >0mm thick), with an emphasis on suitable deposition hole locations. If such locations are seismically suitable then there is confidence that the barrier elements will perform as designed.
Relative humidity	Backfill	Monitored in full-scale and/or *in situ* test (using sensors).	Provides information about water uptake and swelling, which are relevant to several backfill performance targets.
Water content/ saturation	Buffer	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Related to characteristics and processes affecting performance of buffer, e.g. water uptake and swelling.
	Backfill	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Related to characteristics and processes affecting performance of backfill, e.g. water uptake and swelling.
Porewater / groundwater chemistry	Host rock around repository	Monitored directly from access tunnels (away from deposition holes).	Indirectly related to canister, buffer and backfill as these elements are designed to perform within specific boundary conditions. If these conditions are maintained then there is confidence that they will perform as designed, so they are considered useful to monitor.
Mineralogy and chemistry	Buffer	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Related to performance of buffer as expressed in several performance targets (e.g. maintain favourable chemical conditions, should deform sufficiently to maintain canister integrity).
	Backfill	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Related to performance of backfill (e.g. performance target that backfill should have limited potential to be a source of sulphide).
Density (dry and bulk)	Buffer	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Related to various characteristics and processes affecting performance of buffer (e.g. water uptake) as expressed in performance targets (e.g. buffer displacement should be limited, diffusion should be the dominant transport mechanism, limits on isostatic load from buffer swelling, should deform sufficiently to maintain canister integrity).
	Backfill	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Related to various characteristics and processes affecting performance of buffer (e.g. water uptake) as expressed in performance targets (e.g. backfill hydraulic conductivity, swelling pressure, limited deformation and requirement to contribute to mechanical stability of tunnels).
Pore structure	Buffer	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Directly related to the performance target that the buffer should have sufficiently fine pore structure to filter radiocolloids, which is directly relevant to post-closure safety.
Piping and erosion	Backfill	Monitored in full-scale and/or *in situ* test (at installation and dismantling).	Directly relevant to hydraulic conductivity of the backfill, which is the subject of a performance target, as well as to homogenisation of density.

SR-site test case

SKB has submitted a licence application for a spent fuel repository in Forsmark, Sweden, based on the SR-Site safety assessment (SKB, 2011). As for the Olkiluoto repository in Finland, the Forsmark repository would also be based on the KBS-3V concept (Figure 2.5). In the SR-site test case, the starting point for identifying parameters for screening was safety functions (rather than processes), for which relevance to safety has already been established, and for which relations/interdependencies of processes have already been considered within SR-Site. Screening was undertaken for three safety function indicators (calculable quantities which relate to safety functions), relating to different barrier components: hydraulic conductivity/swelling pressure (backfill), charge concentrations of cations (buffer) and copper thickness (canister). These indicators were chosen to illustrate different monitoring strategy elements and resulted in the identification of three parameters.

Table 2.6: Parameters identified in the SR-Site test case.

Parameter	Element	Strategy and Technology	Justification
Permeability/ groundwater flow velocity	Deposition tunnel plug	Monitored directly during operations until tunnels backfilled, using a weir.	Provides information about piping/erosion in the buffer, since flow through the plug is related to flow through unsaturated deposition holes and could therefore indicate piping. This process is directly related to the safety function for the buffer to limit advective mass transfer. There is value in monitoring during the early development of the repository.
Porewater / groundwater chemistry	Host rock around repository	Monitored via borehole sampling.	Relevant to safety functions for backfill and buffer to retain sufficient mass over their lifecycle. To do this, they must be stable in contact with groundwater with a certain total charge equivalent of cations. Therefore, the relevant parameter is the electrical conductivity of the host rock groundwater. There is limited value in monitoring in order to build further confidence in the post-closure safety case as the relevant process is very slow; however, groundwater chemistry is already monitored through sampling at repository level as part of the host rock monitoring programme.
Corrosion rate	Canister	Monitored indirectly using corrosion coupons (*in situ* batch tests).	Directly related to safety function for canister to withstand corrosion (indicator criteria: copper thickness must remain >0mm). There is value in monitoring as understanding the early stages of corrosion may provide additional detailed and/or site-specific understanding not gained through previous RD&D.

Reference Project 2011 test case

The Czech programme is at an early stage of implementation, currently focusing on siting. Limited previous work has been undertaken on developing a repository monitoring programme, and consequently the Reference Project 2011 test case focused on the identification of possible monitoring parameters rather than screening to decide what should be monitored. The main components in the Czech concept are the canister, buffer, backfill, openings (host rock affected by excavation work), and other components (including plugs, grouting and construction materials) (Pospíšková *et al*., 2012). Possible parameters to monitor were identified through: (i) analysis of safety functions and performance/safety assessment assumptions (i.e., parameters needed to verify the assumptions); and (ii) discussions with Czech researchers who have been involved in relevant URL RD&D activities. Technical feasibility was not explicitly assessed as part of the test case, although consideration of potential methods for monitoring parameters has started. Potential monitoring technologies are expected to be tested in URLs in future experiments, and then, based on this, technologies can be selected for use in the repository.

SURAO believes that the Modern2020 Screening Methodology is a useful tool for realising all aspects of monitoring programme development, but has not applied it yet because the Czech programme is not yet sufficiently mature.

2.3.2 Conclusions from the test cases

Conclusions on monitoring objectives

For all participating organisations, undertaking the parameter screening test cases has moved forward internal understanding of monitoring and the development of parameter lists. The test cases provided a good ground for overall reflection and discussion on monitoring objectives, motivations and strategy, which can focus arguments and/or provide input for rethinking these aspects. During the test cases a variety of different objectives for monitoring were also identified, which fell into two categories:

- To provide an indication of EBS behaviour and/or repository performance.
- To build further confidence in the WMO and/or its safety case by demonstrating knowledge of processes and the ability to model them, and demonstrating understanding of the THMC evolution of the near field.

Conclusions on monitoring strategies

In the Modern2020 Project, a monitoring strategy is the high-level approach to the monitoring programme. There is a continuum between this high-level strategy and detailed design. At each point on the continuum, consideration can be made of *what* will be monitored, and *where*, *when* and *how* monitoring will take place, at increasing levels of detail. A high-level strategy describes the overall manner in which these elements are combined in order to describe the main aspects of any specific monitoring programme. Based on the test cases, several generic high-level strategy elements were identified (Table 2.7).

Table 2.7: High-level strategy elements that could be included in a monitoring strategy. Each specific monitoring programme is unlikely to include all elements. From Farrow et al. (2019).

Aspect	High-level strategy elements
Where	• Monitoring *in situ* in the main repository, without retrieval of monitored components at the end of the monitoring period • Monitoring *in situ,* with monitored components retrieved or decommissioned at the end of the monitoring period (and, if waste, re-disposed) • Monitoring in a pilot facility • Monitoring in an on-site test facility
What	• Waste packages (and surrounding EBS and near-field rock) • Dummy packages (and surrounding EBS and near-field rock) • Specific elements of the EBS (e.g. small-scale batch tests) • Geological barrier (near-field rock and far-field rock) • Biosphere
When	• Before repository operation or during commissioning • During the period of waste emplacement • After closure of the repository (in some countries)
How	*Considered in WP3 and WP4*

The strategy elements identified in Table 2.7 can be combined in various ways to form specific monitoring strategies that respond to national-programme drivers (e.g. deriving from the geological environment in which the repository is sited, the repository concept/design, and the relevant legislation). Strategy elements can also be combined in ways which reduce or eliminate inherent weaknesses in each element. Strategies considered in the test cases included:

- Monitoring of emplaced waste packages/EBS *in situ* in the main repository, with no intention to retrieve.
- Monitoring of waste packages/EBS *in situ* in the main repository, with the intention to retrieve and redispose them after the monitoring period.
- Monitoring of waste packages/EBS in a pilot facility.
- Monitoring of dummy packages/EBS in specified parts of the main repository.
- Monitoring of various elements during repository commissioning tests (both active and non-active).
- Long term *in situ* monitoring of specific EBS elements and volumes at various locations within the repository.

Conclusions on monitoring parameters

With the exception of the Reference Project 2011 test case of SURAO, all test cases identified several parameters that, following screening, could be included in a programme-specific repository monitoring programme. None of these are comprehensive lists of all parameters owing to the scope defined for the test cases, but they all represent progress towards this goal. The results of the test cases are also only trial developments of parameter lists and do not represent monitoring parameters that WMOs intend to monitor without further consideration. Comparing the parameters identified by the different test cases, there is minimal overlap and there is no common parameter for all test cases. In addition, the locations and reasoning for monitoring the same parameter vary significantly between test cases. This leads to a conclusion that there is no "standard" list of parameters that should be monitored in every monitoring programme; each national context has its own drivers, constraints and objectives, which exert an influence on choices of monitoring parameters, and need to be carefully considered when developing the monitoring programme.

General conclusions

All of the test cases were able to successfully apply structured approaches based on or comparable to the Modern2020 Screening Methodology. The work allowed the development of a final version of the Methodology, which is presented in the next section.

2.4 The Modern2020 Screening Methodology

From the analysis of and experience gained from implementing the preliminary Methodology in the seven cases described in Section 2.3, a final version Modern2020 Screening Methodology was developed. This is illustrated in Figure 2.7, and described in full in Farrow *et al*. (2019).

The Methodology is a generic process for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. It provides an overview of the steps that a WMO may take in identifying and managing a list of parameters, linked to processes, and repository monitoring strategies and technologies. It was developed to further elaborate the monitoring programme design section of the MoDeRn Monitoring Workflow, which envisaged that a preliminary parameter list would be developed and screened for feasibility in order to identify the parameters to be included in the monitoring programme.

Monitoring of the repository during operations has the potential to introduce operational safety hazards, impacts on passive safety following closure, and logistical challenges. Therefore, it is important that the inclusion of each parameter in a monitoring programme is carefully considered and its need justified. This is consistent with both the IAEA safety requirements and NEA guidance discussed in Section 2.1.1.

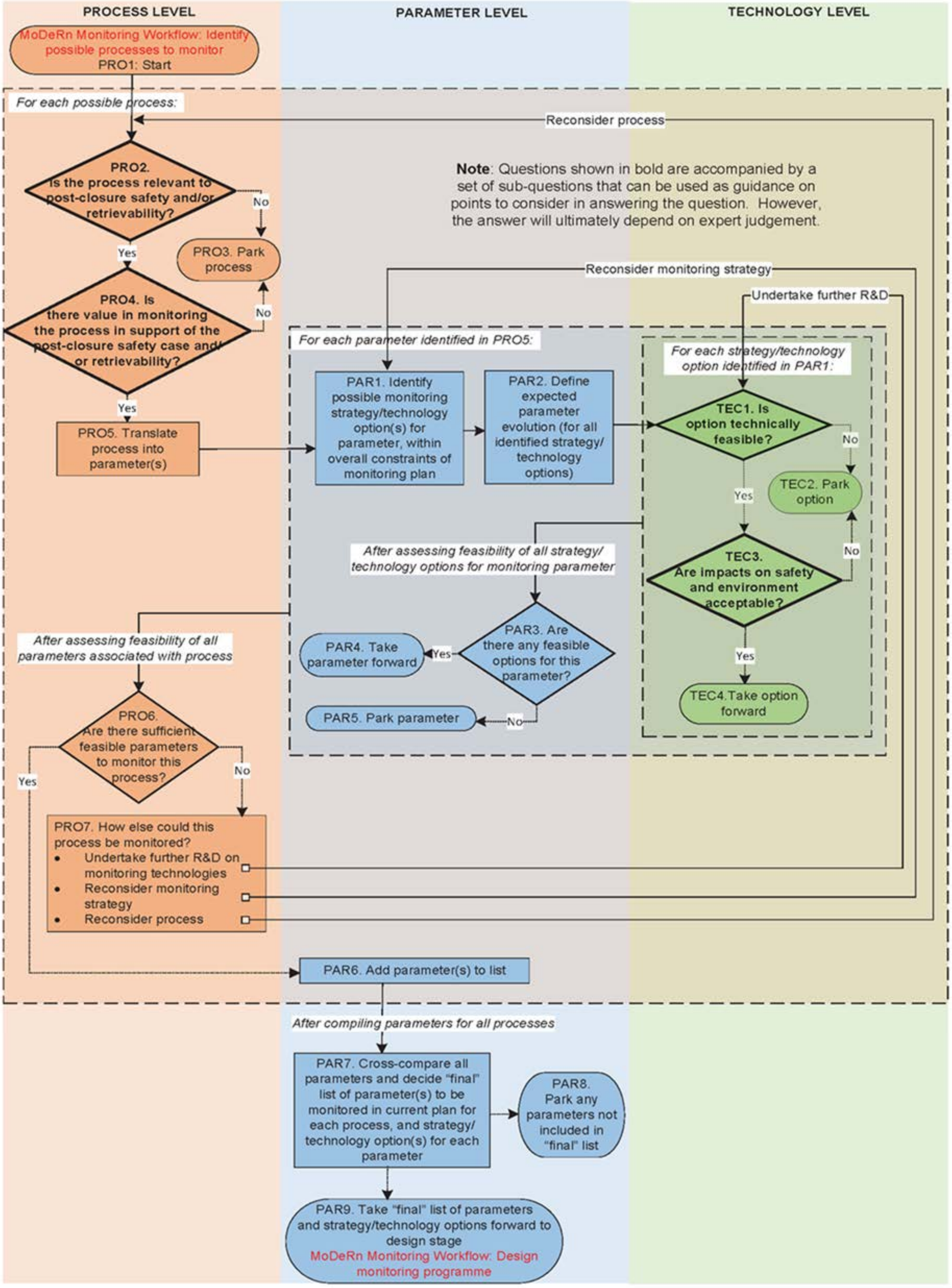


Figure 2.7: The Modern2020 Screening Methodology for selection of monitoring parameters.

The Modern2020 Screening Methodology (and the MoDeRn Monitoring Workflow within which the Screening Methodology sits) is envisaged as an iterative process that would be repeated multiple times during the operational phase of the repository. Interactions with the regulators and other stakeholders would occur during operation of the Methodology in a manner consistent with the regulatory process and with the WMO stakeholder engagement plan. The Screening Methodology might be re-run in parallel with a periodic update to the post-closure safety case, in response to unexpected results from the monitoring programme (responding to monitoring results is discussed below in Section 2.5), or in response to an external request.

One consequence of the Screening Methodology being iterative is that parameters are not screened out of the process at any stage. Instead, parameters are *parked*, so that they remain within the system and can be considered in the next iteration of the Methodology. Parking of parameters requires traceable screening decisions to be made, for example in evaluation tables or in databases. Parking of parameters is not considered to lead to a need for onerous re-evaluation of parameters at each iteration of the Screening Methodology; each WMO can choose not to re-evaluate the parked parameters if they so wish.

The philosophy that underpins the Modern2020 Screening Methodology is to consider each potential monitoring process in turn. The process is considered for each component of the disposal system to which it is relevant, and considers the treatment of the process in, and relevance to, the safety case, at three interlinked levels:

- Processes.
- Parameters.
- Technologies (feasibility).

First, the potential relevance of the process and value of monitoring the process with respect to the post-closure safety case is evaluated. For processes considered to be both relevant and valuable, one or more parameters that could be used to monitor the process are identified. For each parameter, possible monitoring strategy and technology options are identified and the expected parameter evolution with respect to each option determined. The technical feasibility is then judged for each option in turn. Once technical feasibility has been assessed for each parameter option, the outcome is reviewed to determine if there are technically feasible options that allow the parameter to be taken forward. This evaluation in turn allows consideration of whether there are sufficient parameters to monitor each process identified earlier. If there are insufficient parameters to monitor the process, the earlier steps in the Methodology would have to be revisited. Finally, the Methodology includes cross-comparison of monitoring parameters to check completeness and appropriate redundancy, and to ensure that an integrated monitoring programme is developed.

The Methodology is intended to be indicative and flexible rather than prescriptive, and can be regarded as a template that can be adapted by individual WMOs to suit particular needs. Flexibility includes, for example, the possibility to modify the starting points and approaches as appropriate for each waste management programme. Furthermore, the methodology is applicable to other types of radioactive waste disposal facilities, such as near-surface facilities.

2.5 Responding to monitoring results

2.5.1 Introduction

Planning for evaluating and responding to monitoring results was addressed in WP2.3 of the Modern2020 Project (White *et al.*, 2019). As discussed in previous sections of this chapter, general strategies for conducting monitoring during the operational period have been elaborated on a programme-by-programme basis. However, specific programmes that include, for example, lists of parameters to be monitored during the operational period to build further confidence in the post-closure safety case and identification of the technologies that will be used to monitor these parameters, have not been established in almost all cases. Furthermore, each specific monitoring programme will respond to the relevant national context, which includes relevant legislation and regulatory guidance, the wastes to be disposed of, the geological environment, and the repository design. It is therefore not yet feasible to develop specific plans for responding to monitoring results, or for using the information gained through monitoring in decision making. Instead, work carried out as part of the Modern2020 Project has focused on developing generic guidance on planning for evaluating and responding to monitoring results, and the resulting decisions that can be made.

The project considered decision making in other industries, for example, carbon capture and storage, but concluded that monitoring the EBS and near-field rock in support of building further confidence in the post-closure safety case was sufficiently unique that no direct lessons could be applied from elsewhere (White *et al*., 2019).

2.5.2 Types of responses

Responses to monitoring programme results might be based on evaluation of data on an individual basis (i.e. parameter-by-parameter) and/or evaluation of data and information as an integrated data set. Evaluation of an individual parameter might be undertaken against specific evaluation criteria (the prediction of the parameter values) as it is acquired. Such evaluation was referred to in the Modern2020 Project as "continuous evaluation". Evaluation of the full dataset was referred to as "periodic evaluation".

2.5.3 Continuous evaluation

Three types of results are envisaged for the continuous evaluation of individual parameters:

- Monitoring results lie within the range of predicted parameter values and trends indicate that they will continue to do so. In the Modern2020 Project, these results were referred to as *consistent results*. Responding to these results would be to continue monitoring and feed the results into a periodic update of the safety case at the appropriate time.
- Monitoring results lie outside the range of predicted parameter values and/or trends indicate that they will do so in the future, but the results do not contradict assumptions made in the safety case, i.e. the results are insignificant to safety. In the Modern2020 Project, these results were referred to as *inconsistent but insignificant results*. Responding to this kind of monitoring result would not require immediate intervention. Instead, a range of responses could be envisaged, such as evaluating sensor performance, checking results and reporting results that deviate from the parameter value predictions. These results would be compared to other results during a periodic evaluation of the monitoring programme.
- Monitoring results lie outside the range of predicted parameter values and/or trends indicate that they will do so in the future, and the results have the potential to contradict assumptions made in the safety case, i.e. the results are potentially significant to safety. In the Modern2020 Project, these results were referred to as *inconsistent and potentially significant results*. Dependent on an initial assessment of the results, significant actions might be undertaken, including halting emplacement operations whilst further evaluation of the data is undertaken, or undertaking a supplementary periodic evaluation involving additional monitoring data and/or models. More significant actions, for example, initiating design changes, might be taken following a periodic evaluation triggered by such results, in which the full range of data available from the monitoring programme and other ongoing activities would be considered.

2.5.4 Periodic evaluation

As indicated above, monitoring of individual parameters would not provide sufficient information to act as a check on integrated repository performance. Performance depends on the coupled behaviour of processes occurring in the repository, not just on individual parameters. For the example of temperature monitoring, temperatures in the near field might be higher than expected, but, if significant, this (negative performance) might be offset by better than expected performance of other parameters, such as a slower rate of saturation delaying the onset of container corrosion (positive performance). For this reason, it is necessary to consider parameter evolution in terms of the impact on the safety case rather than in terms of individual results.

Therefore, in addition to continuous evaluation of individual parameter results, some programmes may decide it is necessary to cross-compare a broad set of data to gain a holistic understanding of repository performance (periodic evaluation). Three reasons for undertaking a periodic evaluation of results were recognised in the Modern2020 Project (White *et al.*, 2019):

- In response to specific results that are inconsistent and potentially significant.
- Planned periodic updates to the safety case.
- As the result of an external decision (e.g. a request from the regulator or other Government agency).

2.5.5 Generic responses

A range of responses were identified to periodic evaluation, and these are summarised in Table 2.8.

Table 2.8: Generic responses to monitoring results. From White et al. (2019).

Generic Response	Explanation
Desk-based responses	
Evaluate sensor performance	Re-checking of the raw data from sensors to check that the sensor readings are valid.
Check results	Re-checking the analysis of sensor readings to check that the interpretation of the raw data is valid.
Report results	Notifying stakeholders (including regulators) of results.
Root cause analysis	Evaluating the reasons behind particular monitoring results, focused on results that are not consistent with expectations. This might include, for example, literature review.
Revise models / safety assessment	Modifying THMC and safety assessment models to incorporate new process understanding and/or parameter values.
Update monitoring plan	Revising the monitoring programme, taking into account the results from the monitoring programme to date (and any other information generated during the period since the monitoring programme was last updated).
Monitoring Programme Responses	
Continue monitoring in the same way	Continuing the operation of the monitoring programme using the same method (e.g. using the same number and type of sensors, in the same locations, and with acquisition of data at the same frequency).
Change monitoring	Changes in the monitoring programme could relate to changes in the frequency of data acquisition using the current monitoring system, monitoring the same parameter(s) with additional sensors of the same type (additional redundancy), monitoring the same parameter(s) with different sensors (increased diversity), or monitoring of different parameters.
Disposal Programme Responses	
Change operations	The emplacement of waste could be altered by, for example, placing a temporary halt on emplacement operations, or only emplacing waste of a specific type. Monitoring can also support decisions to move from one phase of repository operations to the next, including supporting a decision to close the repository.

Generic Response	Explanation
Change design	Evaluation of the results from the monitoring programme may be used to underpin decisions to change the design of the repository.
Engineering intervention	Changing the properties of the repository near field through engineering measures such as grouting, *in situ* vitrification and construction of new barriers.
Reversal / retrieval	Reversal is removing the waste from the disposal location by reversing the original emplacement process (the term is also used to denote the ability to reverse decisions). Retrieval is removing the waste from the disposal location by any means.

2.5.6 Generic process for responding to monitoring results

The performance of the repository following emplacement of the waste is expected to be consistent with the safety case. Extensive RD&D, backed up by QA/QC during operations, will have been conducted to ensure this is the case. The sensitivity of the safety case to variant scenarios, including scenarios where barriers are performing less well than expected, will have been taken into account in repository design. Therefore, it is not feasible to develop response plans to describe actions that would be taken in response to specific monitoring results; if such results can be imagined, they will be taken into account during the development of the safety case.

Nonetheless, there remains the possibility that the full set of monitoring results indicates that repository performance is inconsistent with the safety case (non-compliant results), for example that there are unknown unknowns that are not considered in the safety case. Therefore, plans should be put in place to respond to results that are inconsistent with the safety case, and much of the focus on planning for responding to monitoring results is on development of the understanding of the type of responses that might occur and development of processes to implement these responses if necessary.

Based on consideration of the types of results likely to come from a monitoring programme, and the types of generic responses, a generic process for responding to monitoring results was developed. The process is illustrated in Figure 2.8.

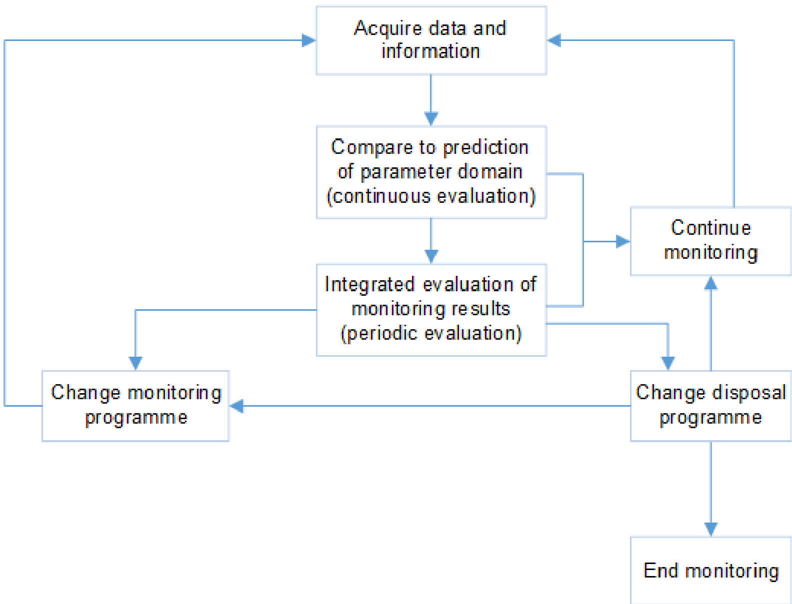


Figure 2.8: Workflow for responding to monitoring results. From White *et al*. (2019).

2.5.7 Guidance on responding to monitoring results

The Modern2020 Project identified the following recommendations and observations on planning for evaluating and responding to monitoring results:

- It is not possible to define a direct link to safety for all monitoring parameters (in all locations and at all times).
- Response plans should be developed to describe actions that could be taken following unanticipated monitoring results.
- Response plans need to be adaptable as the details of unexpected repository system behaviour cannot be predicted in advance, and responses should consider the overall repository system behaviour.
- Assessment of monitoring results might need to consider processes that have not been previously identified as being significant (although extensive research on repository processes means that there should be no new processes identified).
- Usually, the first response to unexpected results is to check data quality/interpretation, and then to consider the implications for safety.
- Monitoring results should be compared to the expected variation of the parameter values in time and space.
- Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the monitoring dataset.
- Periodic evaluation might occur in response to the outcome of a continuous evaluation and/or at a regular interval.
- Response plans should include the organisational set-up for responding to monitoring results.
- The approach to responding to monitoring results can be guided by consideration of a generic action list, comprising desk-based actions and physical actions.
- Responding to monitoring results can be undertaken in dialogue with stakeholders, as determined by programme-specific and country-specific procedures and regulations.
- Decision making is a complex process where monitoring is only one input.

2.6 Conclusions from WP2

2.6.1 The context for the strategy work undertaken in the Modern2020 Project

As noted in Section 1.1, there were many years of international collaboration on monitoring that preceded the Modern2020 Project. This has included production of a technical document by the IAEA (IAEA, 2001), development of international requirements and guidance on monitoring (IAEA, 2011a; 2011b; 2012), a review of monitoring by the NEA (NEA, 2014a) and collaborative efforts under the auspices of the EC (EC, 2004; MoDeRn, 2013a). In parallel, some repository programmes have developed monitoring plans (e.g. Posiva, 2012), monitoring has been undertaken in parallel with operations at the WIPP Facility in the US (e.g. USDOE, 2019), and monitoring of surface and near-surface repositories has been undertaken, for example at the Forsmark site in Sweden (e.g. Berglund and Lindborg, 2017).

One of the common threads of this work is to recognise that monitoring is a broad subject and monitoring can be undertaken for many reasons. For instance, monitoring may be undertaken to support the basis for repository performance evaluations; to support operational safety; to support environmental protection; and/or to support nuclear safeguards (MoDeRn, 2013a). Wider considerations for monitoring include monitoring of the socio-economic impact of repository development in the host community, and monitoring of other programmes and technology developments to ensure that programmes are applying good practice and the best available techniques.

The focus of the Modern2020 Project (and the MoDeRn Project that preceded it) was monitoring of the EBS and near-field during the operational phase in support of building further confidence in the post-closure safety case. The phrase "further confidence" is used because it is recognised that to receive a permit to begin operations, confidence in the post-closure safety case must have been established. Monitoring of the EBS and near-field during the operational phase in support of building further confidence in the post-closure safety case is considered to present the greatest challenge with respect to repository monitoring for the following reasons:

- The processes that occur in EBS and near-field rock following emplacement are typically slow and are transient processes that respond to the recovery of *in situ* conditions following the construction, operation and backfilling of the repository. For example, emplacement of heat-emitting waste can lead to a desaturation of parts of the near-field; longer-term saturation will occur once the thermal output has reduced, and it is only once this has happened that long-term processes directly related to safety can be established (e.g. swelling of bentonite, passivation of metal containers and onset of long-term corrosion processes).
- Monitoring following emplacement of the EBS has the potential to affect the passive safety of the barriers or the delivery of safety functions. This includes the possibility of providing radionuclide migration pathways, disrupting the emplacement of barriers (e.g. reducing the density of bentonite backfills), or affecting long-term performance by introducing foreign materials (e.g. aggressive ions and organic species included in monitoring sensors).

Furthermore, planning for monitoring during the operational period to build further confidence in the post-closure safety case is challenging as there are no specific regulations that define exactly the post-closure-related parameters that must be monitored. Regulations typically refer to the need to monitor processes to provide further understanding, rather than identifying specific processes for monitoring.

Despite these limitations there is a broad agreement that monitoring during the operational phase to provide further confidence in the post-closure safety case is beneficial. In most countries, such monitoring is part of regulations. Furthermore, the repository (at least the access ways to the disposal rooms) will be accessible and available for gaining further understanding for decades, and it is important that this opportunity is used to gather information that will support decision making in the future, in particular, decisions to close the repository, to check that current understanding remains valid, and that the repository has been implemented as envisaged. There is also broad agreement that it is better to know what is happening, at least in certain parts of the repository, and accept a small and insignificant decrease in performance of the system (which would have to be checked by evaluating the impact any monitoring system would have on post-closure performance), than to not undertake monitoring of the EBS and near-field rock.

Developing processes to manage the challenges for conducting such monitoring and realising the benefits has been a key focus of the Modern2020 Project.

2.6.2 Main outcomes and conclusions from WP2

The work on strategic aspects has allowed a common international understanding of generic monitoring programme strategies, parameter-selection methodologies and generic plans for responding to monitoring results. The outcomes and conclusions from WP2 have resulted in the development of the Modern2020 Monitoring Workflow, which is illustrated in Figure 2.9.

It is recognised that monitoring programmes need to be specific to the context of the programme in which it is undertaken. This context includes national regulations, the wastes to be disposed of, the host geological environment, the disposal concept and repository design, and the socio-political context (e.g. the level of trust held by stakeholders).

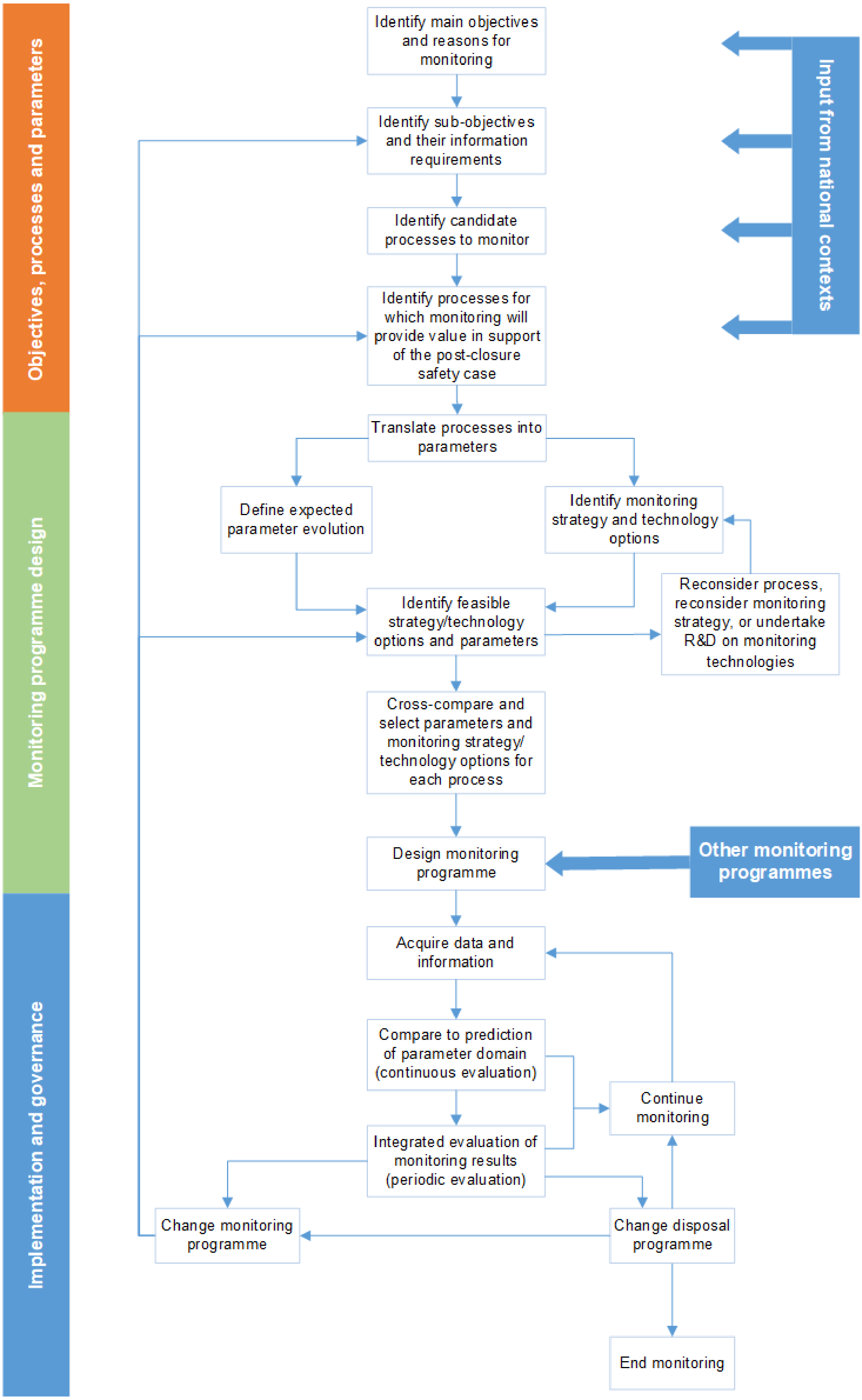


Figure 2.9: The Modern2020 Monitoring Workflow.

WP2 of the Modern2020 Project has provided the basis for WMOs to develop programme-specific repository monitoring programmes focused on building further confidence in the post-closure safety case. Work has included consideration of the role of the monitoring programme in the post-closure safety case, identification of monitoring strategies, conducting seven parameter identification test cases and development of the Modern2020 Screening Methodology. The Methodology is intended to be indicative and flexible rather than prescriptive, and can be regarded as a template that can be adapted by individual WMOs to suit particular needs.

To address the challenges of monitoring during the operational phase to build further confidence in the post-closure safety case described in Section 6.1, WMOs have developed flexible approaches combining monitoring in different ways and utilising different technologies. These flexible approaches include different strategies, and also greater integration of the monitoring programmes with ongoing RD&D and within the post-closure safety case.

Monitoring strategies include monitoring of disposal tunnels in which the waste is emplaced, disposal in representative disposal tunnels, and monitoring of specific elements of the disposal system (including the EBS) in test galleries. Each approach has its own strengths and weaknesses. For example, a strength of monitoring disposal tunnels in which the waste is emplaced allows the impact of most processes to be taken into account, whereas a weakness is the potential impact on post-closure performance. In contrast, a strength of monitoring in representative tunnels is the ability to decommission and dismantle the monitored components (dismantling of test areas can be planned to coincide with periodic updates to the safety case) during which specific measurements can be undertaken and monitoring sensors can be recalibrated, whereas a weakness is demonstrating the representativity of the monitored area.

Although there appears to be significant differences in the monitoring programmes proposed by WMOs (see Section 2.3), there are actually many commonalities. For example, although specific objectives differ, the use of a standalone monitoring gallery is a strategy adopted by many WMOs, such as the Swiss programme (pilot repository), the French programme (Industrial Pilot Phase) and Posiva's programme (Full-Scale *In Situ* System Test). These facilities have a similar role to monitoring of the first emplacement field in the ANSICHT concept in Germany, although considerations of representativity caused the German programme to decide that the first emplacement field had to be part of the main repository.

The work in the Modern2020 Project provided detailed developments to the MoDeRn Monitoring Workflow developed within the MoDeRn Project. These focused on the monitoring programme design and implementation and governance sections.

With respect to monitoring programme design, the focus was on parameter selection. As there will be consensus on the confidence in the post-closure safety case at the outset of the operational phase, and the focus of the monitoring programme will be to build further confidence, the selection of parameters is considered in the Modern2020 Project to be a value judgement, i.e. an evaluation of the value monitoring any one parameter would provide to the overall implementation of geological disposal.

Monitoring might be focused on a comprehensive check on system behaviour by focusing on a broad range of parameters or may be focused on a few monitoring parameters that indicate that overall system performance is consistent with expectations. Such monitoring will feed into revisions to the safety case, and support the programme advancing from one stage to the next Monitoring may also contribute to modifications in the way the repository is operated, for example changes to the emplacements schedule or revisions to the detailed design. Such optimisation of the disposal system design is recognised as a key driver for parameter selection approaches by some WMOs and less so by others.

Determining parameters to be monitored in an implementable and logical repository monitoring programme for the EBS and the near field is challenging but achievable. Finding a balance (appropriate to the national context and drivers) between monitoring everything possible and monitoring only what is valuable is a key challenge. Consistent with IAEA and NEA guidance, a repository should be passively safe without relying on monitoring, and so it is important that all monitoring activities are carefully considered and their need justified.

Two principal justifications for monitoring a parameter are possible: firstly, that parameters are relevant to post-closure safety and/or retrievability, for example through being directly linked to safety functions. However, monitoring during the operational phase to build further confidence in the safety case may include additional demonstration of general THMC understanding (in addition to the understanding demonstrated in the safety case submitted as part of the licence application), so a direct link to safety is not necessarily required for there to be value in monitoring a parameter.

There is no common set of parameters that should be monitored in every repository monitoring programme. Instead, the parameters to be monitored in each programme will depend strongly on the specific drivers, constraints and objectives identified in the national and repository-specific context, and selection of monitoring parameters is a process of expert judgement based on knowledge of the specific programme.

Decisions on parameter screening are more readily undertaken by programmes with detailed safety case approaches and repository performance models, and a more developed understanding of stakeholder expectations regarding monitoring. However, there are advantages to planning repository monitoring at an early stage, such as allowing sufficient time for technology development, ensuring design takes account of monitoring needs, building stakeholder confidence, and enabling some information/confidence requirements to be addressed through long-term experiments instead of or in addition to monitoring. Early thinking about monitoring also ensures that aspects of monitoring relevant to different stages (e.g. siting, construction, commissioning and operation) can be developed and implemented at the appropriate time.

Depending on the type of monitoring adopted by a WMO, processes (and their associated parameters) can be identified through analysis of different safety case inputs, including safety functions, FEPs considered in scenario analysis, safety assessment parameters and general consideration of THMC processes. Regardless of the method used to identify possible monitoring parameters, a screening process is required to ensure that an appropriate set of parameters is taken forward to implementation of the monitoring programme.

The Modern2020 Screening Methodology provides a structured process for screening a list of potential monitoring processes, in order to come up with a list of parameters that are practicable and feasible to monitor during the operational phase. Testing of the Methodology has shown it to be flexible and appropriate to all repository programme contexts. In addition, the testing of the Modern2020 Screening Methodology by seven waste management programmes during the Modern2020 Project allowed the monitoring programmes to advance significantly as a result of the Project.

The Modern2020 Project also provided guidance and recommendations on responding to monitoring results (Section 2.5.7). The guidance includes consideration of responses related to monitoring results from individual parameters (continuous evaluation) and responded to the integrated set of monitoring results (periodic evaluation). Monitoring of individual parameters cannot provide information about overall repository performance, as relatively poor performance of one parameter may be balanced by better than expected performance by other parameters.

Contrary to the view held before the Project, it was argued that specific response plans could not be developed prior to conducting monitoring; if a negative performance could be imagined, it should be dealt with in the safety case (for example by running sensitivity calculations that accounted for the FEPs driving the negative performance). Therefore, the monitoring programme could focus on detecting unknown unknowns (for monitoring focused on checking the detailed performance of the disposal system), and/or in confirming system behaviour. Rather than development of specific response plans, the Modern2020 Project argued that WMOs should identify the processes that will be used to evaluate and respond to monitoring results. To this end, a list of generic responses was developed (**Table 2.8**). It is envisaged that the generic list of monitoring responses will provide a useful tool for WMOs in planning and implementation of monitoring programmes.

Furthermore, consideration of responding to results also emphasised that monitoring data are most likely to be consistent with the safety case, and provide supporting information to make decisions, such as to close the repository, and, potentially, to optimise the design progressively during operations (depending on the programme-specific view of this issue).

2.6.3 Need for further work

The Modern2020 Project has worked collaboratively on an international basis to provide comprehensive guidance on the strategic aspects of repository monitoring. There is a broad consensus for the guidance, tools and approaches proposed within the Project (White *et al.*, 2017; 2019; Farrow *et al.*, 2019). The key requirement now, is for the guidance to be applied in specific programmes, and for detailed operational phase monitoring programmes to be developed.

Future work on monitoring strategies should focus on programme-specific implementation of the guidance, tools and approaches developed in the Modern2020 Project. Activities undertaken in the test cases need to be extended to all relevant components of the underground repository system. There is also a need, in most programmes, to focus on more detailed aspects of monitoring programme design, such as selection of sensor type, number and locations. Detailed assessments of the impact of the monitoring system on the post-closure safety case (such as including sensors in models) will also need to be carried out, especially in cases where sensors are installed inside EBS components.

To be useful and traceable in the future, the screening process and its results must be transparent and understandable to future generations and external stakeholders. Therefore, WMOs must give thought to both the format and the level of detail of how results and their underpinning justification will be presented, as well as giving thought to the ways and means to interpret monitoring results and comparing the results to parameter predictions. Further work on developing implementable monitoring programmes is ongoing for all WMOs.

However, there would also be significant value in continuing international collaboration. In particular, there is likely to be additional learning from applying the guidance, tools and approaches to specific programmes. Examples include learning about the value judgements made in deciding which parameters to monitor, and learning methods for recording justifications for the value judgements, and for providing transparency and traceability in the development of monitoring programmes.

The results of the Modern2020 Project related to responding to monitoring results should be considered and developed further as part of the IAEA Working Group on the Use of Monitoring Programmes in the Safe Development of Geological Disposal Facilities for Radioactive Waste.

International collaboration could be continued by convening a regular meeting of monitoring experts (e.g. on a bi-annual basis) or setting-up a repository monitoring network that would include discussion of strategic aspects of repository monitoring. This network should be broad ranging and discuss all aspects of repository monitoring to continue the transdisciplinary approach adopted in the Modern2020 Project.

3 Modern2020 WP3: Repository Monitoring Technologies

3.1 Technologies for monitoring the EBS and near field following EBS emplacement

This chapter focuses on R&D work undertaken, key results and conclusions of the Modern2020 WP3 work on monitoring technologies intended for use in repository monitoring during the operational period following emplacement of the EBS.

Monitoring in repository-like environments has been undertaken for decades in URL experiments, including full-scale experimental mock-ups of the EBS. These experiments employ extensive monitoring systems, typically with many hundreds of sensors. These monitoring systems have been able to successfully track the THMC processes occurring over the experimental period (typically a few years), and contribute to the development of understanding of EBS behaviour.

As has been indicated in Chapter 2, monitoring of the EBS and the near-field rock during the operational period is likely to be significantly different to monitoring of URL experiments. Experience from monitoring of URL experiments does provide experience and expertise relevant to monitoring of the EBS and the near-field rock during the operational period, but new developments (as described below) are necessary for the monitoring strategies envisaged by some WMOs to be fully implementable. The type of monitoring undertaken and the technology employed will be dependent upon the strategy followed. Monitoring during the operational period will comprise fewer sensors employed in such a way that there is no significant impact on the post-closure safety case. Sensors, cables and other monitoring equipment should be unobtrusive, occupying as little space in and around the repository as possible. The routing of cables through barriers is also currently considered to be unacceptable for strategies involving monitoring of waste packages and associated EBS in situ (the use of cables through barriers may be acceptable for strategies such as pilot repositories or for other types of disposal concept not considered in the Modern2020 project such as disposal of ILW). In addition, monitoring equipment must be able to withstand the environmental conditions. Depending on the disposal concept and the location of the sensors, conditions might include an aggressive chemical environment, high temperatures and high radiation fluxes. The equipment used in repository monitoring must be amenable to qualification ahead of use, to ensure reliable results are achieved over the monitoring period.

To address the technical challenges of monitoring the EBS and near field during the operational period, several approaches are being considered:

- Various monitoring strategies involving monitoring of emplaced waste and the surrounding EBS and geological barrier, pilot repositories, long-term *in situ* monitoring of specific EBS components and monitoring in an on-site test facility (see Chapter 2).
- Monitoring *in situ* and wireless data transmission.
- Monitoring using systems with low impact on the passive safety of the EBS, e.g. the use of distributed fibre optic systems.
- Development of specific new sensors, focused on potential repository monitoring parameters.
- Monitoring using non-intrusive technologies based on geophysical methods.
- Development of a common multi-stage qualification methodology.

Repository monitoring using the technologies mentioned above has been the subject of research previously, for example in the MoDeRn Project. However, at the start of the Modern2020 Project specific fundamental challenges remained before such technologies could be applied in repositories.

With respect to wireless data transmission, the MoDeRn Project successfully developed and analysed the capabilities of data transmission methods. One of the outcomes of the Project was a list of priority technical issues that remain to be further investigated. The required improvements related to either an increase in the operational ranges through geological media or components of the engineered barrier system (EBS) under relevant conditions (e.g. saturated bentonite), or the optimisation of the energy efficiency of the data transmission systems, and the integration of short-range and long-range systems.

The use of wireless data transmission to transmit data from sensors placed in the EBS or near-field rock requires supply of power to the sensor units and data transmitters over decades without direct human intervention. The MoDeRn Project considered the existing state-of-the-art in power supply (energy harvesting using thermal gradients) and the use of high-performance batteries. Since the MoDeRn Project, the state-of-the-art has progressed and additional methods for long-term power supply are sufficiently understood that considering their application in repositories is appropriate.

The potential to use fibre optic sensors for monitoring of distributed temperature and strain was recognised at the outset of the MoDeRn Project. Research was undertaken within the Project to improve understanding and to identify modifications required for application in repositories. Since the MoDeRn Project extensive developments in fibre optic systems for repository monitoring have been undertaken, and new fibre coatings have been developed. These have the potential to monitor additional parameters. Further research in the Modern2020 Project focused on development of fibre optic systems to extend their potential application in repository monitoring.

As development of monitoring programmes has progressed in parallel with technological advances, new requirements for monitoring technology are identified and new possibilities for monitoring processes occurring in the EBS and near field are identified. In the Modern2020 Project, R&D on new sensors included consideration of non-contact techniques for monitoring displacement (e.g. disposal canister movement), development of ion-selective electrodes for monitoring long-term chemical processes, development of thermocouple psychrometers for monitoring relative humidity close to saturation, and development of combined THMC sensors.

With respect to geophysics, in the MoDeRn Project, new algorithms for full waveform elastic inversion of seismic tomography data were developed and practical methods for acquiring tomographic data were developed through testing at the Mont Terri and Grimsel URLs. Key remaining issues with seismic tomography were application of the method in anisotropic media (e.g. in clay host rocks), calculation of differential tomograms to detect temporal changes in monitored data and automatic anomaly detection to reduce the need for extensive data analyses. In addition, recent advances in electrical monitoring techniques have introduced the possibility of using such technologies for repository monitoring.

Therefore, in the Modern2020 Project, work has been undertaken on the above topics to improve the feasibility of monitoring repositories during the operational phase following emplacement of the EBS. The work is summarised in this chapter in the following sections:

- Section 3.2 describes R&D undertaken in the Modern2020 Project on wireless data transmission.
- Section 3.3 describes R&D undertaken in the Modern2020 Project on long-term power supply.
- Section 3.4 describes R&D undertaken in the Modern2020 Project on fibre optic sensors.
- Section 3.5 describes R&D undertaken in the Modern2020 Project on in situ sensors.
- Section 3.6 describes R&D undertaken in the Modern2020 Project on geophysical methods.

- Section 3.7 describes R&D undertaken in the Modern2020 Project on reliability and qualification of repository monitoring systems.
- Section 3.8 summarises how the work carried out within the Modern2020 Project has advanced overall understanding and technical capabilities related to repository monitoring technologies.

The information presented in this chapter is presented in more detail in a WP3 summary report (Amberg *et al*., 2019), which includes an analysis of the technological readiness level of each monitoring technology and in task reports referenced below.

3.2 Wireless data transmission systems

3.2.1 Background to wireless data transmission

As noted in Section 3.1, wireless data transmission technologies have the potential to address technical challenges in monitoring the near field following emplacement of the EBS. In particular, wireless transfer of data would obviate the need for a system of wires between sensors and data loggers. Wireless communication through air using high-frequency radio waves is extensively used in many industrial and consumer applications. However, high-frequency radio waves would be significantly attenuated by rock or EBS materials, on account of their higher electrical conductivities compared to air. Therefore, wireless data transmission for repository systems have focused on the very-low-frequency (VLF) to medium frequency range (3 kHz to 3 MHz). Data transmitted in this range require different technologies for field generation, and result in different propagation behaviour. Therefore, attention has turned towards using magnetic dipole antennas which are able to transmit at low frequencies more efficiently. Which frequencies are most suitable for a given application can be estimated by the so called ‘skin depth’ (Box 1).

However, low-frequency solutions are not without problems; owing to the larger wavelengths, field generation is very inefficient, and the receiver antenna’s sensitivity linearly decreases with decreasing frequency; furthermore, this part of the spectrum is often ‘noisy’.

Box 1: The concept of Skin Depth

A simple concept that allows making first estimations on signal attenuation by interactions with the geologic medium is the so-called 'skin depth' that defines the distance, at which a signal is attenuated by a factor of 1/e. The skin depth δ of an electrical conducting media can be calculated for a frequency f by:

$$\delta[m] = \frac{1}{\sqrt{\pi \cdot f \cdot \sigma \cdot \mu_0}}$$

with μ_o the permeability constant ($1.257 \cdot 10^{-6}$ V·s/A·m).

The electrical conductivity σ of geological media can vary to a large extent, from µS/m to mS/m range for crystalline rock, and mS/m to S/m range for argillaceous rock. The water filled porosity of the geological media or EBS component has an important influence on the conductivity, as well as the pore water composition. The electric conductivity of fresh water is about 10 mS/m to 1 S/m, and the conductivity of saline water can be as high as 1–10 S/m. The table gives some example values for the skin depth at different frequencies and electrical conductivities. More information can be found in Schröder *et al*. (2019).

	Skin depth δ [m]					
	Electrical conductivity σ [mS/m]					
	1	5	10	50	100	1000
1000 Hz	503	225	159	71	50	16
2500 Hz	318	142	101	45	32	10
5000 Hz	225	101	71	32	23	7

3.2.2 Research into wireless data transmission in the Modern2020 Project

Research on wireless data transmission carried out within the Modern2020 project focused on three types of wireless data transmission technology:

- Improving short-range wireless data transmission systems, where the objective is to transmit data over a distance of several metres to a few tens of metres. Such technologies could be useful for monitoring the early-stage response to emplacement of the EBS when underground tunnels are open and accessible to receive data from backfilled parts of the repository. Research in the Modern2020 Project focused on frequencies from 4 kHz to 2.2 MHz.
- Improving long-range wireless data transmission systems based on VLF, and investigating the potential of multi-stage relay systems also using VLF. Here, the objective is to transmit data from the EBS to the surface, either directly or using the relay system. Data transfer in this way could reduce the need for human activity underground, and could, potentially, be used to monitor the near field following repository closure.
- Evaluating the use of integrated wireless data transmission systems, including combinations of wireless data transmission solutions with sensors, or the combination of short- and long range data transmission systems, in order to provide a solution that allows wireless transmission of sensor data in two stages from the EBS to the earth's surface.

The work undertaken and the results achieved are summarised below. More detailed information on this work can be found in the Modern2020 Project Deliverable D3.2 (Schröder *et al*., 2019).

Short-range wireless data transmission systems

As part of the development of short-range wireless data transmission systems in the Modern2020 Project, a Wireless Testing Bench (WTB) was constructed in the Tournemire URL in France. The WTB consists of a 10-metre-long borehole, with a diameter of 60 cm, in which wireless transmitters can be inserted through use of three access boreholes (Figure 3.1). The borehole has been backfilled with both granular bentonite and compacted bentonite blocks and sealed with a cementitious plug. The purpose is to use the WTB to determine the most suitable parameters for transmitting data over different distances and through the various media present.

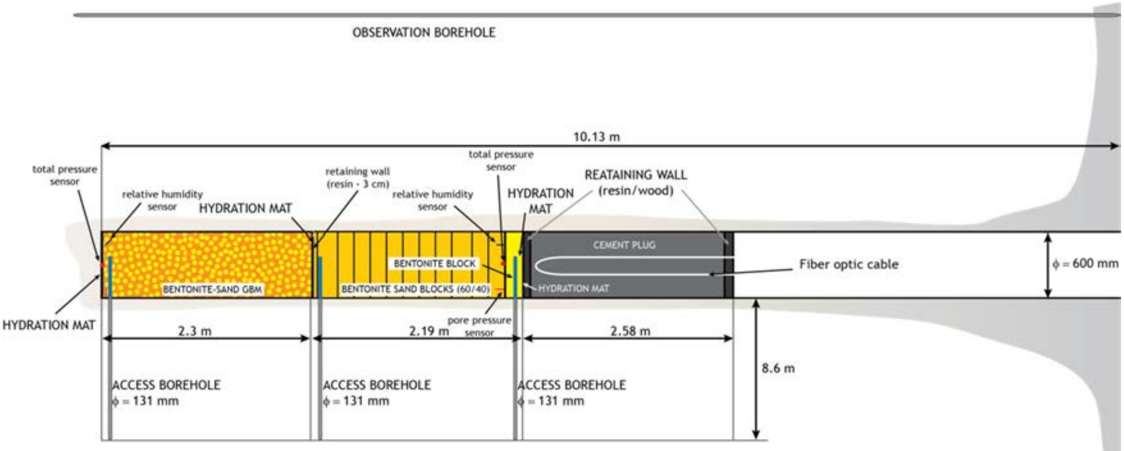


Figure 3.1: Layout of the WTB in the Tournemire URL. From Schröder *et al*. (2019).

To provide solutions suitable for the specific conditions in different repositories (e.g. the electrical conductivity of the host rock and EBS, the minimum transmission distance required, and the available space for the antenna), the work on short-range wireless data transmission systems in the Modern2020 Project focused on three approaches:

- A new 2.2 MHz wireless data transmission system using magnetic inductive coupling was developed to overcome the limitations of the prototype high-frequency (169 MHz) wireless sensor units developed in the MoDeRn project (MoDeRn, 2013a). Developments to the wireless sensor unit included selection of the optimal frequency band for application in a saturating bentonite barrier, incorporation of new electronics, and addition of an inert nylon core to provide mechanical strength (e.g. to resist swelling pressures exerted as a result of bentonite saturation). Testing of the new wireless sensor units at the WTB demonstrated successful transmission over 4 m inside a partially saturated bentonite-based buffer material. Demonstration of the practical use of these sensors was undertaken as part of the LTRBM demonstrator (see Section 4.3).
- Wireless data transmission using magnetic inductive coupling between loop antennae has been developed and tested at VTT's Otaniemi Research Hall I. The objective of this work was to develop an optimal approach to solve the short distance underground communication problem with state-of-the-art low cost commercial technology. Developments to this wireless data transmission system focused on the transmitter and receiver electronics. Successful transmission over a distance of 23 m (including 15 m of rock) at a frequency of 125 kHz and a data rate of 1 bit/s was demonstrated, however the disadvantage of a rapid increase in attenuation of the signal with increasing distance between the transmitter and receiver was noted. This development if particularly focused on transmission of information from a deposition borehole to access tunnels in the KBS-3V concept (see EBS monitoring plan, Section 4.1).
- Commercially available VLF magnetic induction technology used in mines was also investigated. The objective was to adapt and integrate this kind of equipment in an existing wireless sensor unit set-up, and to test it under realistic conditions. The work

involved specification of the electronics (for example, developing a sensor interface to allow connection to standard temperature, mechanical pressure, hydraulic pressure, water content/saturation and displacement sensors), energy budget (based on battery technology) and mechanical design.

The system incorporates a ferrite core antenna allowing the dimensions of the unit to be reduced. The new prototype can be deployed in a single tube (with dimensions of the unit of 69 cm (length) by 89 mm (diameter)), or as three separate sub-systems (battery, transmitter antenna and electronics/sensor interface in three separate 89-mm diameter tubes with lengths of 27 cm, 20 cm and 20 cm respectively).

The system was tested in a Spanish underground coal mine (transmission from one gallery to another through the rock) and in the WTB at Tournemire (from one borehole to another and from one borehole to the access gallery). The tests achieved successful transmission at 1200 bit/s over distances of up to 30 m using a frequency of 4 kHz.

Understanding of the general principles and demonstration of wireless data transmission have been shown in all cases above, and two systems provide versatile solutions, allowing the integration of different analogue and digital sensors. The tested wireless data transmission systems offer a variety of options and transmission frequencies to choose from depending on the desired application.

Long-range systems

Two approaches to transmitting data wirelessly over long distances (hundreds of metres) were explored in the Modern2020 Project at VLF frequencies (8.5 kHz):

- Direct transmission.
- The use of a multi-stage relay system utilising medium- and long-range antennas.

Direct transmission using VLF

The success of transmission over distances of several hundred metres depends on the power and size of the antenna, and the environmental electromagnetic noise. For this purpose, as part of the Modern2020 project, a large loop antenna (diameter 3.75 m) was developed that requires 200 – 300 W of electricity to transmit a signal over a distance of about 300 m. This antenna was tested at the Bure and Tournemire URLs. Testing demonstrated wireless data transmission through 310 m of air, and 270 m of rock. The transmitted signal was found to be weakly attenuated by rocks but strongly deviated by metallic parts such as the rails present in the main tunnel at Tournemire. Tests investigating the feasibility of transmitting signals greater than ~300 m only achieved signal strengths a few times greater than background noise, leading to the conclusion that transmission of distances in excess of this are not feasible for the current configuration of the wireless data transmission system.

Multi-stage Relay Systems

Several types of miniaturised transmitters have been developed (e.g. Figure 3.2), some of which are capable of data transmission over distances greater than 250 m. However, owing to inverse relation between magnetic field strength and transmission distance (Takamura *et al*., 2009) these transmitters have high energy requirements, and an external power source was required for these transmitters to operate. To address this, a multi-stage relay system was proposed to shorten the required transmission distance between devices, and reduce the energy needs. A function to change the transmission route in the event of some devices failing was also introduced to improve the redundancy of the relay system (Figure 3.3). Successful transmission over 95 m was demonstrated. In addition, to validate the durability of the system, an endurance test with the configuration shown in Figure 3.3 was undertaken. The test period was six months, and more than 4,000 data transmissions were executed without loss of data. The number of data transmissions were larger than the number of transmissions planned for 10 years of repository monitoring

Conclusions on long-range transmission

Each of these approaches (single-staged long-range transmission system and multi-stage relay system) has its own advantages and drawbacks: single-stage long-range transmission systems are easily installed due to their simplicity, and have fewer units which reduces the probability of malfunction. However, the large antennas take up a lot of space, their high power consumption requires a high-capacity power source, and the single route of transmission does not provide any redundancy if components fail (they could be installed with additional redundancy, but this would reduce the simplicity of their installation). Multi-route systems, through their nature of consisting of multiple relay components, have the advantage of redundancy if a component were to malfunction. Other advantages owe to their smaller size, which is useful in a repository where space is limited, and their lower power consumption which reduces the demand on the power supply. Disadvantages of the multi-route relay system relate to its complicated installation (e.g. the need for multiple sites in which to place the relays) and increased probability of malfunction due to the large number of necessary units.

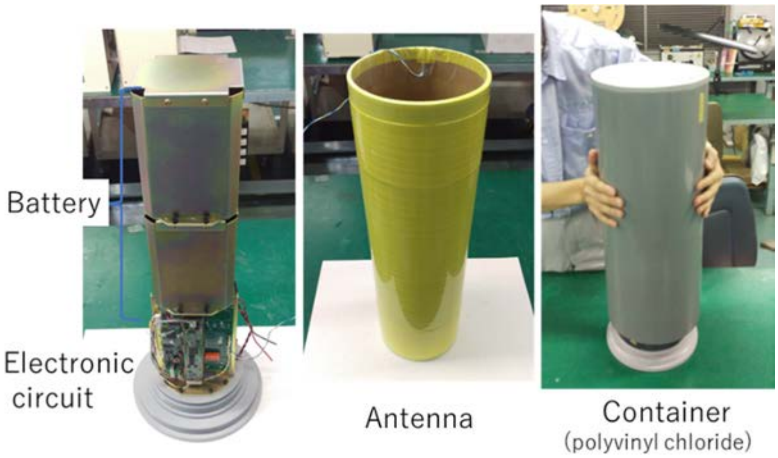


Figure 3.2: Conceptual design of a wireless data transmitter. From Schröder et al. (2019).

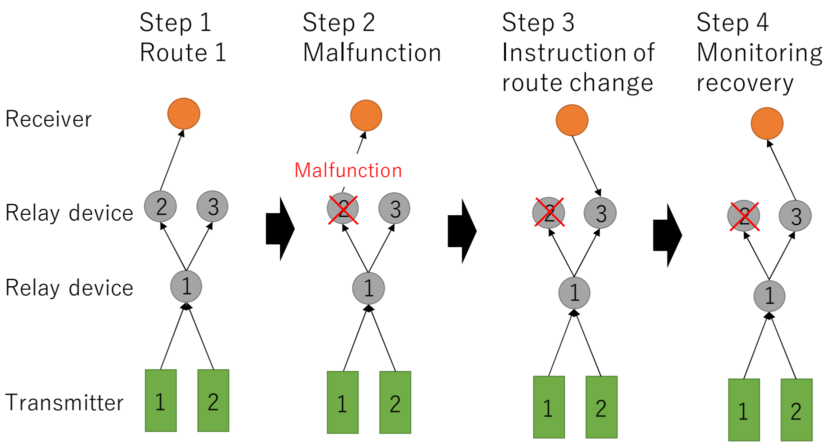


Figure 3.3: Conceptual diagram for a multi-hopping data relay transmission system, also illustrating the concept of route change in the case of device malfunction. From Schröder et al. (2019).

Combination of wireless technologies operating over different ranges

For the given state-of-the-art, a solution combining short-range and long-range wireless data transmission systems would provide the greatest flexibility in transferring data acquired by placing sensors in the EBS or near-field rock to the surface without the installation of cables. The basic set-up and technology of a combined solution was developed within the Modern2020 project and demonstrated in the LTRBM demonstrator. Section 4.3 describes the LTRBM demonstrator, including the components used for short-range and long-range transmission.

The combined system is used to transmit data from wireless sensor units and conventional (wired) sensors to the surface (Figure 3.4). Data is gathered from the sensors by the wireless sensor units and then is transmitted a distance of between 5-10 m to a master wireless sensor unit that records the incoming data. A data acquisition system then collects and stores data from all the sensors. The long-range subsurface transmitter requests data from the data acquisition system via a wired interface and transmits received data to the surface through 275 m of overburden.

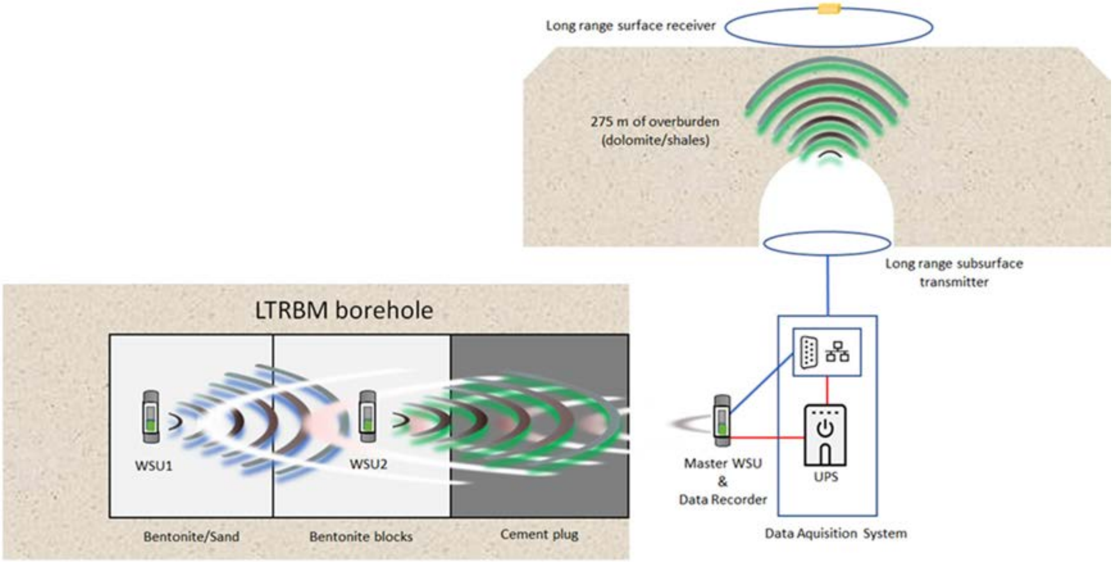


Figure 3.4: Overall set-up of the combined wireless data transmission chain from the LTRBM demonstrator to the surface.

3.2.3 Conclusions from Modern2020 Project research into wireless data transmission

The Modern2020 has made significant advances in understanding, designing and demonstrating solutions allowing the wireless transmission of data through components of the EBS and rock overburden. Different technological solutions covering transmission distances between 1 m and 275 m have been developed and tested under realistic condition (e.g. through the EBS of the WTB, and through clay rocks at Tournemire and crystalline rocks in VTT laboratories), covering a variety of application situations, disposal concepts and host rocks. Energy efficiency was found to be a critical consideration for long-range transmission, but, in the current stage of development, less important for short-range transmission. An overview of recent experiments illustrating the state-of-the-art in wireless data transmission systems is provided in Table 3.1.

For transmission over short ranges, several options were investigated as part of the Modern2020 Project, operating at high (2.2 MHz), medium (125 kHz) and low (4 kHz) frequencies. Each of the used frequency ranges has its own advantages and field of application. The high-frequency and low-frequency wireless sensor units developed in the Modern2020 Project offer versatile solutions which allow the integration of analogue and digital sensors and can transmit data wirelessly over 4 m (using a high frequency) and 30 m (using a low frequency).

Table 3.1: Overview of recent experiments on wireless data transmission in URLs.

Distance	Transmission mode	Frequency	Host rock/barrier (location)	Organisation	Reference
0.1 m	Resonant cavity antenna	2.4 GHz	Concrete buffer	EURIDICE	Schröder *et al.*, 2019, Chapter 7.2
4 m	Electric dipole antenna	169 MHz	Bentonite/shotcrete	Aitemin	Aitemin, 2013
4 - 6 m	λ/4 loop antenna	2.2 MHz	(Partially) saturated bentonite (Tournemire URL)	Arquimea	Schröder *et al.*, 2019, Chapter 5.2
5 - 10 m	Magnetic loop antenna	8.5 kHz	(Partially) saturated bentonite (Tournemire URL)	Andra	Schröder *et al.*, 2019, Chapter 7.1
23 m	Magnetic loop antenna	125 kHz	Granite and air	VTT	Schröder *et al.*, 2019, Chapter 5.3
25 m	Magnetic loop antenna	8.5 kHz	Sedimentary rock (Meuse/Haute Marne URL)	RWMC/Andra	Suzuki *et al.*, 2013
30 m	Magnetic loop antenna	4.0 kHz	(Partially) saturated bentonite (Tournemire URL)	Amberg	Schröder *et al.*, 2019, Chapter 5.4
30 m	Magnetic loop antenna	575 Hz	Bentonite/shotcrete (Grimsel URL)	Microwave Integrated Systems Laboratory	Spillman, 2013.
225 m	Magnetic loop antenna	1.8 kHz.	Boom Clay and saturated sandy aquifer (Hades URL)	NRG	Schröder and Rosca-Bocancea, 2013
250 m	Magnetic loop antenna/relay system	8.5 kHz	Sedimentary rock (Horonobe URL)	RWMC	Tsubono *et al.*, 2012
275 m	Magnetic loop antenna	8.5 kHz	Limestone and shale	Andra	Schröder *et al.*, 2019, Chapter 6.1
275 m	Magnetic loop antenna	8.7 kHz	Limestone and shale	NRG	Schröder *et al.*, 2019, Chapter 7.3.3

For data transmission over long ranges, experiments as part of the Modern2020 project have demonstrated transmission through 275 m of rock. The long range system demonstrated data transmission with only minor amounts of energy (±5 mWs/bit), providing no practical limitation for the application case. The system used a custom-tailored set-up, based on two systematic field characterization campaigns performed in Tournemire. The methods and tools allow optimisation of the technical set-up for a location of interest, were successfully applied in Mol and Tournemire, and can be used to evaluate transmission set-ups in other locations of interest as well. Besides single-staged systems, in which data is transmitted directly between two antennas, also a multi-staged relay system has been developed. This improved multi-stage method has the advantage of requiring smaller antennas and incorporating system redundancy through the multiple routes available for data transmission. Disadvantages relate to its more complicated installation compared to the direct transmission methods.

An integrated solution combining short-range and long-range technologies has been devised and its feasibility evaluated. A major limitation for the application of autonomous operating wireless sensor units discussed here is their need for longer-lasting power sources and interim power storage solutions than are currently available. This area has been researched as part of the Modern2020 project and is discussed in Section 3.3.

3.2.4 Further research requirements

When considering application of wireless data transmission in operating repositories, as opposed to the currently used URL environments, interference of metallic objects with the wireless data transmission environment may occur, and the systems may be placed in harsh environments (e.g. high temperature and pressures, high levels of radiation, chemical attack, etc.). Therefore, further research involving testing in environments closer to operating repositories might be required to address this. Beyond this, research would be required to evaluate the long-term reliability of wireless transmission systems, i.e. operation over several decades.

To bring short-range wireless technology into practical industrial use, technical development rather than basic research is now required; for example, the high-frequency and low-frequency systems mentioned here would benefit from further development to reduce system size, improve energy management and fabrication procedure, and the medium-frequency system developed using 125 kHz would benefit from improved reliability and energy consumption. With time and adequate funding these problems are expected to be successfully solved, and doing so would rapidly raise the readiness level of short-range wireless data transmission technologies for future use in geological repositories.

3.3 Long-term power supply

3.3.1 Background to long-term power supply

Repository monitoring sensors require a power supply in order to function and to transmit data to data loggers. Repository monitoring during the operational period of a repository might continue for several decades. However, a power source that could facilitate this is not yet available, in particular, in the case of wireless sensor units emplaced in the EBS and near-field. Commercially-available chemical batteries are considered to have too short a life span for monitoring over decades, with maximum lifetimes estimated to be in the region of 10-20 years for lithium thionyl chloride batteries. Therefore, to provide power over longer periods alternative power supply systems have to be developed. Power supply systems can be considered as consisting of three parts: power sourcing; intermediate energy storage; and energy management, which is required for connecting the available power with power consuming subsystems (i.e. the sensor and communication payloads).

3.3.2 Research into long-term power supply in the Modern2020 Project

Within the Modern2020 Project, research has focused on providing long-term power supply through:

- Electric power generation within the repository.
- Wireless energy transfer through the EBS and host rock to wireless sensor units.
- Interim energy storage.

The work undertaken and the results achieved are summarised below. More detailed information on this work can be found in the Modern2020 Project Deliverable D3.3 (Strömmer *et al*., 2019).

Electric power generation within a repository

Two methods of electric power generation within a repository have been investigated as part of the Modern2020 project:

- Harvesting electrical energy from low thermal gradients using thermoelectric harvesters.
- Generating electrical energy using radioisotope power systems, with particular focus on radioisotope thermoelectric generators.

Thermoelectric harvesters

Within a repository, heat produced by radioactive decay creates a thermal gradient between the waste and the surrounding rock. This energy can be harvested by using a thermoelectric harvester, which is comprised of thermoelectric generator and an energy management device (see Box 2). However, the thermal gradients in the EBS can be low, so the resulting energy is not easily converted into useable electric energy.

Within the Modern2020 Project, a feasibility analysis on the potential to generate energy from low thermal gradients using thermoelectric generators was conducted based on the Dutch OPERA disposal concept in Boom Clay. Calculations for typical thermal gradients which would exist after 100 or more years suggested that in order to provide power over such a period, thermoelectric generators must be able to operate at temperature differences of 2°C or less.

Currently, commercial energy management devices require at least 20 mV to operate, leading to a preliminary requirement for the thermoelectric generator to provide about 100 mV/°C, assuming a small difference in temperature across the generator of <0.5°C. Tests to characterise the relevant performance parameters of thermoelectric harvesters and their interactions with several energy management devices at small temperature gradients were conducted at a thermoelectric test bench. The tested combinations demonstrated that electrical power can be supplied to sensors with temperature differences of 0.44°C or higher. Factors limiting the amount of harvested energy were identified as being the minimum input voltage of the energy management device, its' efficiency, and its' self-power consumption. For the considered application in the OPERA concept (see Figure 2.4), energy can be provided to power sensors for more than 100 years.

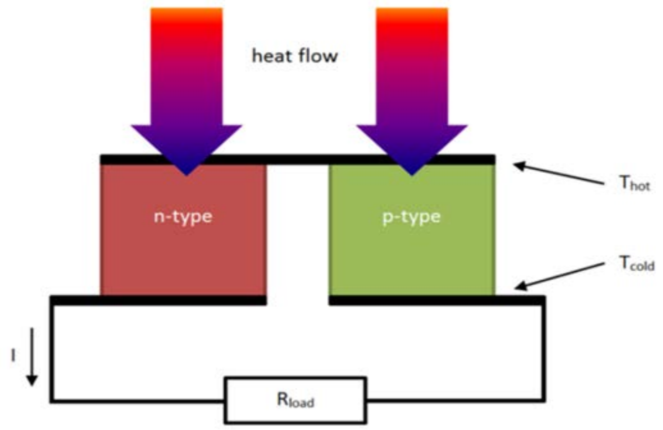
Box 2: The Seebeck Effect and Thermoelectric Generators

Heat flow in metals and semiconductors creates a voltage, U_s[V] owing to the Seebeck effect (i.e. the phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances). Through this effect, a voltage can be generated across a thermal gradient according to the equation:

$$U_s = \alpha \cdot \Delta T$$

Where ΔT is the temperature difference [°C] and α is the Seebeck coefficient [V/°C] which is a material dependent parameter.

A thermoelectric generator, consisting of different semiconductor materials, uses this effect to generate electrical energy. For low thermal gradients, the generated current is small and an energy management device is required to perform voltage boosting, power conditioning and storage. Use of an energy management device allows small amounts of generated energy to accumulate over the periods between two measurements such that sufficient power is eventually available for a measurement cycle of a sensor. The combination of a thermoelectric generator and an energy management device is referred to as a thermoelectric harvester.



Schematic showing the basic principles of a thermoelectric generator. Semiconductors (in this case n-type and p-type semiconductors) and the direction of heat flow are indicated.

Radioisotope power systems

Another means of power generation within a repository is the use of a radioisotope power system (Box 3). Work in this area in the Modern2020 Project included a state-of-the-art study on the possibilities offered by various types of radioisotope power system and their technical limitations resulting from the physical conditions they would experience if employed in a repository. Radioisotope thermoelectric generators were found to be the most mature at present. They are already applied in, for example, the spacecraft industry.

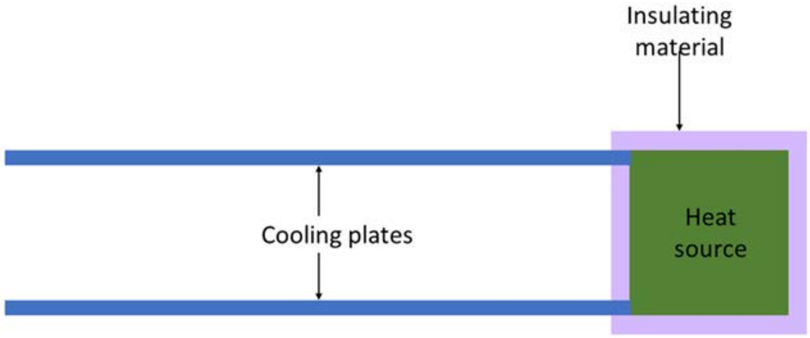
In addition, preliminary design and thermal modelling of a radioisotope thermoelectric generator placed within an ILW-LL vault was carried out to demonstrate the possibilities and technical limitations of this arrangement. So far, the isotopes most commonly used for space applications have been Plutonium (^{238}Pu), Americium (^{241}Am), and Polonium (^{210}Po). However, the scarcity of ^{238}Pu and the radiotoxicity and high volatility of ^{210}Po has driven consideration of alternative radioisotopes. Therefore, the work focused specifically on using the radioisotope ^{241}Am to supply energy within the radioisotope thermoelectric generator.

In the feasibility study, calculations were undertaken to determine the temperature difference that could be achieved using an radioisotope thermoelectric generator composed of a heat source surrounded by insulation material and a few cooling plates. The role of the cooling plates is to generate the thermal gradient between the hot side (heat source of the radioisotope thermoelectric generator) and the cold side (EBS material or host rock) as shown in the illustration in Box 3.

Box 3: Radioisotope Power Systems and Radioisotope Thermoelectric Generators

Radioisotope Power Systems are nuclear power systems which derive their energy from the spontaneous decay of radionuclides (Lange and Carrol, 2008). They consist of two components: a radioisotope source, and an energy conversion system. There are several technologies available for converting the heat generated or radiation emitted from radioactive decay of the radioisotope into electrical power.

These power sources have several advantages over traditional chemical batteries; they can scale to small sizes, have the potential for use in low-power, long-life applications, and are more suitable than chemical batteries for use in harsh environments (for example, high temperatures) (Colozza and Cataldo, 2018). Radioisotope thermoelectric generators are a type of radioisotope power system which use a thermoelectric generator to convert the heat released by the decay of radioactive material into electricity. The physical operation principle is the same as in the energy harvesting from thermal gradients, but instead of exploiting the heat generated by the waste, radioisotope thermoelectric generators exploit the heat released by the decay of nuclear material. Radioisotope thermoelectric generators have demonstrated their success whenever simplicity and long lifetime are required.



Schematic view of an radioisotope thermoelectric generator. Cooling plates may be composed of a compound such as bismuth telluride.

The main conclusion gathered from the work conducted on radioisotope power systems was that radioisotope thermoelectric generators are considered to be a potentially suitable source of power within a repository. To fully conclude whether the resulting prototype is suitable for repository monitoring, it would need to be built according to this reference design, and tests performed in the laboratory and on site to assess its practical suitability and performance.

Wireless energy transfer

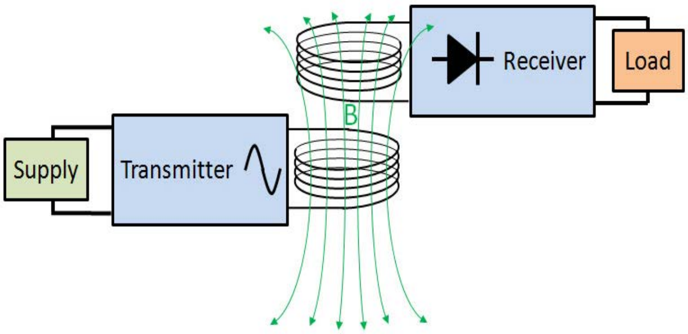
An alternative to supplying power from within the emplaced EBS could be to supply power remotely using wireless energy transfer. Work investigating the feasibility of wireless energy transfer focused on using inductive coupling between two loop antennas (Box 4). This work consisted of:

- A generic feasibility analysis for an inductive coupling system with no medium interaction, and analysis of potential effects of an electrically conductive medium on relevant design parameters and power transfer.
- Theoretical analysis on the effects of the electrically conductive medium to the power transfer performance.
- The construction and evaluation of two pilot systems.
    - Pilot system focused on wireless energy transfer through a medium with low electrical conductivity, i.e. bedrock (this system was also tested through air, and included a communication add-on).
    - Pilot system focused on wireless energy transfer through a medium with high electrical conductivity (such as saturated EBS components).

Box 4: Inductive coupling between loop antennas

Two conductors are said to be inductively coupled when a change in current in one conductor induces a voltage across the ends of the other conductor. This happens because the changing current in the first conductor creates a changing magnetic field, which in turn induces a voltage across the ends of the second conductor if it resides within the changing magnetic field – this is called electromagnetic induction.

A loop antenna is a loop of wire (or other electrical conductor) and these can be used as transmitter or receiver conductors in inductive coupling.



Wireless power transfer between two coils through electromagnetic induction. The magnetic field produced by current in the transmitter coil is denoted by "B".

Results from the generic feasibility analysis for an inductive coupling system with no medium interaction suggested that wireless transfer of 10 µW over 10 m is possible with a transmitter antenna diameter of 2 m, receiver antenna diameter of 0.15 m and transmitter power of 100 W. This was demonstrated experimentally, through air and through granite (see, for example, Table 6.3 in Strömmer *et al.*, 2019). Increasing the antenna diameters and transmitter power was shown to increase the received power.

In the first pilot system exploring transmission through low-electrical-conductivity media**,** 50.5 µW of power was transmitted across 10 m of air, with a transmitter power of 100 W, and 79.4 µW of power was successfully transmitted through 7 m of granite bedrock using a carrier frequency of 125 kHz and a transmission power of 25 W.

The second pilot scheme investigated power transmission through high-electrical-conductivity media. A series of experiments were performed where the transmitter and receiver antennas were placed in the air above unsaturated ground, on the surface of unsaturated ground, and on the surface of partially-saturated ground. The general set-up can be seen in Figure 3.5. Power levels between 10 µW and 1 mW were transferred over wireless distances between 5 and 10 m, with a link input power of 0.2 W. Results confirmed that interactions such as attenuation are negligible when transmitting energy through low-electrical-conductivity media (air and unsaturated ground), but significant when transmitting energy through high electrical conductivity media (partially saturated ground). Comparison of experimental results with feasibility study calculations showed efficiency reduction of 90% relative to what can be expected without medium interactions. Supporting this was the observation that increasing antenna separation resulted in increased additional attenuation by interactions with the medium for partially-saturated ground but not for unsaturated ground.

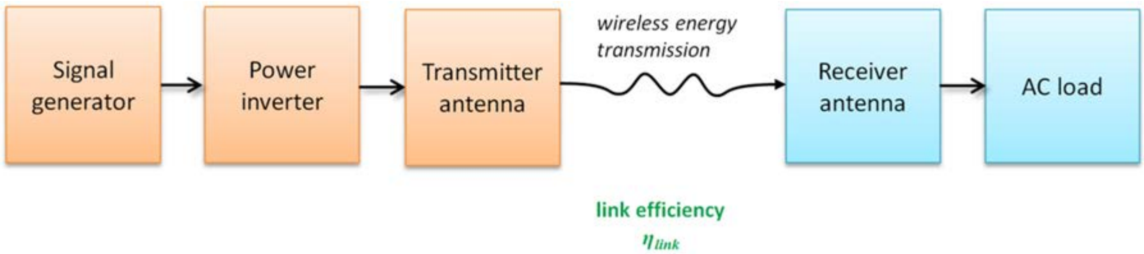


Figure 3.5: The wireless energy transmission set-up used in the pilot scheme involving a high-electrical-conductivity medium. From Strömmer et al. (2019).

The conclusion of the feasibility analyses and pilot schemes is that using wireless inductive energy transfer at low frequencies (such as 125 kHz) is a method that can be considered for powering repository monitoring sensors, and the main processes that determine the efficiency of such a link can be extrapolated to the longer distances that would be necessary in a repository. The interactions with a conducting medium are understood sufficiently well to anticipate these effects in the design, allowing to provide an efficient coupling even in a saturated medium. Despite this, obtaining adequate power by this method requires higher input power than is usually required for short distance wireless inductive energy transfer.

Improved energy storage solutions

Power sources such as those discussed above are likely to provide a limited and intermittent energy supply, and the wireless sensor units they would power in a repository are also likely to function intermittently. Therefore, a rechargeable, intermediate means of energy storage within the wireless sensor unit would often be required if some of the power sources discussed above were to be used as part of a wireless sensor unit.

The practical requirements that must be met by energy storage devices if they are to be used in a repository (i.e. the physical conditions in which the devices must be able to function) are such that obtaining a solution from the current commercial state-of-the-art is not possible. For example, their self-discharge has to be low enough with respect to the low power availability from energy sourcing methods, and they have to have a sufficient operating lifetime (e.g. several decades).

As part of the work conducted for the Modern2020 Project, analysis of the specific energy storage requirements of wireless sensor units intended for use in repository monitoring was performed, and the conditions in which they would be able to operate were identified. The current state-of-the-art of existing energy storage technologies and their suitability for use in repository monitoring was also reviewed. The technologies assessed were: batteries, electrostatic double-layer capacitors, electrochemical pseudo-capacitors and hybrid capacitor devices which combine several energy storage technologies.

The most essential requirements for energy storage devices which would be used in a repository were identified as:

- Self-discharge, or leakage power, that is lower than the supplied power from energy sourcing means within the repository.
- Sufficient energy storage capacity.
- Current output capacity that is sufficient to supply the power peaks required by the sensor and communication payload during the activity cycles of the wireless sensor unit.
- The need for an appropriate voltage range.

The final three points can be adjusted by connecting several energy storage components together, provided that this can be done without violating the first point.

Consideration of energy storage options currently offered by the state-of-the-art led to the conclusion that the current options are not yet suitable for use in repository monitoring, and that the most fundamental issues that must be addressed relate to their aging (in terms of charge-discharge cycles and time) and self-discharge (through which sourced energy is dissipated). Currently, rechargeable batteries are unsuitable due to the degradation which reduces their lifetime, and supercapacitors, although capable of providing a higher current output and higher cycle life (i.e. the number of charge-discharge cycles) than batteries, have a comparably short calendar life and high self-discharge rates. Electrochemical pseudo-capacitors and hybrid capacitors (such as lithium-ion capacitors and battery-supercapacitor storage devices) combine the best features of rechargeable batteries and supercapacitors and overcome their individual limitations; they currently offer the greatest potential for improving energy storage devices for repository monitoring.

3.3.3 Summary of research results

All three energy sourcing technologies (energy generation using thermoelectric harvesters, radioisotope thermoelectric generators, and wireless energy transfer) researched within this work package have been concluded to be both relevant and potentially feasible means of powering repository monitoring wireless sensor units. Improved understanding of the effects of a repository environment on the performance of each power sourcing method has also been achieved. The availability of several powering options with their individual strengths should allow systems to be defined that address the needs of different disposal systems. A review of interim energy storage options offered by the current state-of-the-art concluded that technical solutions exist and are sufficient for the purposes of repository monitoring.

3.3.4 Further research requirements

Further research to further develop and verify the energy sourcing technologies and integrate them into a realistic monitoring system is required if they are to be used to power repository monitoring sensors and systems. Testing such a system *in situ* at a URL would also provide valuable verification that these means of energy sourcing are suitable for repository monitoring. Steps to improve radioisotope thermoelectric generator prototypes to make them more suitable for repository monitoring were identified:

- Specify a reference for the design of a radioisotope thermoelectric generator.
- Identify the nature of the heat source, such as the appropriate radioisotope compound and its quantity.
- Identify the most appropriate thermoelectric materials for the thermoelectric generator.
- Assess the mechanical and thermal feasibility of the resulting radioisotope thermoelectric generator.

3.4 Optical fibre sensors

3.4.1 Background to optical fibre sensors

Optical fibre sensors (OFS) have recently received particular attention in the context of repository monitoring (Box 5). OFS have benefits over classical wired sensors which make them more suitable for certain types of repository monitoring; for example, they are resistant to corrosion and electrical interference, are capable of carrying signals longer distances without a repeater compared to copper cables, have a larger bandwidth and possess the capability to monitor several different parameters using the same cable. Fibre optic cables are also smaller and therefore less intrusive than traditional copper wires and can be several kilometres in length. The sensors are generally highly-durable, although they must be installed with care. Weak points in the system include the splice and/or connectors between fibres, which are, for example, susceptible to dust. Fibre optic cables must be connected to a source of light and need to be calibrated regularly.

Two types of monitoring using OFS have been considered in the Modern2020 Project: distributed sensing and localised sensing.

In distributed sensing, the forward propagating light generates backscattered light from all points along the fibre. Raman backscattered light is used for temperature monitoring. The wavelengths of the Raman backscattered light are different to that of the forward propagating light, and are named "Stokes" and "anti-Stokes". The amplitude of the Stokes light is weakly dependent on temperature, whilst the amplitude of the anti-Stokes light is strongly dependent on temperature, and absolute temperature can be calculated from the ratio of the amplitude of the Stokes and the anti-Stokes detected light. The spatial localisation of the backscattered light is determined through knowledge of the propagation speed inside the fibre. Monitoring of strain is based on measurement of the frequency shift of Brillouin or Rayleigh scattered light, which is dependent on both temperature and strain. The spatial resolution of distributed sensing is typically metres to decimetres. Therefore, localised monitoring is required for some applications.

Localised monitoring is based on the introduction of a local anomaly in the optical fibre in the form of a periodic pattern of refractive index change, which is inscribed along the fibre core. One type of inscription, which is the focus of research into repository monitoring using localised OFS sensing, is known as a fibre Bragg grating. The grating results in a particular wavelength of light, the Bragg wavelength, which is a function of the grating spacing, to be reflected back; now, the whole incident spectrum except for the Bragg wavelength proceeds along the fibre. The Bragg wavelength can be changed when the optical fibre undergoes a strain change (which has the effect of altering the grating spacing) or the refractive index of the grating is altered.

Monitoring using OFS requires a fibre to pass through the EBS and/or near-field rock in order to transmit the light signal and to record the back-scattered light. The acceptability of this fibre within the post-closure safety case remains to be tested.

3.4.2 R&D on optical fibre sensors in the Modern2020 Project

R&D on OFS technologies carried out within the Modern2020 project focused on three areas:

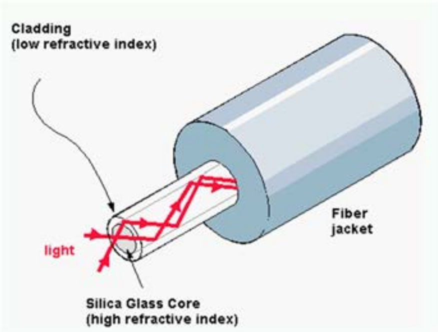
- Localised monitoring of hydrogen and pH.
- Distributed monitoring of temperature and strain, hydrogen, and gamma radiation.
- Active distributed temperature sensing to determine thermal conductivity, density and water content.

The work undertaken and the results achieved are summarised below. More detailed information on this work can be found in the Modern2020 Project Deliverable D3.4 (Bertrand *et al.*, 2019), and, for the active distributed sensing, further information can be found in Sakaki *et al.* (2018).

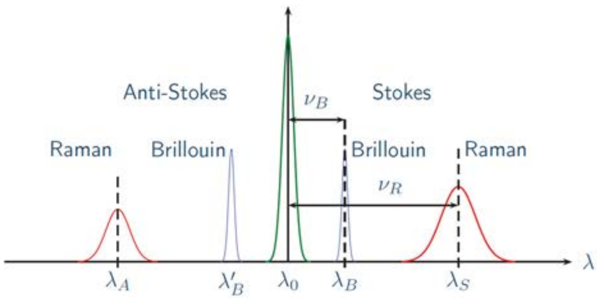
Box 5: Optical Fibre Sensors (OFS)

An optical fibre is a flexible fibre about the diameter of a human hair (0.1mm) that can be used as a means of transmitting light (i.e. an electromagnetic wave with frequencies on the order of 100 THz). A wide array of optical fibres have been developed using either glass or plastic, with solid or hollow cores and in various different shapes. Plastic fibres are unsuitable for use in most repository applications owing to their short design life and susceptibility to damage from radiation.

Optical fibres are composed of a core, a cladding and a protective jacket or coating. The core and cladding are usually made from the same material with the inclusion of dopants (such as germanium or fluorine) to modify the refractive indexes of the materials. When the cladding has a lower refractive index, light is kept within core and propagated along it due to total internal reflection.



Structure of an optical fibre.



Typical spectra of waves scattered through interactions with an optical fibre.

OFS works by recording back scattered light from the optical fibre. There are three main scattering processes: Rayleigh, Brillouin and Raman. Rayleigh and Brillouin scatterings are sensitive to both strain and temperature, whereas Raman scattering depends only on temperature.

Localised monitoring of hydrogen and pH

As noted in Section 3.4.1 fibre Bragg gratings are traditionally used for localised monitoring of temperature and strain. Fibre Bragg gratings can also be used as sensors for parameters which do not directly affect the fibre Bragg grating properties if a suitable coating is applied which either swells (i.e. causes a strain change in the fibre) or exhibits a refractive index change in response to a change in the parameter.

In the Modern2020 Project, research was conducted to evaluate the potential for using fibre Bragg gratings to monitor hydrogen and pH. The principle applications considered were monitoring of HLW disposal cells in Andra's HLW repository, where hydrogen generation might provide an explosion hazard and affect the ability to reverse the disposal process, and monitoring of Andra's ILW disposal galleries where a high pH is expected to develop following emplacement of the EBS. The first step was to conduct a literature review to identify the most promising coatings and sensor modifications.

For hydrogen use of a coating comprised of a platinum alloy paired with tungsten oxide was selected for further research. Trials were undertaken and hydrogen sensors successfully manufactured. However, the coating was fragile and maintaining layer adhesion between the coating and the fibre cladding was problematic. Additionally, the radiation robustness of the sensor was unknown, and further testing in this area is required before they are suitable for testing in a demonstrator.

For pH sensors, the literature survey identified several approaches for monitoring pH with optical fibres, but further development of the identified approaches is required to allow monitoring of pH values in the expected range of Andra's ILW disposal galleries (i.e. 11-13).

Distributed monitoring of temperature and strain, hydrogen, and gamma radiation

Research into developing distributed OFS for measuring temperature, strain, hydrogen and gamma radiation was conducted within the Modern2020 Project, with the aim of eventually integrating these methods into a single optoelectric sensing chain that could measure all these parameters separately or at the same time. This integrated sensing chain is not yet an industrial system, but progress was made in developing OFS for each of the four parameters individually. The main research results were as follows:

- Temperature can be monitored using Raman scattering in a multimode fibre. A carbon coating is required to prevent hydrogen diffusion if the sensor is placed in area of the repository expected to see significant hydrogen fluxes (i.e. > 4%), and fluorine doping is required to reduce radiation induced attenuation (should the sensor be used in an area of high radiation flux).
- Strain can be measured using Brillouin or Rayleigh scattering in a single-mode fibre. For repository applications a fluorine-doped fibre is required to reduce radiation-induced attenuation) and the Brillouin frequency shift. Coupled effects of temperature and radiation have been studied. Temperature reduces the negative impact of radiation on distributed sensors exploiting the Stimulated Brillouin Scattering. At 80 °C, 100 °C and 120 °C, the radiation induced attenuation is significantly reduced and maximal distance range will thus be improved. This affect remains to be quantified. The Brillouin frequency shift is in the order of 4 MHz at 1 MGy for the germanium-doped fibre and only 2 MHz with the developed fluorine-doped fibre, which approximately corresponds to 40 µm/m maximal error in strain measurement. The sensitivity to gamma radiation of single-mode optical fibres were investigated using three dopants: aluminium, germanium phosphide and germanium. The aluminium-doped fibre was the most radiation sensitive up to a radiation dose of 470 Gy; beyond this, the germanium phosphide-doped fibre performed more favourably up to a radiation dose of 4 kGy, and beyond this the germanium-doped fibre performed best, despite having a low sensitivity.
- The feasibility of hydrogen sensing using silica optical fibres which operated by Brillouin scattering was demonstrated.

Active distributed temperature sensing to determine thermal conductivity, density and water content

Active distributed temperature sensing involves the electrical heating of the optical fibre and measuring the temperature response along its length. The temperature response can be used to determine the thermal conductivity of the material in which the fibre is placed. Research into active distributed temperature sensing in the Modern2020 Project focused on application of the method to determining of the dry density at the time of emplacement and monitoring of water content in granulated bentonite mixture (GBM), i.e. the disposal drift backfill in Nagra's reference HLW disposal concept.

The dry density and water content of the GBM is known at the time of emplacement through quality control measurements made during the emplacement process, and the relationship between thermal conductivity and dry density (or water content) are established using a set of calibration experiments. At the time of emplacement the water content of the GBM is assumed to be stable and homogenous. Therefore, the thermal conductivity (at the time of the emplacement) is dependent on the dry density distribution of the GBM. Once the dry density distribution is known, which assumed to remain unchanged, then changes in the thermal conductivity reflect the changes in the saturation of the GBM and can be monitored using the heatable optical fibre.

The work undertaken was based on use of a commercially available heatable fibre optic cable, consisting of four optical fibres embedded in a stainless steel tube and surrounded by copper and stainless steel wires (Figure 3.6). The fibres are used for temperature sensing and the copper wires for heating. The work focused on emplacement techniques for the cable, identification of optimum heating power, calibration schemes and interpretation of results to derive physical parameters, and involved use of a mock-up in the Grimsel Test Site (GTS) and on-site verification in the FE Experiment at Mont Terri (Sakaki *et al*., 2018).

The results of the research indicated that heatable distributed temperature sensing was a potentially useful technique for estimating the dry density of the GBM on emplacement and for monitoring its subsequent saturation.

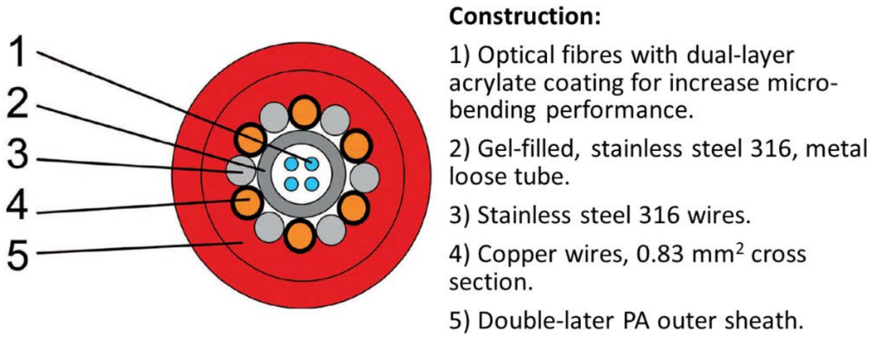


Figure 3.6: Schematic cross-section of the heatable fibre optic cable used to evaluate active distributed temperature sensing. From Solifos (2019).

3.4.3 Summary of research results

Custom-made fibre Bragg gratings were developed, by adapting an irradiation sensor, improving a hydrogen sensor, and developing a new pH sensor. An optoelectric sensing chain using three scattering methods (Brillouin, Rayleigh and Raman) was developed to provide distributed measurements of temperature, strain, hydrogen and radiation. A distributed fibre-optic sensing solution for measuring thermal conductivity, density and water content in the EBS was developed using heatable fibre-optic cables.

3.4.4 Further research requirements

The fibre-optic technologies developed within the Modern2020 Project still face challenges before they are suitable for repository use. Measuring temperature using Raman scattering is mature but further work is required to minimize the radiation impacts. Further improvement has been done to discriminate the temperature and strain component: some configuration has been proposed to measurement strain using Brillouin or Rayleigh scattering. Furthermore, a combination of Al and Ge doped fibres is needed to measure the radiation spatial distribution in the MGy range – further work is needed in this area. Proof of concept for hydrogen sensing has been obtained but research is still required to assess the lifetime of the sensor in repository-like conditions. The FO cable to measure bentonite properties through distributed Raman temperature still require work to meet the readiness level.

3.5 New Sensors

To measure parameters of potential interest in a repository, the development of new sensors is often required when current technologies do not comply with the required performance, or do not exist at all. Research within the Modern2020 Project focused on developing sensors or techniques in the following areas:

- Non-invasive techniques for measuring short-range displacement (Section 3.5.1).
- Chemical measurement techniques (Section 3.5.2).
- Thermocouple psychrometers for measuring water content (Section 3.5.3).
- Combined thermal, hydraulic and mechanical (THM) sensors (Section 3.5.4).

Conclusions from the research are provided in Section 3.5.5. The work undertaken and the results achieved are summarised below. More detailed information on this work can be found in the Modern2020 Project Deliverable D3.4 (Bertrand *et al.*, 2019).

3.5.1 Non-invasive short-range displacement measurement techniques

In URL experiments, technologies used for monitoring displacement, for example the displacement related to potential movement of waste packages and disposal canisters following emplacement of the buffer and backfill, have typically utilised extensometers attached to the rock walls and the canisters. However, these sensors are prone to failure in the long term (e.g. owing to the mechanical effects of the surrounding buffer material and/or corrosion), and use of extensometers in waste disposal galleries would introduce preferential pathways for radionuclide transport in the long term. Research related to non-contact techniques within the Modern2020 Project was undertaken to identify alternative methods for monitoring the position of canisters within a repository which did not rely on contact techniques.

Three non-contact techniques for monitoring short-range displacement were investigated:

- Electromagnetic techniques, for example use of ground-penetrating radar (GPR).
- Monitoring of the gravitational field, including monitoring of the gravitational field (gravimetric techniques) and monitoring of the field gradient (gradiometric techniques).
- Ultrasonic techniques, i.e. using ultrasound probes (with a frequency of 20-50 kHz) located close to the canister.

A literature review and an analysis of signal propagation using each of these three techniques was undertaken. Preliminary results indicate that all approaches could be suitable, yet several technical issues need resolving before the best solution can be identified, which will be the result of a trade-off among accuracy, depth of penetration and complexity of the detection system.

3.5.2 Chemical measurement techniques

Many safety relevant functions of the compacted bentonite buffer in the EBS rely on processes influenced by the chemical composition of the pore water in bentonite. These include swelling, alteration, precipitation and dissolution reactions, and transport of colloids and solutes. Therefore, for some programmes, monitoring of water chemistry might provide additional information of value to understanding of the post-closure safety case.

Direct measurement of ion activities in pore water of compacted bentonite are difficult to perform because of the swelling pressure (which most sensors cannot withstand), the low amount of free water available for the sensors, and the long measuring times. As part of the Modern2020 Project, methods for measuring ion activity (using chlorine-sensitive and sodium-sensitive electrodes) and pH (using hydrogen-sensitive electrodes) were developed.

The work involved production of bespoke electrodes and modification of commercial electrodes, and testing using squeezing cells (for batch experiments with chlorine and sodium) and diffusion cells (for monitoring of hydrogen diffusion). Chlorine-sensitive electrodes use silver and silver chloride coated silver wires. The stability of sodium electrodes was improved by introduction of a Natrium Super Ionic Conductor membrane. Solid iridium oxide pH electrodes were prepared using high-temperature oxidation in which an iridium oxide film is formed on iridium metal wire in a lithium carbonate melt environment.

Results showed monitoring of chlorine and sodium concentrations, and pH consistent with expectations. However, the techniques have so far only been developed for application in the laboratory rather than directly in the sub-surface. Thorough validation of the technologies in repository-like conditions is still required. Demonstration of the electrodes was undertaken as part of the LTRBM demonstrator (see Section 4.3).

3.5.3 Thermocouple psychrometers for water content measurement

Thermocouple psychrometers have been used extensively for monitoring the water content of bentonite-based material with high water contents. However, currently available measuring electronics for long-term monitoring only operate using the psychrometric method, which is discontinuous and challenging owing to the different mathematical criteria used to determine the stabilisation of the cooling ramp.

The objective of research carried out in the Modern2020 Project was to develop new sensors based on thermocouple psychrometers operating under the more accurate dew point method to measure water content in the bentonite barriers when close to saturation state. The work focused on:

- The development of new electronics and software to perform measurements using the dew point method.
- The integration of these new electronics with a commercial thermocouple psychrometer in a robust body to operate under the repository conditions.

Commercially available dew point measuring devices are scarce, complex, voluminous and expensive. Moreover, they are usually based on old electronics. The main goal was to find a new, cost-effective solution for handling the dew point measurement process over a long period. To achieve this, the following steps were taken:

- Analysis of available measuring devices and their technical documentation.
- Study of scientific papers to comprehend the physics involved and the most appropriate way to handle this task.
- Prototyping of regulation and acquisition system following specifications found in the precedent studies.
- Comparison of measurement between prototype and commercial devices using calibrated samples.
- Tuning of prototype system.
- Final design of boards.
- Fabrication of several units for their final calibration and installation at the LTRBM.

The outcome was the development and testing of a new sensor system to measure relative humidity through the dew point method using psychrometer sensors. Using calibrated samples, it was demonstrated that the new sensor is sensitive to changes in relative humidity. The new system is small in size and low cost. Demonstration of the new sensor was undertaken as part of the LTRBM demonstrator (see Section 4.3).

3.5.4 Combined THM monitoring

Work towards the development of a single sensor for use in the EBS capable of taking integrated measurements of total pressure, temperature, pore pressure and relative humidity was undertaken within the Modern2020 Project. Existing sensors which can monitor these parameters are reliable, but have disadvantages relating to their large size, and the necessity to use several sensors (and associated cabling) in combination to obtain information on multiple parameters puts even more demand on space. The new sensor introduced here was designed to allow measurement of these parameters whilst imposing fewer demands on space, cabling and power.

Work undertaken included three design iterations, with manufacturing and testing of prototypes, and development of the miniaturised cell electronics (Figure 3.7). One of the advantages of the electronics developed is that the data acquisition electronics provide a complete solution to the processing of the signals recorded by the integrated sensors and give the use digital output with no further processing required. However, the pressure transducer in the combined sensor utilises traditional materials in the pressure exchanger (e.g. oil), which are likely to be incompatible with safety case assumptions. Demonstration of the THM sensor was undertaken as part of the LTRBM demonstrator (see Section 4.3).

Figure 3.7: Photographs of the combined THM sensor. The sensor is 80 mm in diameter and 25 mm in height. From Bertrand *et al*. (2019).

3.5.5 Conclusions on research into new sensors

The Modern2020 Project has contributed to the toolbox of approaches available for repository monitoring by undertaking a range of new sensor developments:

- Promising non-contact techniques for short-range displacement sensors were investigated.
- Methods for monitoring ion activity and pH were developed.
- A new psychrometer sensor system to measure relative humidity through the dew point method was developed, tested, and demonstrated to be sensitive to changes in relative humidity.
- An integrated cell which combines THM measurements in a single, reduced-sized, unit was developed.

3.5.6 Further research requirements

Although progress was made in developing the new sensors, the sensors and sensing techniques require further work. Definition of that work will in part be based on analysis of the performance of the prototypes in the LTRBM demonstrator. In particular, actions are needed to improve the resistance of the sensors to expected repository conditions, with emphasis on radiation shielding.

3.6 Geophysical Methods for Repository Monitoring

3.6.1 Background to geophysical methods

Geophysical surveying offers a non-intrusive means of repository monitoring, allowing changes within the repository to be monitored without jeopardising the integrity of engineered barriers. Furthermore, geophysical methods provide a method for monitoring in three dimensions, and could potentially provide powerful solutions in combination with point measurements made by localised sensors. Such monitoring could capture local anomalies that sensors might not detect. Geophysics might be used to monitor parameters that affect the propagation of signals through the medium, for example changes in density, structural health (caused, for example, by cracking), water content and temperature.

3.6.2 R&D on geophysical methods in the Modern2020 Project

R&D on geophysical methods carried out within the Modern2020 project focused on three areas:

- Seismic imaging techniques.
- Differential tomography.
- Anomaly detection algorithms.
- Geoelectric techniques.

The work undertaken and the results achieved are summarised below. More detailed information on this work can be found in the Modern2020 Project Deliverable D3.5 (ETH *et al.*, 2019).

Seismic imaging techniques

Controlled source seismic tomography (Marelli, 2011) offers the potential for high-resolution imaging of the EBS. Seismic imaging is based on the fact that any heterogeneity in the elastic properties of the medium (e.g., seismic wave velocity, density and attenuation) affects the wave propagation characteristics, and will cause changes in the waveforms (e.g. travel time, amplitude and phase). Tomographic imaging allows a detailed image of the subsurface elastic properties to be developed based on processing of the characteristics of the seismic signals that have travelled through the medium of interest (Box 6).

Travel-time tomography exploits the arrival times of selected seismic phases to create the velocity images, whereas ray-based amplitude tomography uses the maximum amplitudes of the waves to deduce the attenuation characteristics of the medium of interest. In contrast, full waveform inversion techniques exploit the full information content of the seismograms, and consider both the amplitude as well as the phase of the recorded signals.

In a repository context, seismic imaging is expected to be useful in detecting changing material properties in and around the repository. For example, the increase in bentonite density as it saturates and swells would cause seismic velocities to increase, and the appearance of cracks in the engineered barriers or the host rock would cause a decrease in seismic velocities.

Box 6: Full-waveform inversion (FWI)

Full-waveform inversion is a method of processing seismic data which produces high-resolution velocity models of the subsurface, by iteratively determining and minimising the difference between modelled and recorded data. It goes beyond traditional refraction and reflection tomography techniques, which use only the travel time kinematics of the seismic data, by using additional information provided by the amplitude and phase of the seismic waveform (CGG, 2019).

Full-waveform inversion (FWI) is a seismic imaging technique that is considered the most promising option for the remote monitoring of repositories. However, it has several caveats; it is computationally expensive, involves extensive data analysis and requires methodological improvements to improve the tomographic images obtained from surveys of rock that is significantly anisotropic (clay environments in particular). As part of the Modern2020 Project, FWI has been further developed in an attempt to address some of these issues:

- Suitable parameterisation of anisotropy has been found and implemented.
- Structural constraints for improving the reliability of FWI inversions have been established
- Suitable pre-processing workflows have been developed.

This new methodology has been tested with field data.

A parallel task was conducted with the aim of developing automatic anomaly detection algorithms capable of detecting small-scale temporal changes in seismic data. A detection algorithm was established and tested with synthetic data. Additional tests with field data are required to further validate the algorithm.

Differential tomography

Differential inversions of geophysical subsurface imaging data allow temporal changes within a volume of interest to be monitored. This approach is expected to yield more accurate results since only differential changes between sets of data are considered, and consequently the results are less susceptible to systematic errors compared with traditional inversions. This method is particularly useful when data differences can be determined more accurately and/or more consistently than the actual data. It can be applied to data types such as GPR, seismic surveys or geoelectrical data.

As part of the Modern2020 project, a novel procedure was developed for determining precise and highly-consistent GPR travel time data, to which double-difference travel tomography could be applied. The methodology was based on the double-difference strategy in which inversion of travel time to velocity is undertaken directly based on the difference in the travel times between the two datasets (Asnaashari *et al*., 2015). The methodology involved first improving the accuracy and consistency of the first break arrivals, and then computing the differential tomograms to visualise changes in the velocity structure

This methodology was tested on a GPR data set that was acquired during the FE Experiment. In the Experiment, heaters were placed in a tunnel backfilled with bentonite (see Section 4.4 for a description of the FE Experiment). The tomograms were able to illustrate a decrease in GPR velocities above the heaters which results from a decrease in the dielectric permittivity owing to the heating. The double-difference strategy methodology applied in this work is potentially applicable to other geophysical data (e.g. seismic and geoelectric data).

Geoelectrical techniques

ERT and induced polarisation tomography (IPT) are potentially suitable techniques for monitoring the EBS in repositories because (Box 7):

- They could be implemented as a non-intrusive monitoring technique.
- They allow the measurement of local anomalies that local sensors might not detect.
- Electrical resistivity and dielectric permittivity are very sensitive to changes in water content and temperature, and therefore offer a potential method for monitoring these parameters.

Box 7: Electrical Resistivity Tomography (ERT) and Induced Polarisation Topography (IPT)

Electrical Resistivity Tomography is a method of characterising the subsurface by passing an electrical current through the earth between two electrodes and measuring the resulting voltage difference between two other electrodes. A model of the subsurface based on the electrical resistivities of the materials below can then be established.

Induced Polarisation Topography is performed in a similar manner and can be carried out in parallel with ERT as a complimentary method since it is sensitive to additional parameters such as chargeability.

Combined use of ERT and IPT is widely used and provide a convenient method of evaluating spatial and temporal variations in moisture and heterogeneity of geological structures; for example, the electrical conductivity of compacted bentonite blocks is influenced by porosity, dry unit weight, pore water (gravimetric water content, degree of saturation and volumetric water content) and pore water salinity.

Within the Modern2020 Project, work has been done to develop combined ERT/IPT 4D imaging. The 4D, or time-lapse, method involves repeating identical 3D surveys using a fixed network of electrodes. New procedures for time-lapse inversions (image reconstructions) were developed and tested using a laboratory experiment in which a container of bentonite pellets was injected with saline water (Figure 3.8). The experiment consisted of a plexiglass tube of 20 cm inner diameter and 80 cm height filled up to the 55 cm level with bentonite pellets. The plexiglass tube was equipped with four vertical electrode chains of 16 electrodes. The experiment was conducted over a period of 53 days. The bentonite pellets were injected six times with 1,000 g of saline water, with five of the injections occurring in the first week of the experiment and the final injection after 24 days. The aim of the experiment was to collect time-lapse 3-D resistivity distributions and time-lapse 3-D IP distributions illustrating the progress of the saline wetting front. IP distributions were imaged using the percent frequency effect (PPE), i.e. the percent difference in apparent resistivity. Through imaging the wetting front, it is anticipated that data for calibration of 3-D reactive transport modelling can be provided.

Examples of the ERT and IP data are provided in Figure 3.8 and Figure 3.9. These demonstrate that the infiltration fronts and water content changes could be mapped using the ERT/IPT methods described above, the trends of which corroborate with results from similar experiments performed elsewhere (e.g. Rahimi and Siddiqua, 2018).

In addition to the development of the combined ERT/IPT 4D imaging, calibration studies were performed on bentonite samples in a laboratory experiment to establish the relationships between electrical properties (e.g. resistivity and chargeability) and physical parameters (e.g. temperature and moisture content). The information was used to aid interpretation of the results of ERT/IPT experiments in URLs (e.g. at Tournemire URL). In contrast to previous studies where the ERT electrodes were installed inside the EBS, here they were installed in boreholes adjacent to the buffer. The results revealed expected relationships between resistivity and moisture content, and resistivity and temperature (i.e. a decreasing resistivity with increasing volumetric water content, and decreasing resistivity with increasing temperature). The relationships between chargeability and moisture content, and chargeability and temperature did not exhibit a clear trend.

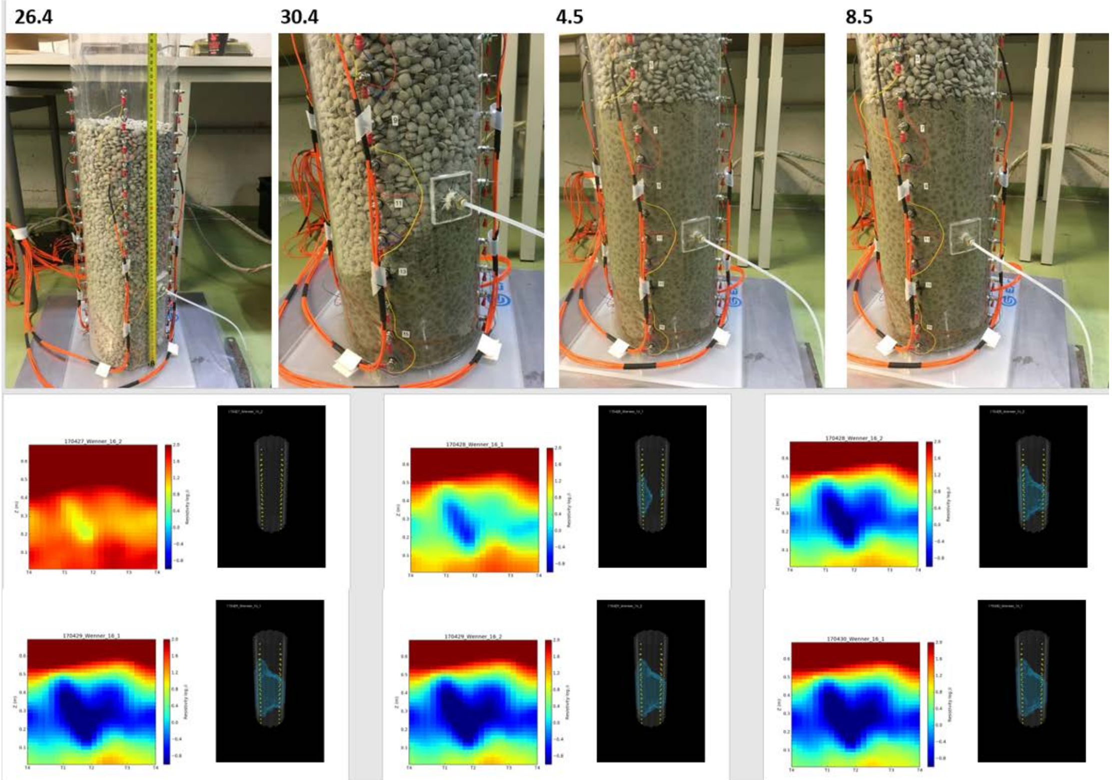


Figure 3.8: The laboratory experiment used to test new ERT/IPT monitoring methodologies. The photographs along the top illustrate the bentonite pellet column and the location of the electrodes. Dates are shown in the top-left of each photograph in the format day.month. The injection line for the saline water is on the right side of the column and the wetting front is illustrated by the dark grey region of pellets. Visualisation of the wetting front using ERT is illustrated in the lower diagrams. From ETH *et al.* (2019).

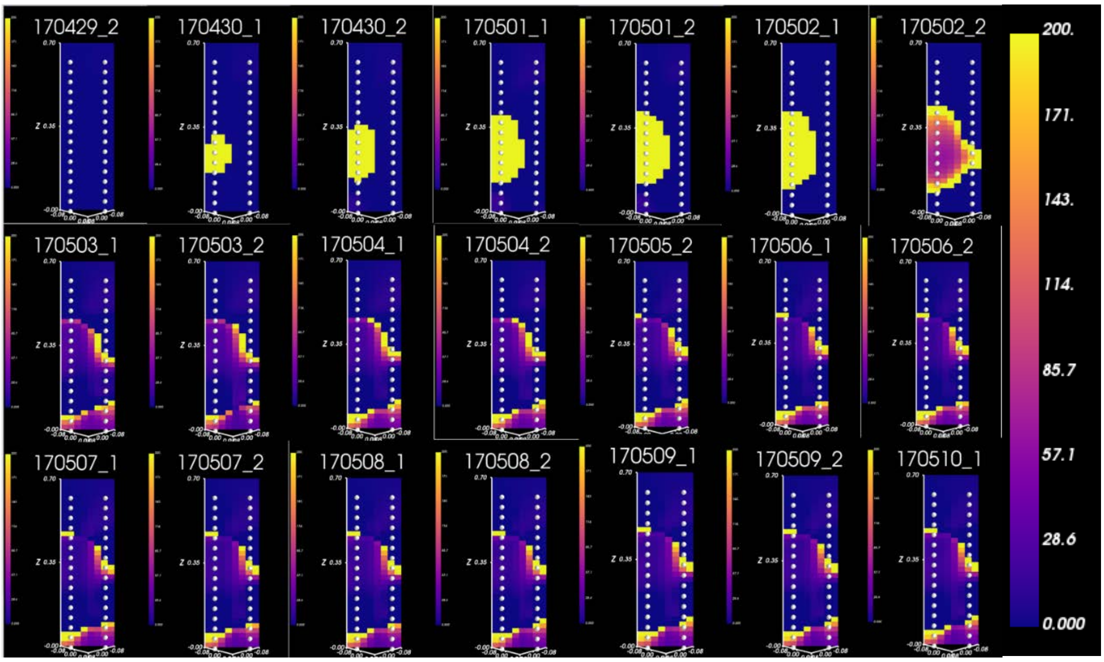


Figure 3.9: The PFE calculated from the 3D inverted resistance data. From ETH *et al.* (2019).

3.6.3 Summary of research results

Seismic FWI has been unsuitable for use in repository monitoring so far due to the seismic anisotropy of the host rocks, particularly clay. Within the framework of the Modern2020 Project, measures to develop seismic FWI into a suitable method for repository monitoring by overcoming this issue have been undertaken. In summary, this has been addressed by finding and implementing suitable parameterisations of anisotropy, establishing structural constrains for improving the reliability of FWI inversions, and developing suitable pre-processing workflows. Additionally, algorithms were developed which could identify small-scale temporal changes in seismic data.

Differential tomography algorithms were established which allowed consistent and highly-precise identification of differential changes of physical parameters. These algorithms were tested successfully using data from the FE Experiment.

ERT and IPT were shown through experiments to be a suitable method of monitoring changes in temperature and moisture content non-intrusively. New ERT and IPT algorithms were tested and validated, and the relationships between resistivity and temperature and moisture content were established.

3.6.4 Further research requirements

In all areas discussed (seismic FWI, differential tomography, ERT and IPT) further research and field experiments are required to validate methods and algorithms developed as part of Modern2020. In some cases, this is already underway, for example, the methodology for calibrating electrical parameters with physical parameters in bentonite samples is currently being tested in Tournemire URL.

3.7 Reliability and Qualification of a Repository Monitoring System

3.7.1 Background and need for a qualification methodology

Sensors and other components of a repository monitoring system are expected to face harsh conditions that could degrade equipment and impair its performance; for example, high temperatures, pressures, levels of radiation, humidity, saturation and chemically aggressive species. Ensuring that a repository monitoring system is reliable, durable and able to offer repeatable quality through its life (e.g. several decades) is a critical consideration in forming a repository monitoring plan, so the effect of such an environment on sensor performance is of great interest in this context.

A common qualification methodology for ensuring the reliability of monitoring equipment would provide additional confidence that the system will perform as specified. As noted elsewhere in this report the design of repositories and the nature of the monitoring programme varies between countries, in response to the national context. Therefore, any common qualification methodology that is common to all must be able to transcend these differences. A common methodology is described in this section. The methodology builds on experience from qualification in other industries where reliability under harsh conditions is needed, i.e. the power generation (nuclear and hydropower) and space industries, as well as experience from radioactive waste disposal RD&D.

3.7.2 A common multi-stage qualification methodology

Work within the Modern2020 project aimed to develop a common multi-stage qualification methodology applicable to all components of a repository monitoring system. This was achieved by:

- Gathering and analysing transferable experience from other industries (power generation and space) on the qualification of monitoring equipment.
- Considering the qualification process used in Andra’s Cigéo Project.
- Considering experience of monitoring system reliability from URL experiments.
- Developing the proposed qualification methodology.

The work undertaken and the results achieved are summarised below. More detailed information on this work can be found in the Modern2020 Project Deliverable D3.6 (IRSN *et al*., 2018).

Transferable experience from the power and space industries

In terms of the power industries, EDF has significant challenges regarding monitoring of dams and nuclear power plants owing to accessibility and requirement for intensive monitoring (large numbers of sensors). EDF has defined and implemented an industrial policy for the choice, the qualification and the maintenance in operational conditions of monitoring equipment (Figure **3.10**) based on the following principles:

- Use of a limited number of types of equipment,
- Development of a selection and qualification process for materials,
- Sustainability of qualified materials.

Concerning the space field, The European Space Agency has created the European Space Components Coordination (ESCC) organisation for equipment qualification, with only accredited companies allowed to select components. The qualification process is similar to that developed in the energy field. It includes the analysis of performances, design, operational, environment, manufacturing and testing. The testing of components requires qualification campaigns in space simulators, controlled clean environments, thermal vacuum space cycling, vibration pot and irradiation facilities and is considered complete when a Part Approval Document (PAD) is approved.

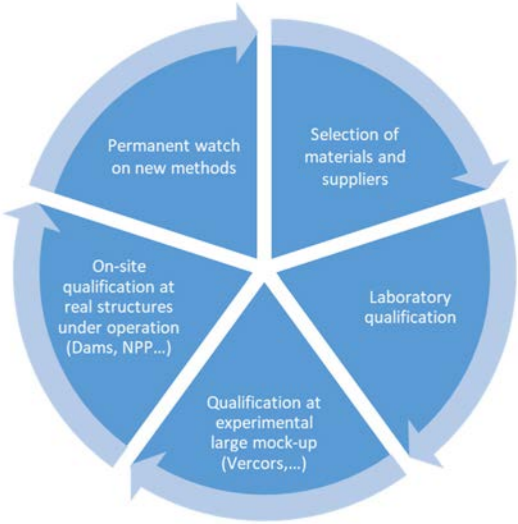


Figure 3.10: Selection and qualification process implemented at EDF for monitoring components. From IRSN *et al*. (2018).

Qualification in Andra's Cigéo Project

Andra's qualification process entails testing and qualifying the complete measurement chain, by progressive steps, predicting failure rates and controlling possible long term drift in monitoring system performance. The overall process is inspired from a qualification guide for non-destructive methods. The global test sequence includes four stages as illustrated in Figure **3.11**.

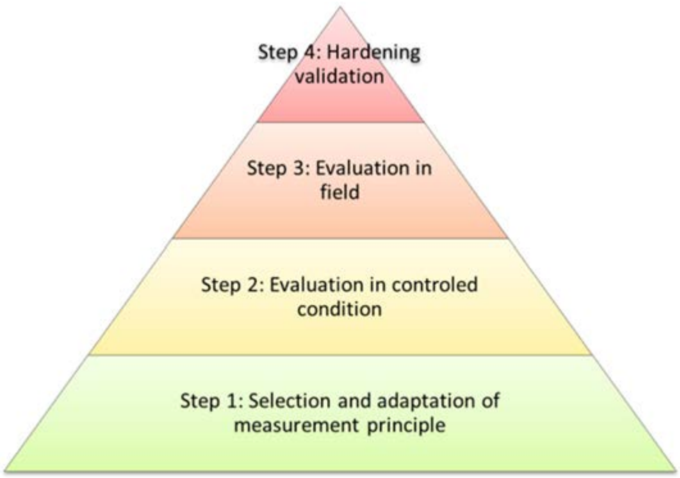


Figure 3.11: Qualification process for technology implementation in the Cigéo Project. From IRSN *et al*. (2018).

Transferable experience from URL experiments

Experience from URL experiments potentially allows the success of qualification methods previously used to select monitoring systems to be assessed. Therefore, information on ageing, accuracy, possible drift over time and robustness of sensors installed was collated for six experiments (Table 3.2). Information on reliability has to take into account the context of the experiment, some experiments have deliberately selected innovative sensors to test their performance as part of the experiment and some sensors have failed when known failure conditions (e.g. full saturation for relative humidity sensors) have been reached.

Table 3.2: Behaviour of sensors for a selection of experiments at URLs.

Partner	ANDRA	NAGRA AMBERG	IRSN	SKB	VTT	SKB
URL (country)	Bure (F)	GTS (CH)	Tournemire (F)	Äspö (S)	ONKALO (FIN)	Äspö (S)
Dismantled experiments	GCR	FEBEX				
Ongoing experiments			SEALEX	MPT	POPLU	PROTOTYPE
Duration (years)	6	18	6	5	5	8
Total number of sensors						
Wired/Wireless	-	176/0	149/105	194/33	132/0	328/0
Total/Number of Failed Sensors	134/9	176/108	149/113	227/99	132/20	328/125
% survival rate	93%	39%	24%	56%	85%	61%

Acronyms: GTS: Grimsel Test Site; GCR: Galerie Concept Rigide; FEBEX: Full-Scale Engineered Barriers Experiment; SEALEX: Sealing Experiment; MPT: Multi-Purpose Test; POPLU: Posiva Plug; PROTOTYPE: The Prototype Repository.

Proposed common multi-stage qualification methodology

From the work carried out, a common multi-stage qualification methodology intended to satisfy the needs of WMOs was proposed (Figure 3.12):

1. **Selection of components.** This step concerns the selection of components such as sensors, cables, housing, etc., and would typically involve substantial input from manufacturers and prior tests performed at accredited laboratories. Of those reviewed/considered, selected components should have the highest technology readiness level (TRL) and best reliability features e.g. mean time to failure of critical components. Verification of metrological and functional characteristics, compliance with current safety standards and sensitivity to parameters such as temperature, humidity, radiation, etc. must also be taken into account.
2. **Laboratory tests.** This step involves the testing of components under adverse conditions in a laboratory setting to identify their weaknesses. The tests performed would investigate robustness, ageing and cybersafe communication.
3. **On-site or mock-up tests.** These are designed to assess the whole repository monitoring system under realistic conditions. These tests also have the potential to serve as safety demonstrations. Mock-up tests are considered optional in the methodology.

Following this methodology is intended to result in the improved selection of components of a repository monitoring system. To present this methodology via a user-friendly interface, a template for an Approval Document (ADOC) was created (see IRSN, 2018).

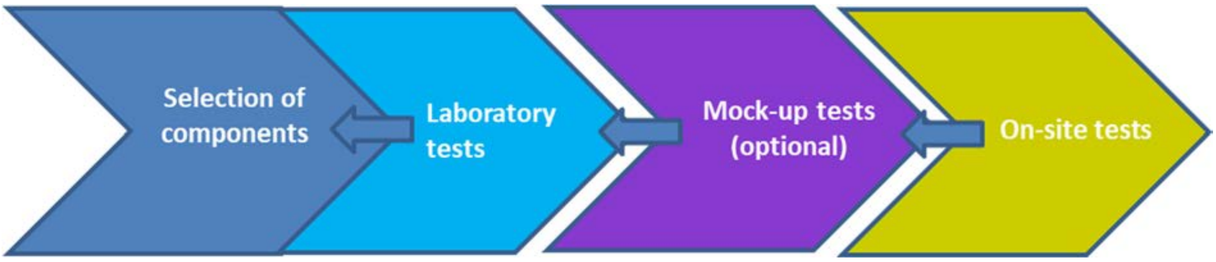


Figure 3.12: Global sketch for the qualification of repository monitoring components. From IRSN *et al*. (2018).

3.7.3 Summary of research results

The study included: i) the study of transferable experience gained from other industry fields, ii) the analysis of case studies operating in conditions close to those expected in repositories, iii) the initiatives for the development of a qualification process for selecting and testing the monitoring components and at last iv) the proposal for a global qualification methodology appropriate to all monitoring contexts. The main conclusions are that:

- A strong synergy with respect to the monitoring components exists between energy and space fields, and the needs of a repository such as robustness, long-life power supply, and optimisation of communications. The qualification process of those different fields always considers at least three stages including i) selection of components, ii) the laboratory qualification and iii) on-site qualification.
- Despite a strict selection of the best technical solution of the moment, *in situ* and long-term experiments performed at URLs or at large mock-ups suggest improvements that can only be checked *in situ* where conditions will be as close as possible to repository conditions.
- A generalised qualification methodology must combine robustness, ageing and on-field tests.

3.7.4 Further research requirements

The guidelines developed for the multi-stage qualification methodology applicable to each component of the monitoring system needs to be applied systematically in order to ascertain its validity and improve it if required. This includes the application and testing of the methodology to specific monitoring programmes.

3.8 Summary and Conclusions on Monitoring Technologies

3.8.1 Context for monitoring technologies work in the Modern2020 Project

Development of monitoring programmes is able to build on decades of research in URLs in which monitoring methods have been developed, employed and evolved. This work has included extensive instrumentation of experiments looking at the performance of specific materials in repository-like environments (e.g. host rocks, concretes, bentonites and metals), and also the conduct of large integrated mock-up experiments. These include, for example: the ALC Experiment in the Bure URL, France (Gugala, 2015); FEBEX in the GTS (Lanyon and Gaus, 2016), Switzerland; the FE Experiment in the Mont Terri URL, Switzerland (Nagra, 2019); the PRACLAY Heater Test in the HADES URL in Belgium (Dizier *et al*., 2017); the MPT in the Äspö HRL (Kronberg and Gugala, 2015), Sweden; and the Prototype Repository, also in Äspö (Svemar *et al*., 2013).

Monitoring of these experiments and mock-ups has typically used hundreds of sensors tracking the evolution of the system. They have provided a test bed for development of new sensors, and provide examples of monitoring integrated systems, including, for example:

- Development of approaches for qualification, installation and operation of monitoring sensors.
- Development and experience in intensive data acquisition systems.
- Use of monitoring data in decision making (e.g. management of the experiment) and experience in development of extensive monitoring databases (e.g. Firat Lüthi, 2018).
- Use of the results from modelling to develop further understanding of THMC processes and use of monitoring data in THMC modelling.

However, the monitoring of repositories during the operational phase is expected to differ quite significantly to monitoring of large integrated mock-up experiments in URLs. In particular, monitoring in operating repositories will have to be consistent with passive safety, which is currently assumed by most WMOs to mean reducing the number of wired sensors or removal of sensors that transmit data using wires completely, and reducing the intensity of monitoring for practical purposes (see discussion in Section 2.1.1 and NEA, 2014a). Therefore, there is a requirement for application of monitoring systems in new ways, and, for some monitoring strategies, transmission of data using wireless technologies.

3.8.2 Main outcomes and conclusions from WP3

WP3 of the Modern2020 Project aimed to fundamentally develop or improve the TRL of several technologies relevant to repository monitoring. The work carried out has been successful in achieving this aim; it has increased existing monitoring capabilities and also expanded the range of what it is possible to monitor.

Whilst methods for devising a monitoring strategy are becoming more mature (for example, work carried out in WP2 of the Modern2020 Project), and the value in monitoring certain processes is becoming better understood, specific parameters and means of monitoring them are not prescribed, and are open to interpretation based on different repository concepts and national contexts. The work in WP3 contributes to expanding the toolbox of solutions available for monitoring a wide range of parameters, the selection of which may or may not be chosen for monitoring by individual programmes.

Key outcomes of the work conducted in WP3 are summarised below:

- Significant advances were made in understanding, designing and demonstrating solutions allowing the wireless transmission of data through components of the EBS and rock overburden, however technical development of these technologies is still required to bring them into practical industrial use. Different technological solutions covering transmission distances between 0.5 m and 275 m through different types of media have been developed and tested under realistic conditions. Versatile solutions for short-range wireless data transmission were developed based on high- and low-frequency systems. For data transmission over long ranges, very-low-frequency systems demonstrated the wireless transmission of data through 270 m of rock, and a more energy efficient method using multi-stage relay devices was also developed. An integrated solution combining short- and long-range technologies has also been devised and its feasibility evaluated.

- Alternative solutions for providing power to sensors in a repository (either through using alternative power sources within the repository, achieving the wireless transmission of energy across EBS components, or improving battery life such that they become a viable option) have been developed or their applicability to a repository monitoring context reviewed. The energy sourcing technologies researched (energy generation within a repository using thermoelectric generators and radioisotope thermoelectric generators, and wireless energy transfer) were concluded to be both relevant and feasible means of powering repository monitoring systems. A review of energy storage options offered by the current state-of-the-art concluded that electrochemical pseudo-capacitors and hybrid capacitors have the most potential for offering energy storage solutions which are sufficient for the purposes of repository monitoring. Continued research to further develop and verify the energy sourcing technologies and integrate them into a realistic monitoring system is still required.
- Several new sensors and measurement systems based on fibre optic technology were developed. Sensors based on fibre Bragg gratings were developed which could be used to monitor water content, water chemistry, pH and irradiation. Optoelectric sensing chains were developed which used Brillouin, Rayleigh and Raman scattering to provide distributed measurements of strain and temperature. A distributed fibre-optic sensing solution for measuring thermal conductivity, density and water content in the EBS was developed using heatable fibre-optic cables. Advancement was also made on the development of fibre-optic pressure cells for boreholes. Further work is mainly required to ensure these technologies can withstand the repository-like conditions.
- Other new sensors have been developed for measuring short-range displacement non-invasively, the water content and its chemical composition in bentonite, and THMC measurements in a single sensor. These sensors require testing and implementation in conditions similar to those expected in a repository.
- Non-invasive monitoring based on geophysical techniques was developed. Seismic FWI algorithms have been improved, and an automatic anomaly detection algorithm was developed. Differential tomography algorithms were established which allowed consistent and highly-precise identification of differential changes of physical parameters. ERT and IPT algorithms were tested and shown to be a suitable method of monitoring changes in temperature and moisture content non-intrusively. Further research in these areas is mainly required to validate the methods and algorithms.
- A multi-stage qualification methodology was developed that is applicable to all components of a repository monitoring system. A user-friendly interface (the Approval Document – ADOC) was also designed. This methodology still needs to be applied systematically in order to ascertain its validity and make improvements, if required.

Overall, the monitoring technology developments in the Modern2020 Project have demonstrated that there are sufficient technologies, with different strengths and weaknesses to conduct repository monitoring as envisaged through the strategic work undertaken in WP2.

However, as is evident from the discussion of the results from WP2 above, there are not yet detailed specifications that define requirements on monitoring technology for specific monitoring programmes. Therefore, as noted above, technology development has focused on provision of a toolbox of methods, rather than tailored solutions. The demonstrators developed in WP4 provide the first steps towards bridging this gap on an international basis. Further development of the specific monitoring programmes (as proposed above) will help to guide further technology development to a greater extent.

Nonetheless, the technology development in the Modern2020 Project has presented solutions that are considered to be applicable to a wide range of monitoring strategies. For example, the understanding of wireless data transmission systems developed in WP3 and demonstrated in WP4 has reached the stage where the range of available solutions allows a site-specific solution to be achievable for most disposal concepts.

A key consideration for any monitoring technology is the impact on the passive safety of the disposal system. Assessment of the impact of any sensors introduced into the EBS and near-field rock will be required within the post-closure safety case on a case-by-case basis. However, such considerations should not limit the application of the technology; as shown in the discussions in WP2, there are multiple strategies through which monitoring might be undertaken, and some technologies might be suitable for some strategies and not for others.

As has been noted in the discussion of WP2 results, deciding on the parameters to monitor during the operational phase to build further confidence in the post-closure safety case is a value judgement. One of the judgements that impacts directly on the manner in which certain technologies can be used for repository monitoring is whether or not it is acceptable for the design of the repository to be modified significantly for additional monitoring to be undertaken. For example, wireless data transmission becomes is more flexible when the diameter of the antenna can be increased, so one judgement that a WMO considering wireless data transmission must make is whether it is acceptable to change the repository design to allow the use of a large-diameter antennae.

Linked to this point, is development of an understanding of the density of monitoring technology that needs to be employed within the EBS and host rock for meaningful information to be acquired. Whereas the presence of one monitoring sensor may not have significant impact on post-closure performance, presence of many tens of sensors may not be acceptable. Therefore, WMOs need to develop methods for determining the acceptable limit of monitoring technologies for the strategies they intend to employ for repository monitoring.

As has been seen from the progress in monitoring technologies since the start of the MoDeRn Project in 2009, development of novel technologies takes time and a significant international collaboration to be fruitful. The Modern2020 Project has demonstrated significant advancements in monitoring technologies and practical implementation of monitoring, and provides a platform for preparation of site-specific monitoring programmes.

Further work

A key success of the Modern2020 Project has been to undertake collaborative work at the cutting-edge of technology development, which could provide additional capabilities to monitor the EBS and the near-field during the operational phase. To undertake RD&D such as this requires international collaboration to pool resources. As has been discussed above, the technologies developed in the Modern2020 Project have been proven as being feasible, but are not yet ready for deployment in repositories. Therefore, further international collaboration on repository monitoring technologies should be undertaken to increase the range of technologies that can be applied during the operational phase. The test benches and laboratory facilities developed in the Modern2020 Project will be useful in this respect. For example, the WTB at the Tournemire URL is a valuable facility for future development of wireless data transmission systems.

There are several generic issues which apply to all, or most, technologies mentioned above. One is the subject of energy management, particularly if the monitoring strategy envisaged by the WMO includes sensors emplaced in the EBS with wireless transmission of data. For monitoring programmes employing this strategy, given the long period over which monitoring components are envisaged to operate, and the difficulties in providing generous amounts of energy within a repository, the ability to supply adequate levels of energy to monitoring system components is crucial to their successful performance. This means that improving the energy efficiency of sensors and other monitoring system components, combined with finding ways of supplying a reliable supply of energy (for example, by using interim energy storage solutions at sensor locations) is an area of high importance requiring further research.

Another common issue amongst newly developed technologies for use in a repository environment is their long-term reliability. Although some work on reliability and radiation hardness has been done, in particular for FO sensors, more extended testing is recommended, particularly for the wireless data transmission solutions.

Finally, cost is an important practical consideration when choosing whether to use any repository monitoring technology, and cost evaluation should also be undertaken where possible for technologies with a sufficiently high TRL.

In parallel with the development of measurement techniques such as those researched in WP3, the systems for gathering, filtering, managing and displaying information also required attention. The monitoring techniques described in WP3 allow the collection of huge amounts of data that standard data acquisition systems cannot properly handle.

In summary, WP3 of the Modern2020 Project has made substantial advances in developing new or adapting existing technologies such that their TRL for use in a repository monitoring context has been raised. Fundamental research into new methods of measurement of relevance to repository monitoring needs has also been conducted with success. However, as discussed above, further research is required to fully bring these technologies into practical use in an industrial setting, and additional funds and time are required to achieve this.

4 Modern2020 WP4: Monitoring Demonstrators

This chapter provides a summary of the work undertaken, key results and conclusions of the Modern2020 Project WP4 work on the demonstration of monitoring implementation in repository-like conditions.

- Sections 4.1 to 4.4 provide descriptions and discussion of individual *in situ* monitoring demonstrations undertaken as part of the Modern2020 Project. This includes:
  - Development of an EBS monitoring plan for the Olkiluoto repository, Finland (Section 4.1).
  - The monitoring programme at Cigéo, France (Section 4.2).
  - The LTRBM in Tournemire, France (Section 4.3).
  - The FE Experiment in Mont Terri, Switzerland (Section 4.4).
- Section 0 provides a summary and conclusions of the work carried out in WP4.

The information presented in this chapter is described in more detail in the five WP4 task reports:

- Deliverable D4.1 (VTT *et al.,* 2019) which provides details of the work carried out during the full-scale *in situ* EBS system test at ONKALO in Finland.
- Deliverable D4.2 (Andra and EDF, 2019) which provides details of the work carried out on the monitoring programme at Cigéo, France.
- Deliverable D4.3 (Dick *et al*., 2019) which provides details of the work carried out at the long-term rock buffer monitoring (LTRBM) in Tournemire, France.
- Deliverable D4.4 (Fisch *et al.,* 2019) which provides details of the full-scale emplacement (FE) experiment in Mont Terri, Switzerland.
- Deliverable D4.5 (Verstricht *et al*., 2019) which provides a summary and conclusions from all work described in Deliverables D4.1 to D4.4.

4.1 Development of an EBS monitoring plan at ONKALO, Finland

This section describes the work undertaken in Modern2020 Project Task 4.1, which consisted of a desk-based study on the planning and design of a monitoring system for the disposal of spent fuel in the disposal facility at Olkiluoto, Finland. To achieve this, an EBS monitoring plan for an illustrative deposition tunnel based on Posiva's full-scale EBS system test, called FISST (full-scale *in situ* system test) was developed. It focused on showing compliance with the safety case, primarily covering long-term monitoring aspects, and aimed to demonstrate the applicability of monitoring strategies such as that developed in the test case. This EBS monitoring plan will be used as a basis for Posiva's planned full-scale demonstrations at the rock characterisation facility ONKALO at Olkiluoto. This work, which developed the technical and practical aspects of an EBS monitoring plan, built upon the work on developing monitoring strategies carried out in WP2.

Further information can be found in the Modern2020 Project Deliverable D4.1 (VTT *et al.,* 2019).

4.1.1 Posiva's EBS monitoring programme

Posiva's safety concept for the geological disposal of spent nuclear fuel is based on the KBS-3V design of a geological repository and the characteristics of the Olkiluoto site (see summary discussion in Section 2.3.1).

Monitoring of the EBS comprises one part of five within the monitoring programme set out by Posiva that focuses on monitoring site properties to detect changes caused by construction activities associated with the disposal facility. EBS monitoring is currently in the R&D phase, and it is expected that an EBS monitoring plan will be produced as part of the operational monitoring programme, which is planned to be ready by the end of 2020.

As part of the Modern2020 Project WP4, Posiva built on the strategy work and parameter selection test case carried out in WP2, going a step further by developing a plan for the technical and practical execution of an EBS monitoring plan for an illustrative deposition tunnel. The deposition tunnel considered in this EBS monitoring plan will be separate from the main disposal galleries and will utilise three heaters (dummy canisters) rather than disposal containers (see Figure 4.1).

Real site information and component specifications from Posiva's plans for final disposal of spent nuclear fuel were used; such information was gathered from ongoing site investigations and monitoring programme, and models for EBS component behaviour. The main processes to be monitored were proposed, and a programme to implement monitoring, based on ideas from earlier tests and demonstrations (including work by other WMOs) was suggested.

The EBS monitoring plan is a design example for monitoring of a full-scale test of the EBS system to be installed at ONKALO™. The role of the monitoring and related instrumentation in the test is to:

- Learn about interactions between installed components following installation and based on design information.
- Increase knowledge of THM processes occurring within the EBS.
- Increase the chances of identifying expected or unexpected evolution of EBS components at an early stage.
- Increase understanding of EBS component system interactions with site conditions.

4.1.2 Choosing monitoring parameters

The process of choosing which parameters to monitor was based on the methods employed during the Modern2020 Screening Methodology test case carried out by Posiva (Section 2.3.1). This test case was based on the Posiva's previous safety case, TURVA 2012, since Posiva's current safety case for the spent fuel repository and Olkiluoto was being updated at the time.

Owing to this, a modified set of processes and parameters to monitor was developed within WP4.

As discussed in Chapter 2, there are advantages and disadvantages to equipping the EBS with extensive instrumentation in order to monitor it. Instrumentation allows information about the EBS evolution to be collected, which could provide information of THMC processes occurring in EBS components immediately following their installation, increases the chances of identifying unexpected evolution of EBS components at an early stage, and improves understanding of the interactions between the EBS and the site conditions. However, there are also disadvantages to extensive instrumentation: disturbance to the EBS caused by instrumentation (particularly the use of wires and cables) may impair the performance of the EBS, and there is a risk that installed sensors may malfunction and give incorrect readings that are not detected and lead to inappropriate responses.

Development a monitoring strategy involves a compromise between different factors such as these, including consideration of the detailed objectives of the monitoring programme. Decisions made following the consideration of these compromises influence instrumentation and the monitoring plan design.

Based on these factors, the following processes were selected for inclusion in the EBS monitoring plan (see justification in VTT *et al*., 2019):

- Thermal evolution of the canister.
- Water uptake and swelling of buffer (density homogenisation).
- Saturation and deformation of the backfill.

4.1.3 Expected evolution of the EBS and host rock

Predicting the expected evolution of the site and EBS, and hence the predicted sensor readings, is necessary to inform planning decisions, for executing a monitoring plan, and for preparing for decision making in response to monitoring results. Here, the expected evolution has been derived from thermo-hydraulic (TH) simulations for the *in situ* EBS system test. This section gives a short overview of the expected evolution; further information and details of the model are given in Kristensson (2015) and VTT *et al*. (2019).

The tunnel geometry and dimensions that were used in the model for simulating TH evolution of the site and EBS can be seen in Figure 4.1. The model was run for two cases: one where there were no fractures in the rock, and one where fractures were present. The nature and locations of fractures, as used in the fractured case simulations, can be seen in Figure 4.2. The canisters were expected to output 1,700 W. Processes which were investigated using this model were:

- Temperature in the rock (see below).
- Degree of saturation in the buffer and backfill (see below).
- Temperature in the buffer (see VTT *et al*., 2019).
- Liquid pressure (saturation) in the rock (see VTT *et al*., 2019).

Important events in the time scale of the model occur at:

- t = -1000 days: Tunnel excavation. At this time, the open tunnel has relative humidity of 100%.
- t = -800 days: the relative humidity of the open tunnel was set to 90%.
- t = 200 days: all EBS components are installed and the heating is turned on.

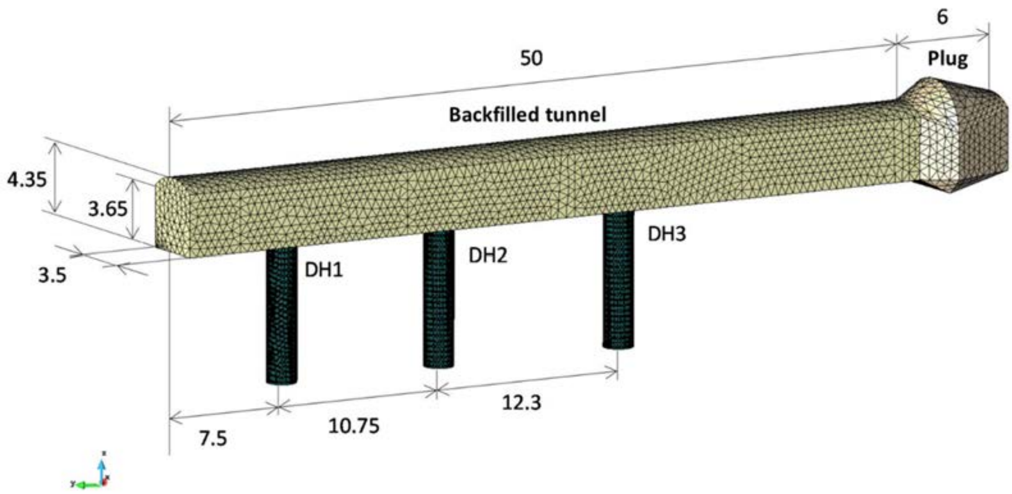


Figure 4.1: The experiment tunnel geometry and dimensions, as used in the thermo-hydraulic simulations for the *in situ* EBS system test. Each deposition hole (DH1 to DH3) contains a canister surrounded by a bentonite buffer. From VTT *et al.* (2019).

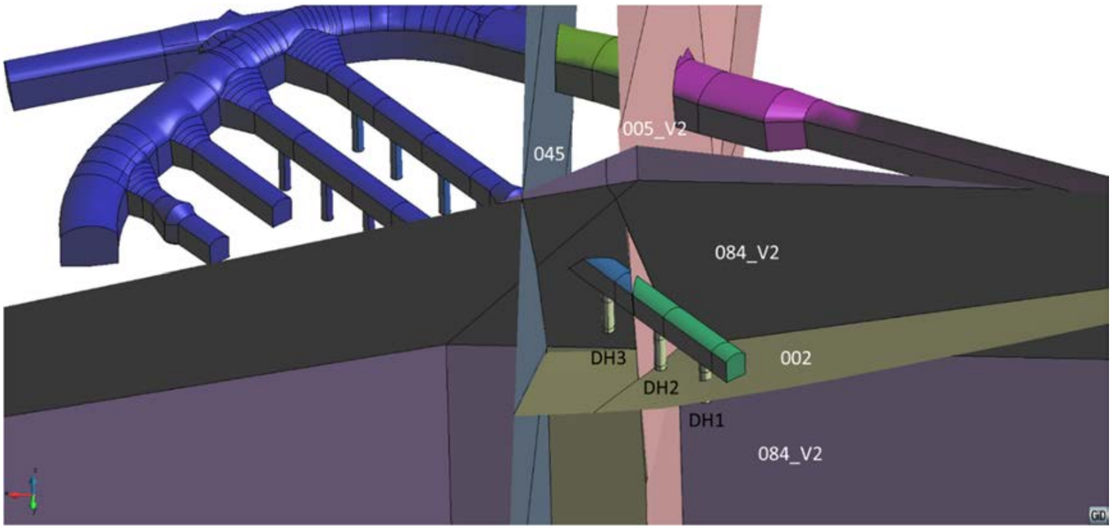


Figure 4.2: The geometry and location of fractures used as input to the model for its fractured case. From VTT *et al.* (2019).

Temperature in the rock

The temperature distribution after approximately one and fifteen years is presented in cross-section in Figure 4.3.

Degree of saturation in the buffer and backfill

The degree of saturation in the buffer and backfill is presented in Figure 4.4. The figure presents a vertical cross-section of the backfilled deposition tunnel. The figures show that the fractured case saturates more quickly but less uniformly than the unsaturated case.

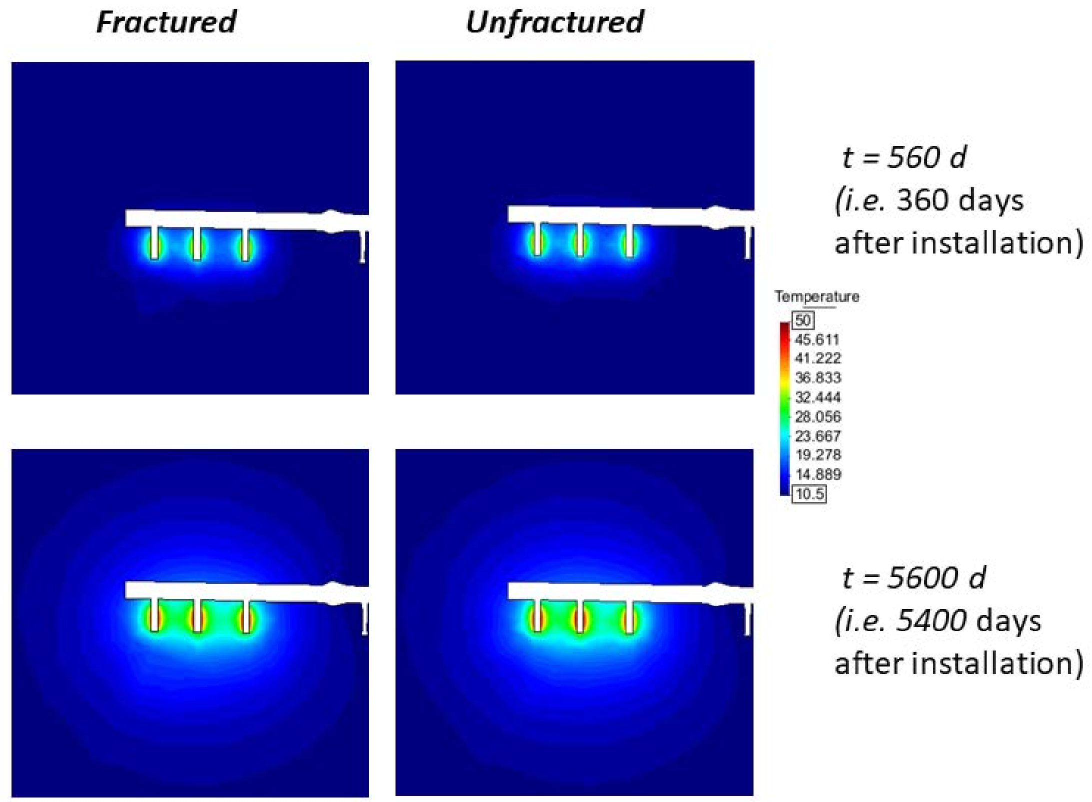


Figure 4.3: Temperature distribution (°C) in the rock at 360 days (top) and 5400 days (bottom) after installation, for the fractured (left) and unfractured (right) cases. From Kristensson (2015).

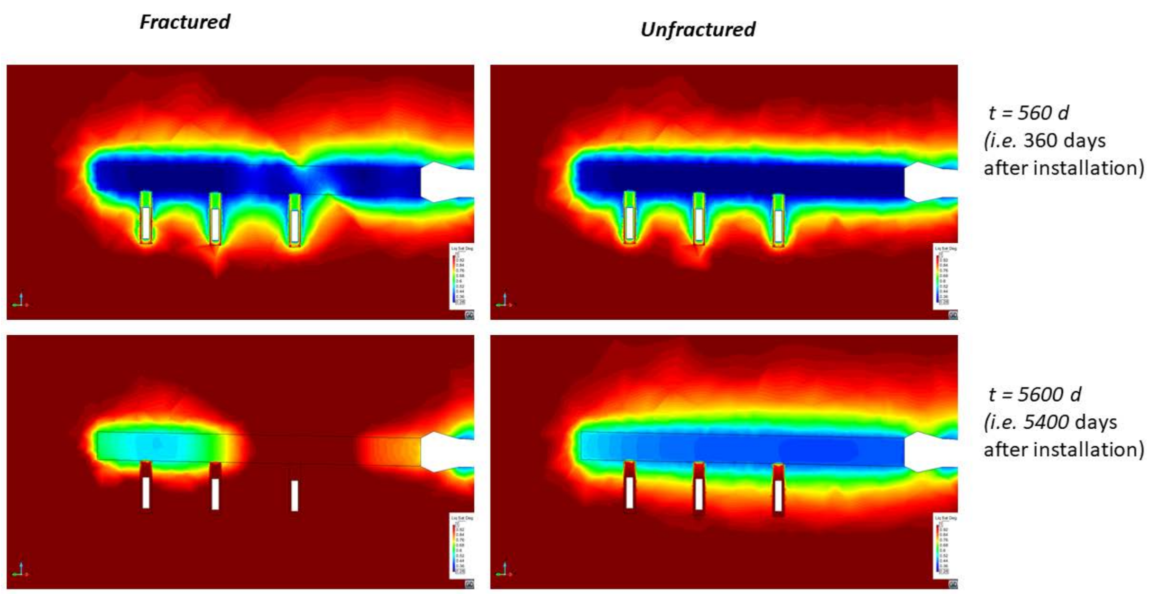


Figure 4.4: Vertical cross sections showing the degree of saturation in the buffer and backfill of the deposition tunnel 360 days (top) and 5400 days (bottom) after installation of the EBS, for the fractured (left) and unfractured (right) cases. Higher degrees of saturation are denoted by the red colour, and lowest degrees of saturation are denoted by the blue colour. From Kristensson (2015).

4.1.4 Measurement methods and sensor locations

In this section, the technologies and measurement methods (i.e. sensors or monitoring equipment and their locations) used for monitoring the processes listed at the end of section 4.1.2 and described in more detail in VTT *et al*. (2019) are given. The methods selected for EBS monitoring below are based on the assessment work described in VTT *et al*. (2019).

Thermal evolution of the canister

The thermal evolution of the canister will be monitored by taking temperature measurements at the exterior surface of the mechanical insert, using k-type thermocouples, and at the surface of the copper canister, using multipoint thermocouples. Pt100 sensors will be placed within 12 heaters located inside the canister's iron insert in order to provide feedback to the temperature controlling system. The locations of both of these types of temperature sensor can be seen on Figure 4.5.

Additionally, integrated temperature measurements will be taken using total pressure sensors, pore pressure sensors and relative humidity sensors.

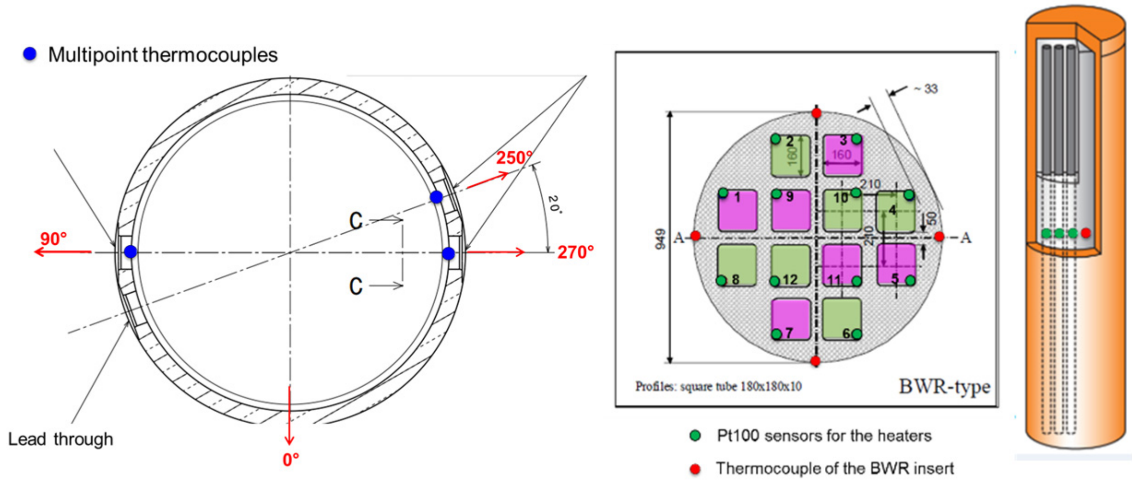


Figure 4.5: The locations of K-type multipoint thermocouples on the inner surface of the copper canister (left). The locations of Pt100 sensors on the canister's iron insert, and thermocouples (K-type) on the surface of the BWR insert (right). From VTT *et al.* (2019).

Water uptake and swelling of the buffer

To monitor water uptake and swelling of the buffer, the parameters chosen for monitoring were geometry, density, water content/degree of saturation at installation and dismantling and the swelling pressure.

No technically feasible method of directly measuring density change during the test implementation was identified. Therefore, the methods of detecting swelling and density changes comprise of the following sensors which would be placed in or around the deposition tunnel, or in the buffer:

- **Total pressure** measurements, which will be taken in the deposition hole (Figure 4.6).
- **Pore pressure** measurements, which will be taken in the deposition hole (Figure 4.6).
- **Relative humidity**, using capacitive humidity transducers and thermocouple psychrometers which will be installed on the rock wall of the experimental deposition tunnel and bentonite buffer (Figure 4.6 and Figure 4.7).
- **Temperature** (as this influences hydraulic and mechanical processes), which will be measured in the experimental deposition holes (Figure 4.6), buffer (Figure 4.7) and in the deposition tunnel.

- **Resistivity** measurements, using an ERT system deployed in the deposition tunnel (Figure 4.8). This would allow the saturation process to be followed with minimal disturbance to the buffer and installation process. Using this system, variations in resistivity in the buffer and backfill can be derived in 3D, which could be used for calculating the water content or degree of saturation of the bentonite for a fixed density, temperature and pore water chemistry.

The water saturation of the buffer and backfill can be determined by using the resistivity measurements and the relative humidity measurements.

Saturation and deformation of the backfill

Saturation and homogenisation of the backfill close to the tunnel roof would influence deformation processes such as the upward swelling of the buffer, and the backfill in this region may also be sensitive to processes such as piping and erosion. The following measurements will be made in the backfill:

- **Total pressure** measurements, using sensors situated on the backfill tunnel wall and vault in several locations (Figure 4.9).
- **Pore pressure** measurements, using sensors installed on the backfill tunnel wall in several locations (Figure 4.10).
- **Resistivity** measurements, using ERT electrode chains (based on the technology described in Section 3.6.2) installed into the walls and vault of the backfill tunnels (Figure 4.11).

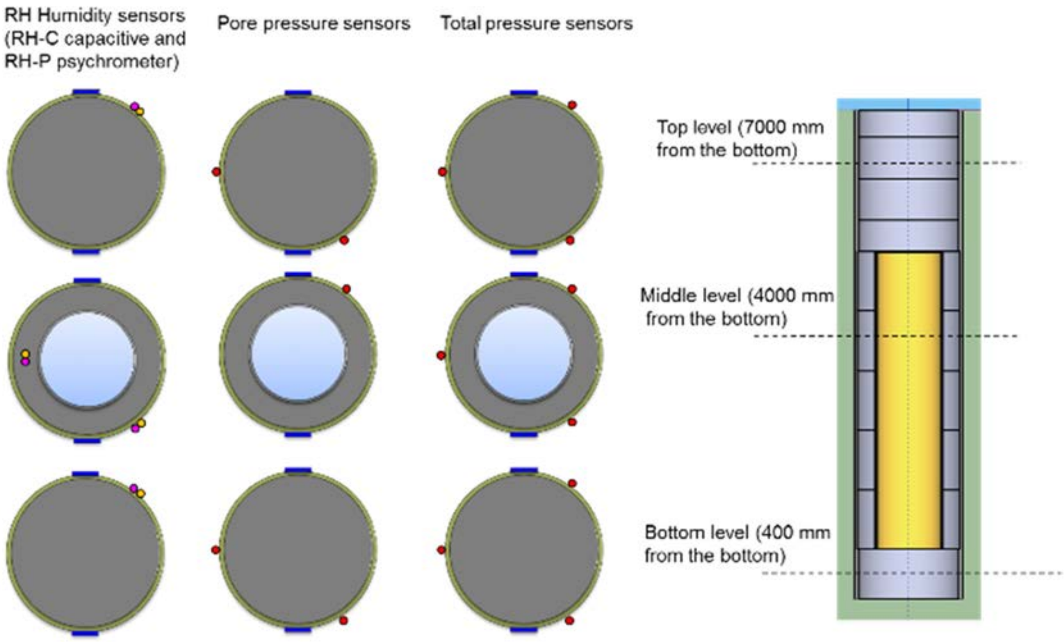


Figure 4.6: The locations of relative humidity, pore pressure and total pressure sensors in the deposition tunnel, on the surface of the rock. Temperature is also measured by all of these sensors. From VTT et al. (2019).

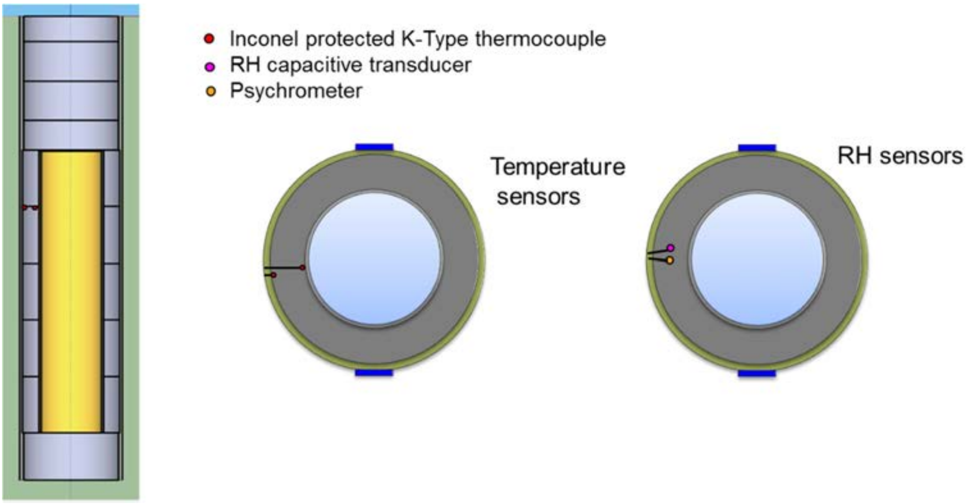


Figure 4.7: The location of temperature sensors and relative humidity sensors in the buffer. From VTT *et al.* (2019).

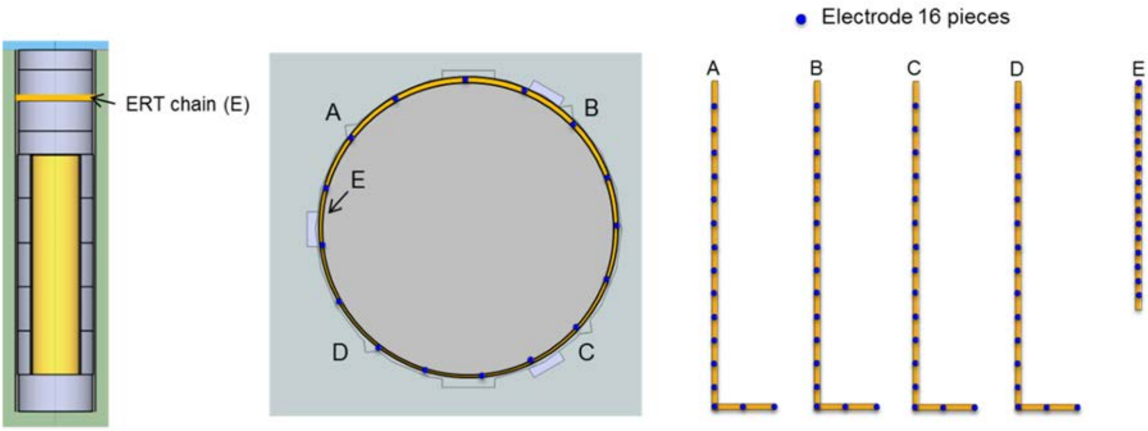


Figure 4.8: Locations of the ERT electrode chains in the experimental deposition hole. From VTT *et al.* (2019).

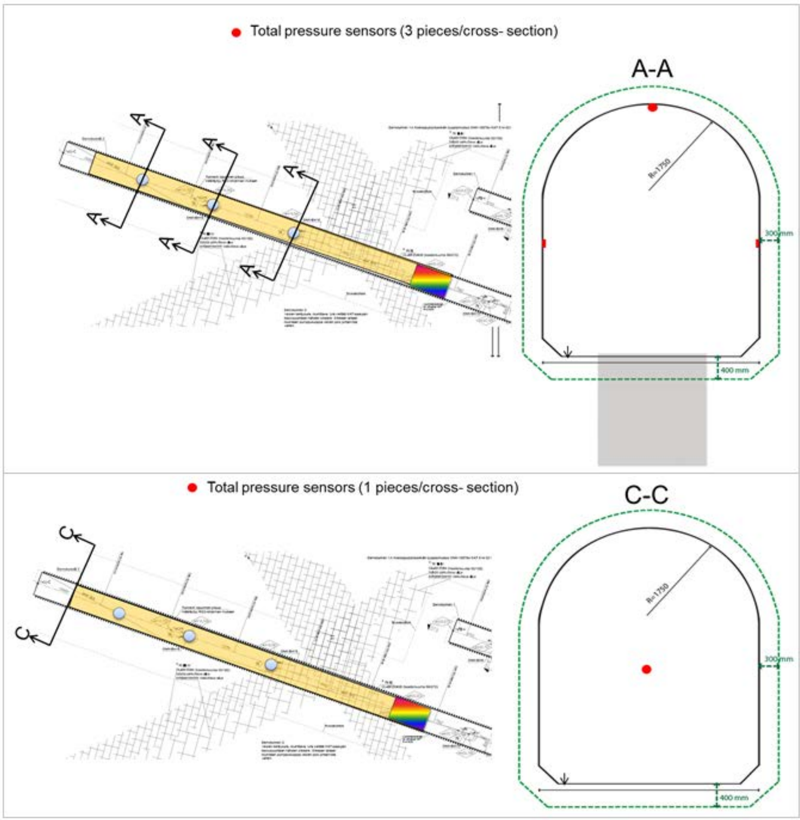


Figure 4.9: The locations of total pressure sensors in the backfill tunnel. From VTT *et al.* (2019).

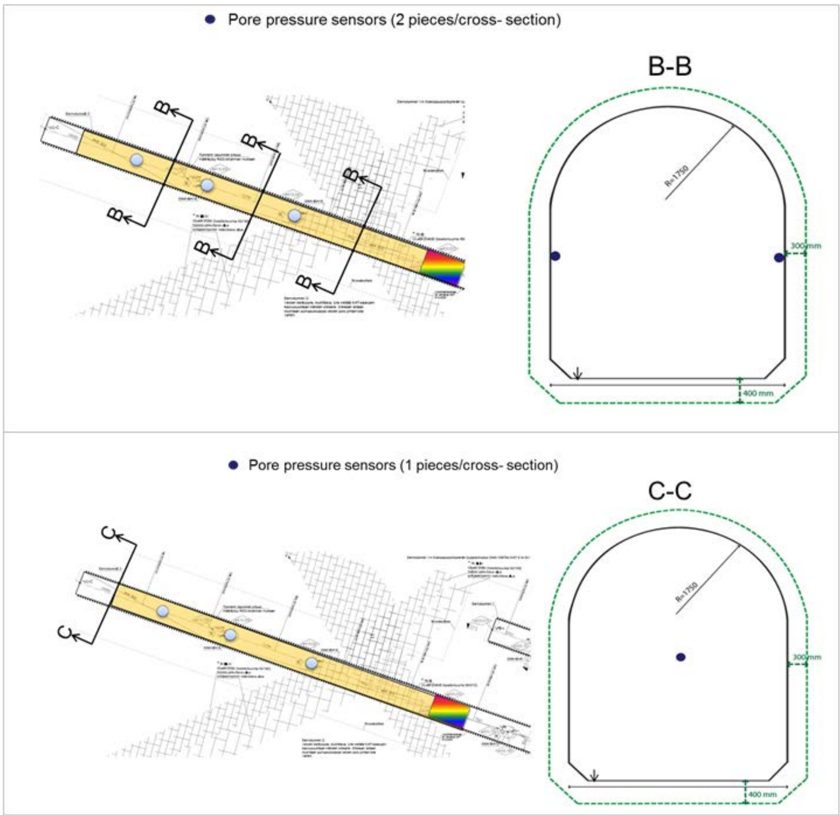


Figure 4.10: The location of pore pressure sensors emplaced on the backfill tunnel wall. From VTT *et al.* (2019).

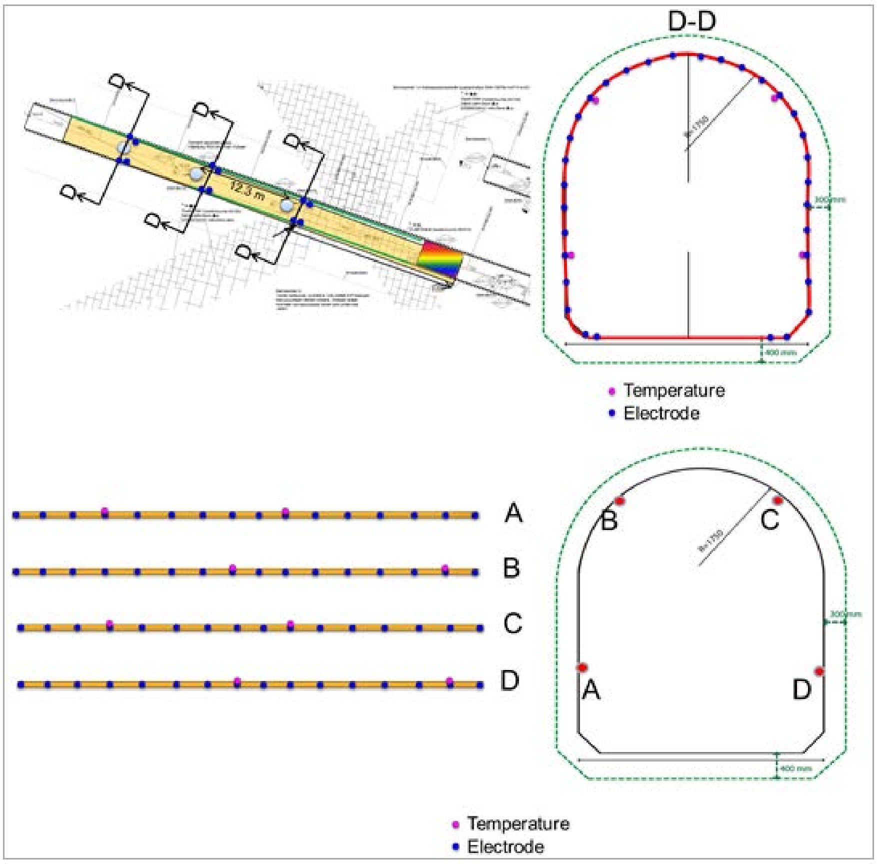


Figure 4.11: The locations of ERT electrode chains in the backfill tunnel, along the tunnel cross section (top) and longitudinally along the tunnel (bottom). From VTT *et al.* (2019).

4.1.5 EBS monitoring plan strategy and execution

Part of Posiva's monitoring objectives is to check for the occurrence of unexpected events. Therefore, the monitoring system requires data to be measured at a relatively high frequency and for relatively long periods (i.e. decades).

The general strategy that was adopted was to collect data with a relatively high frequency at the beginning of the full-scale test, and reduce the frequency thereafter. There are several reasons for this. THM processes are expected to evolve relatively quick at the beginning of the test but slow down as the saturation of the bentonite progresses. Therefore, taking frequent measurements in the beginning of the test minimises the risk of missing some information during this period when the most changes are occurring. Collecting data too frequently would also result in an impractical volume of data requiring storage. This adjustment of measurement frequency according to the experiment evolution is possible for most sensors.

The monitoring plan strategy for each set of measurements is summarised below.

- Temperature, water pressure and total pressure in the canister, buffer and backfill.
- Temperature and water pressure in borehole sections in the crystalline bedrock.
- Moisture in the buffer and backfill using ERT.
- Moisture and pressure in the deposition tunnel plug.

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

In the EBS monitoring plan, the measurement frequency for the canister, buffer and backfill can be adjusted and is suggested to be more frequent in beginning and based on the results and their interpretation from first months the frequency can be reduced.

Temperature and water pressure in borehole sections in the crystalline rock

The most relevant site properties for supporting the monitoring of EBS components are hydrogeological and hydrogeochemical properties in the host rock, and some of its mechanical properties. In this EBS monitoring plan, the temperature and pressure conditions in surrounding rock are the supporting elements, and these will be followed simultaneously. These processes may be monitored as part of the EBS monitoring plan, or, as is often the case, they are monitored as part of a site monitoring programme. Either way, it is important to consider the requirements on site monitoring from the point of view of understanding the EBS evolution. In this EBS monitoring plan, these supporting site measurements are collected by the existing ONKALO general monitoring system, however some additional measuring points will be added to the existing monitoring programme.

Moisture in the buffer and backfill using ERT

Since monitoring all locations is not very practical, a novel method is planned to be used to monitor the moisture distribution in buffer and backfill – ERT. This measurement system differs from those which use individual sensors, in that it is an active process which applies current through the medium between electrodes and measures the resistivity over buffer and backfill. This is done in campaigns, in which it takes approximately a couple of days to take measurements. The attained data is then analysed and a variation in the spatial distribution in resistivity over backfill and buffer is presented. This can be converted to water ratio of saturation rate. The ERT measurements do require other types of moisture sensors to support the interpretation of the results; these more conventional moisture sensors are installed in the vicinity of ERT probes, and their measurement frequency will be similar to that of the pressure sensors.

Moisture and pressure in the deposition tunnel plug

The deposition tunnel plug, encompassing the filter and seal layer, is essentially part of the backfill. The plug construction will take place months after the buffer and first part of the backfill are emplaced, and therefore an independent monitoring system is needed. A separate approach to monitor a plug system is tested as part of the DOMPLU (Grahm *et al*., 2015) and POPLU (Holt and Koho, 2016) projects as part of the EC DOPAS Project.

4.1.6 Conclusions

This EBS monitoring plan describes the processes to be monitored, proposes the instrumentation to be used for monitoring, and proposes a monitoring design plan for the experimental deposition tunnel, which can be used as basis for designing a full-scale experiment where monitoring aspects are included as part of the test. The results from model predictions for the expected evolution of the EBS and surrounding rock are presented, and these were used to influence and inform the monitoring plan strategy based on the assessment of available methods and sensors. It is worth noting that in practice, the objectives set for an EBS monitoring plan may differ according to many different types of test setups and experiments, and just once example is presented here.

The objectives set for a monitoring plan will be verified by comparing monitoring results to predictions, and the disagreements discussed from the perspective of the safety case. In most cases, differences between predictions and monitoring results will have no implication for the safety case, however this should still be analysed. This type of verification is not a feature of the EBS monitoring plan presented here.

Monitoring data, information gathered during dismantling, and parallel development work will be used for improving the understanding of THM processes during the course of the project. This understanding can in turn be used for the adjusting the detailed design of EBS components (e.g. the canister, buffer and backfill).

4.2 Monitoring plan development during the HLW disposal cell demonstrator in Bure URL, France

This section provides an overview of the work done during the HLW disposal cell demonstrator conducted by Andra in their URL in Bure, France. The work focused on the qualification programme to contribute to the system that can be used for monitoring of HLW disposal cells during the Industrial Pilot Phase of Cigéo operation (including a small pilot HLW disposal). This work is undertaken in a stepwise fashion by conducting a series of demonstration experiments with each experiment progressively demonstrating more aspects of the full monitoring system.

The main objectives of the work were to identify the monitoring parameters to be tested in demonstrators; describe the technology envisaged for use in monitoring each parameter; identify the qualification process (in the surface laboratory and *in situ*) for the monitoring system components; describe the design of the envisaged monitoring system dedicated to HLW cells in Cigéo; and demonstrate the feasibility of monitoring through commissioning of two demonstrator disposal cells (AHA1604 and ALC1605), according to the concept envisaged in the pilot phase. More information can be found in the Modern2020 Project Deliverable D4.2 (Andra and EDF, 2019).

4.2.1 Identification of monitoring parameters

The parameters to be monitored in the two demonstrators were identified through consideration of the results of the parameter screening exercise undertaken in Task 2.2 of the Modern2020 Project (see Section 2.3.1) and through specific consideration of the demonstrator (i.e. the need to qualify specific monitoring technologies as part of the experiments). The selected parameters, and the technologies used to monitor each parameter are listed in Table 4.1.

Table 4.1: The monitoring parameters chosen and technology options selected as result of Andra's selection monitoring parameter identification process.

Parameter	Component	Technology Option for Demonstrators
Temperature	Disposal cell / near-field rock	Platinum probe and/or optical fibre sensors
Pore-water pressure	Near-field rock	Vibrating wire extensometers or optical fibre piezometers
Confining pressure	Total pressure on cell sleeve	Optical fibre sensors
Displacement	Cell sleeve	Optical fibre sensors and 3D scan
Strain	Cell sleeve	Vibrating wire extensometers or optical fibre sensors
Hydrogen concentration	Cell atmosphere	LiDAR and/or thermal gas conductivity and/or gas density and viscosity measurements
Oxygen concentration	Cell atmosphere	LiDAR
Relative humidity	Cell atmosphere	Capacitive sensor (based on an electrical capacitor)
Pore-water pH	Near-field rock	pH meter
Thickness	Cell sleeve	Corrosion coupons
	Overpack	Corrosion coupons
Corrosion rate	Cell sleeve	Electrical resistance probes and mass loss of coupons
	Overpack	Electrical resistance probes and mass loss of coupons

4.2.2 Description of the Bure URL

Andra's main research facility is the URL in Bure (Figure 4.12). This facility is situated within Callovo-Oxfordian clay layer in the Eastern section of the Paris Basin; this geological setting is considered a suitable site for a repository as the argillaceous layer is thick (thickness between 120 m to 160 m), relatively homogeneous, and free of faults. The facility was licensed in August 1999 and its construction (access shafts, basic drift network with underground ventilation) was completed in 2006. Further drifts and galleries are being excavated for ongoing geological surveys and experimental programmes.

In the URL, disposal cells demonstrator are sub-horizontal dead-ended tunnels with a diameter of 0.92 m (see Figure 2.1). The cells are comprised of a cell head and a usable part for emplacement of heaters representing waste packages. To prevent rock deformation and enable the potential retrieval of disposal packages during the operating period, the cells are equipped with a steel sleeve. The gap between this liner and the rock is filled with a cement-based grout, which helps to limit the sleeve corrosion rate.

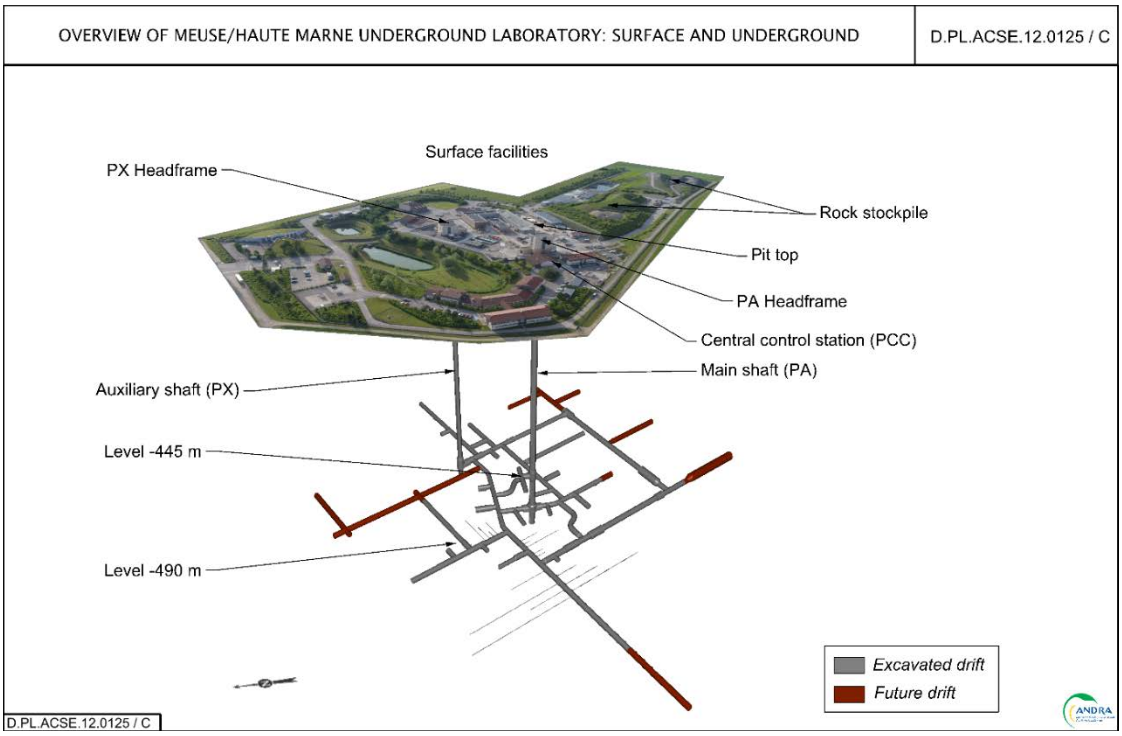


Figure 4.12: Overview of the Bure URL, including the surface facilities. The dashed red ellipse indicates the location of the demonstrators where HLW cells are located. From Andra and EDF (2019).

4.2.3 The AHA1604 and ALC1605 demonstrators at Bure URL

Two *in situ* HLW disposal cell demonstrators in Andra's Bure URL were dedicated to the demonstration and evaluation of the monitoring system for the HLW disposal cells – the AHA1604 and ALC1605 demonstrators. These were designed to:

- Demonstrate the implementation of a monitoring system in real conditions with realistic construction constraints.
- Qualify the monitoring design to provide THMC information, in repository-like conditions.
- Demonstrate Andra's ability to continuously monitor the integrity of structures in real-time for several decades.
- Qualify sensors in a repository-like environment.

The AHA1604 demonstrator

The AHA1604 demonstrator was 112.5 m in length (Figure 4.13). The main objectives of the demonstrator were:

- To validate the drilling method and grout injection at a depth of 100 m, by monitoring the strain distribution around the cell.
- To test new OFS cables.
- To evaluate OFS configuration to measure the deformation of the tube.

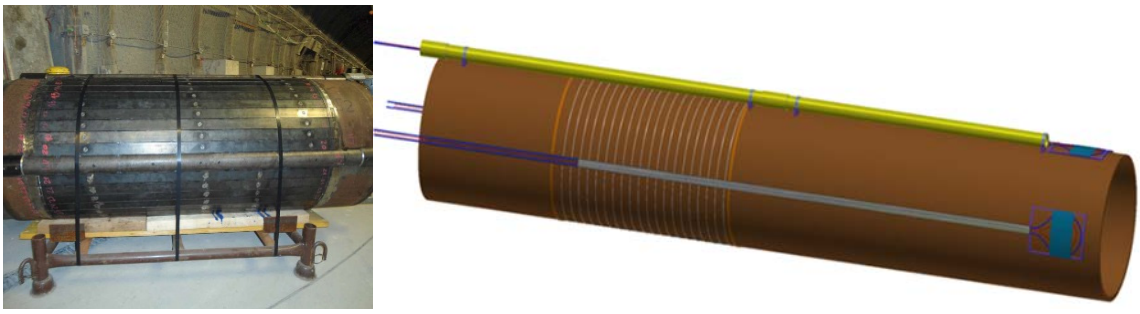


Figure 4.13: The steel liner used in the AHA1604 demonstrator equipped with OFS cables for monitoring strain. From Andra and EDF (2019).

Three types of OFS were installed on the exterior surface of the metallic casing (Figure 4.14):

- Single-mode FO cables (SSV9 sensors from Brugg) to take distributed Brillouin and Rayleigh measurements of deformation (or strain). These were glued in place longitudinally along the first 15 m of the liner (measured from the access gallery).
- Multi-mode FO cables (T85 sensors from Brugg) to take Raman distributed temperature measurements. These were glued in place longitudinally along the first 15 m of the liner (measured from the access gallery).
- Single-mode FO modules (Emboss FN-SILL-3 sensors from Neubrex) to detect deformation of the liner using the Brillouin and Rayleigh methods. These OFS were coiled and glued around the circumference of the exterior surface of the liners 12 m from the access gallery.

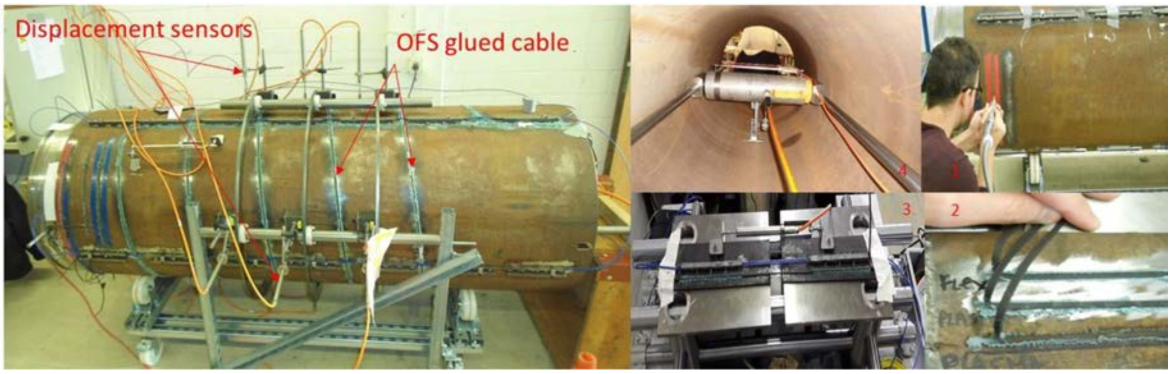


Figure 4.14: Photos of the sleeve equipped with OFS cables, the Sleeve equipped with (outside) classical sensors and OFS cables spiraled and (inside) hydraulic jack used to apply the radial loading (left) and the different steps of the laboratory test (1) surface preparation, (2) glue test, (3) axial strains up to break, (4) load test, and (right). The test bench is used for the calibration of the system. From Andra and EDF (2019).

The implementation includes the design, the docking system and the development of the protection system needed when installing the tube section. All of the OFS sensors were successfully installed without any damage (100% survival rate). Dynamic strain and temperature measurements were obtained during the installation and grouting phase of the experiment, providing demonstration of the filling of the gap between the liner and the rock.

The ALC1605 demonstrator cell

The ALC1606 demonstrator is 28.5 m in length. Heating elements are installed inside the ALC1605 cell, and the thermo-mechanical behaviour of the EBS and host rock will be monitored when heating commences in September 2019. The main objectives of the demonstrator are:

- To study the impact of thermal loading on the thermo-mechanical behaviour of the cell liner in the presence of filler material, by monitoring the direction and amplitude of liner deformation, axial thermal expansion and water movement. The data acquired will complement those obtained from the AHA1604 demonstrator experiment where no thermal loading took place.
- To study the impact of thermal loading on the THM behaviour of rock in the near-field (but beyond the excavation damage zone (EDZ)) and far-field in the presence of filler material. The evolution of temperature and interstitial pressure around the cell and at different distances from the gallery access will be monitored. Comparison of the results with the previous ALC1604 Experiment, which was undertaken during the LUCOEX Project (Gugala, 2015), will allow the potential impact of the filling material on the kinetics and amplitudes of the thermal overpressures in the near-field and far-field to be identified.
- To evaluate the performance of gas sensors.

Similarly to the AHA1604 demonstrator, OFS cables have been installed to measure temperature, strain and liner deformation. Additional sensors for chemical measurements have been installed in one location in order to assess the installation method and the resistance of the OFS cables to the repository environment.

ALC1605 also offers the opportunity to assess the performance of sensors in representative thermal conditions. For that, a specific OFS cable was developed (evolution of Emboss FN-SIL) and tested in order to operate at temperatures of 90°C. In addition, the steel liner was modified in order to be more precisely centred in the cell. This modification allowed for the protection installed around the OFS cables to be reduced, which reduces the complexity of the installation process.

In addition, new sensors were tested in order to provide additional information and a comparison to the results obtained using the OFS. For instance, vibrating wire extensometers were installed at eight locations on one sleeve where spiralled OFS cables were situated, and displacement sensors were placed inside the sleeve.

Chemical sensors have been installed at the external face of the casing, in order to provide information about the oxygen content, hydrogen content, pressure, relative humidity and water pH in the cement-based materials around the casing.

4.2.4 Outcomes and conclusions

A summary of the failure rate of the sensors in the two demonstrator experiments is provided in Table 4.2. As can be seen in the table, the only sensors to fail were conventional sensors (one vibrating wire sensor and one platinum probe).

Table 4.2: Performance of sensors in HLW disposal cell demonstrators at Andra's Bure URL.

Cell	Sensor Type	Monitored Parameter	Sensor Location		Total Sensors	Failed Sensors	Survival Rate
			Linear Exterior	Linear Interior			
AHA1604	OFS cable longitudinal	Strain	X		3	0	100%
		Temperature	X		3	0	100%
	OFS cable spiral	Deformation	X		1	0	100%
	Platinum probe	Temperature	X				100%
ALC1605	OFS cable longitudinal	Strain	X		3	0	100%
		Temperature	X		3	0	100%
	OFS cable spiral	Deformation	X		1	0	100%
	Vibrating wire extensometer	Strain	X		8	1	88%
	Thermistor	Temperature	X		8	0	100%
	Hydrogen	H_2	X		1	0	100%
	Oxygen	O_2	X		1	0	100%
	Platinum probe	Temperature	X		5	1	80%
	LVDT	Convergence		X	24	0	100%

Acronym: LVDT: Linear variable differential transformer.

AHA1604 demonstrator

Data were collected during three periods:

- During installation: to determine whether the OFS cables experienced significant strain as a result of construction.
- During grouting: to assess the filling quality of the injected material.
- Over the long-term: to monitor liner deformation, longitudinal strain and heating.

The results were of good quality. However, an increase in the laser optical power caused failure of the calibration adjustment procedure for some of the OFS measurements; this is likely to have caused a constant offset in measurements along the fibre.

Several recommendations were identified as ways in which measurement and data quality could be improved when monitoring during installation. First, Brillouin-based monitoring methods should be replaced by Rayleigh-based monitoring methods to improve accuracy. The frequency range of these Rayleigh-based monitoring should be as narrow as possible to reduce measurement time, and when calculating frequency shifts, the previous measurement should be used as a reference.

Recommendations for improving monitoring during grout injection were also identified:

- The use of Rayleigh measurements would allow better detection of movement in the grout.
- Since it is installed in a spiral pattern, using embossed OFS cables allow a better spatial resolution to be obtained.
- The OFS cables are protected by metal strips, which may have influenced the recorded strain measurements. Therefore, it may be difficult to determine the movement of the grout based on strain measurements from these OF cables only, and a secondary method of monitoring would be useful for providing further information.

ALC1605 demonstrator

The installation of OFS sensors on the ALC1605 demonstrator was generally successful as a result of using feedback from the AHA1604 demonstrator in the design process. The data acquired during installation clearly reflected the gap between the casing and surrounding rock becoming filled with grout (Figure 4.15). Furthermore, these data were a good fit with the expected trends, which have previously been observed during other *in situ* demonstrations and in numerical models.

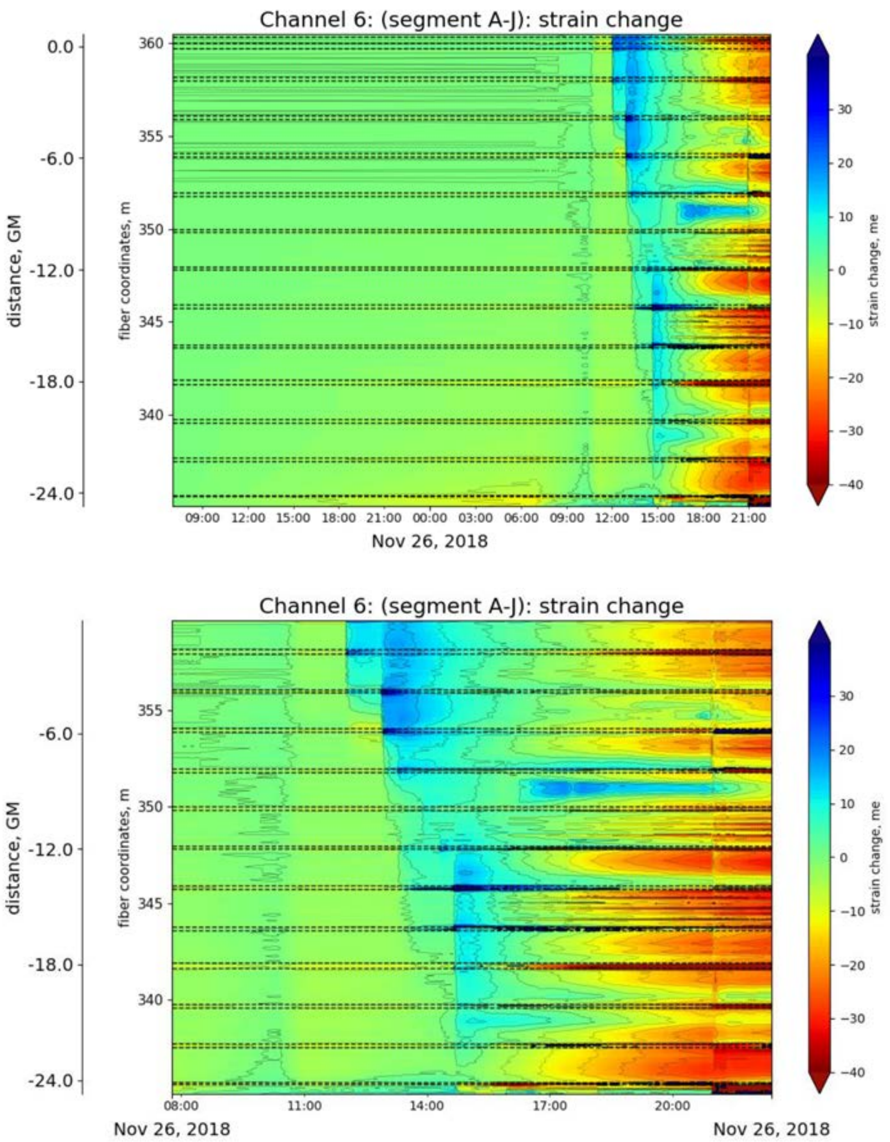


Figure 4.15: Strain change recorded by OF during the installation of the ALC1605 demonstrator.

4.2.5 Conclusions from the HLW demonstrators

The HLW disposal cell demonstrators have demonstrated the ability to qualify novel technologies for monitoring the THMC conditions of HLW disposal cells. This demonstration is part of the process for preparing for implementation of geological disposal in Callovo-Oxfordian Clay, and contributes to development of confidence that such monitoring can be undertaken successfully.

4.2.6 Further work

Plans are in place to test a complete monitoring system in another demonstrator, AHA1605, in mid-2019. In this demonstrator, 80 m of liner will be instrumented in order to prove Andra's capacity to monitor thermo-mechanical and chemical parameters of a complete HLW disposal cell.

4.3 The LTRBM Experiment in the Tournemire URL, France

This section provides a summary of the design and field operations of an *in situ* test, called the Long-Term Rock Buffer Monitoring (LTRBM) Experiment at the Tournemire URL in France. The LTRBM Experiment aimed to demonstrate the performance, under real *in situ* conditions (e.g. within an EBS), of new sensors developed in WP3 of the Modern2020 Project. Additionally, demonstration of wireless data transmission from the LTRBM Experiment to the ground surface (a distance of 275 m through rock) was attempted.

Further details of this work can be found in the Modern2020 Project Deliverable D4.3 (Dick *et al.*, 2019).

4.3.1 The LTRBM borehole layout

The LTRBM design was based on a series of performance assessment sealing experiments called SEALEX (Barnichon *et al.*, 2012), implemented at IRSN'S Tournemire URL, and uses the existing infrastructure of these experiments (including the data acquisition system) in order to minimise development costs. The main investigation area of the Tournemire URL is located in the Upper Toarcian-Lower Aalenian shale formation of the Mesozoic Causse basin in SW France (Figure 4.16).

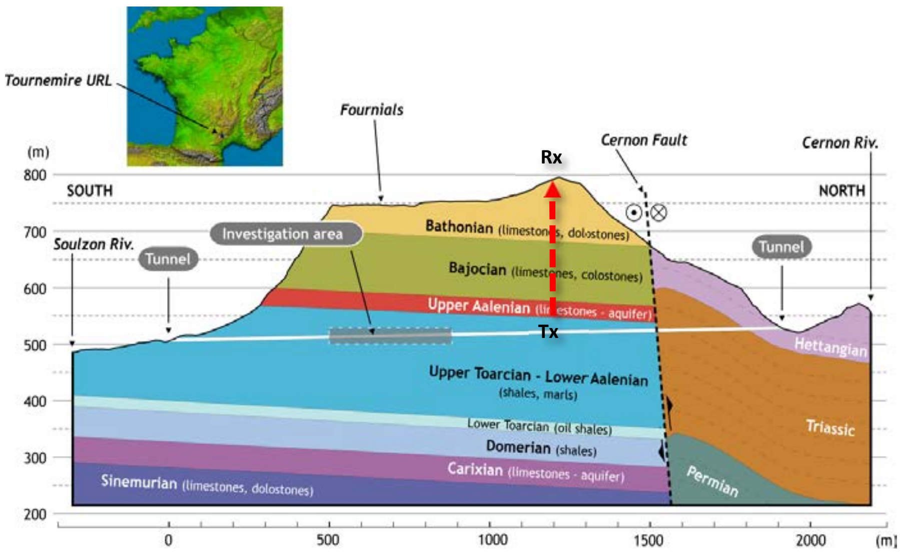


Figure 4.16: A cross section of the geological setting within which the Tournemire URL resides. The figure also shows the location of the long range data transmitter and receiver demonstrated within LTRBM. 'Tx' indicates the location of the subsurface transmitter, and 'Rx' the surface receiver. The transmission distance is 275 m. From Dick *et al.* (2019).

The general layout of the LTRBM Experiment consists of a main horizontal borehole (MB) measuring 60 cm in diameter and 10 m in length. The MB was backfilled with a 4 m long bentonite-sand buffer (highly compacted bentonite-sand blocks and a granular bentonite-sand mixture) and confined by means of a 2 m long bentonite-cement plug (Figure 4.17). The buffer was equipped with five independent artificial saturation systems, composed of hydration mats inside the MB which were connected to a water injection system; these were used to accelerate the saturation of the buffer.

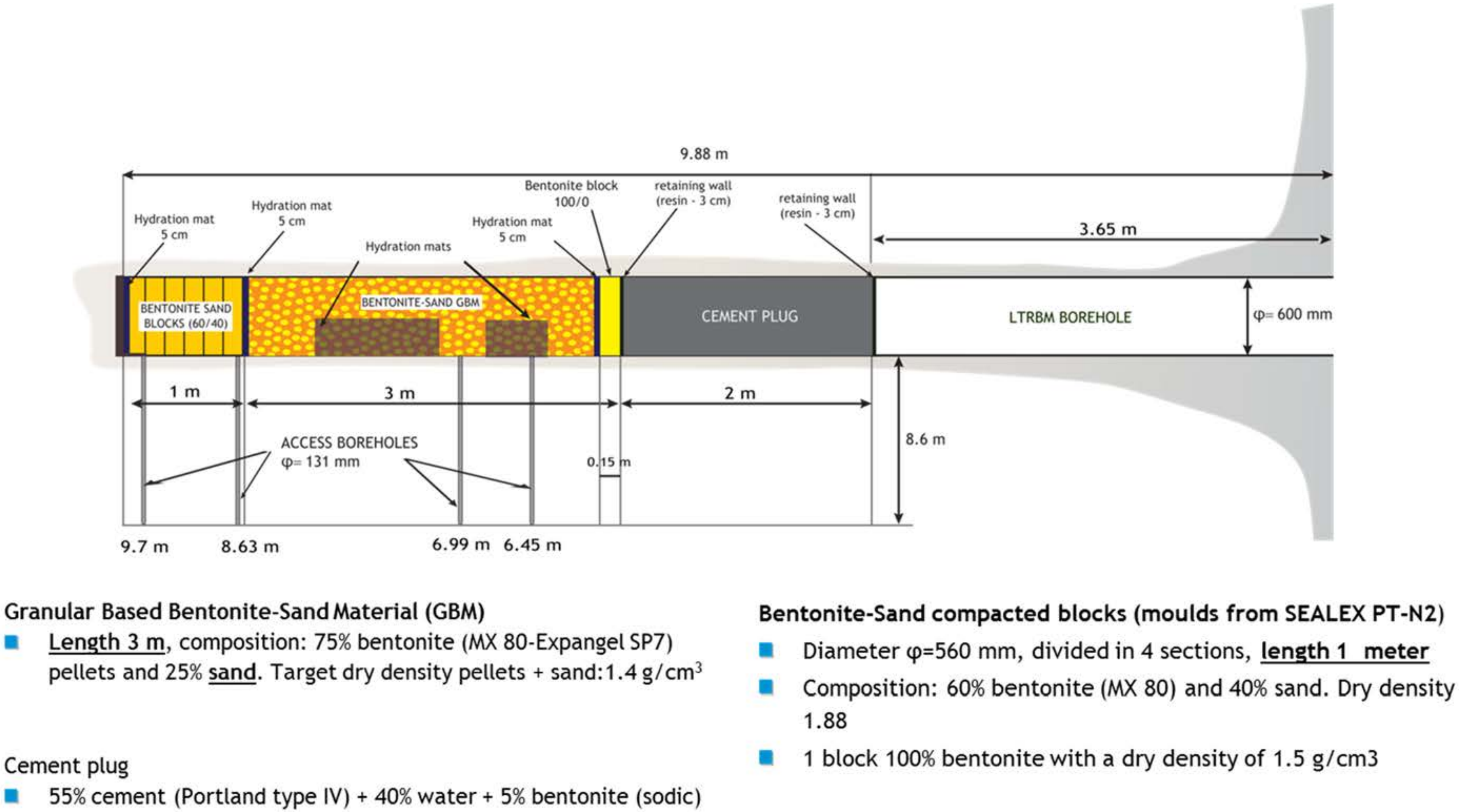


Figure 4.17: Plan view of the engineered barrier layout distribution inside the main borehole (MB) of the LTRBM experiment. From Dick *et al*. (2019).

In addition to the MB, nine auxiliary boreholes were drilled either perpendicular or parallel to the MB:

- Four were drilled perpendicular to the MB and used to pass the hydration lines and wired cables from the buffer to the data acquisition system, thus avoiding having cables running through the buffer which would have created preferential pathways. The boreholes were PVC cased and cemented with a high-performance resin to protect them from water flow inside the boreholes.
- Four were drilled parallel to the MB; these were used to house four geophysical streamers for ERT surveys.
- One was drilled parallel to the MB, at a distance of 1.5 m, to house wireless receivers.

Several EDZ structures can be observed around and along the MB. These structures are associated with the construction of the borehole and more particularly to the natural ventilation of the galleries causing the development of desaturation fractures. These structures are oriented parallel to the bedding and have a radial extension of ~7 cm. A water injection experiment (located next to LTRBM) combined with numerical modelling has shown that these fractures reseal a few years after resaturation and the permeability of the host rock recovers to pre-excavation values (Thatcher *et al.*, 2016).

4.3.2 Instrumentation

Three types of instrumentation were installed in the bentonite buffer:

- New measuring sensors that had never been tested *in situ*, either developed within the Modern2020 Project in WP3, or outside the project.
- Standard (commercial) measuring instruments.
- Instrumentation required to control and monitor test evolution.

These sensors were installed in the bentonite blocks, inside the GBM, and, in the case of ERT equipment, around the MB; details for these sensors can be found in Table 4.3.

Table 4.3: Sensors installed in the LTRBM.

	Sensor	Element	Parameter	Provider	Data Transmission
New sensors from WP3	Chemical sensors	Precompacted blocks (60/40)	pH, Eh & Cl^- ions	VTT	Wired
	Thermocouple Psychrometers	Precompacted blocks (60/40) and GBM	Relative Humidity (RH) - 95% RH to 99.9% RH	ARQUIMEA	Wireless
	Integrated THM sensor	Precompacted blocks (100/0))	Total pressure, temperature, pore pressure and humidity	CTU	Wired
Other new sensors	Porewater sensors (vibrating wire based) attached to a wireless transmitter	Precompacted blocks (60/40) and GBM	Pressure in kPa	Andra	Wireless
	Total pressure (fibre-optics based)	Precompacted blocks (60/40)	Pressure in MPa (up to 7 MPa)	Andra	Wired
	ERT probes	Host rock	Volts	IRSN	Wired

	Sensor	Element	Parameter	Provider	Data Transmission
Standard sensors	Fibre optic cable	Cement plug	Strain (up to 1% strain) and temperature (-30°C – 70°C)	IRSN	Wired
	Miniature piezoresistive pore pressure sensors	Precompacted blocks (60/40) and GBM	Pressure (0 to 0.5 MPa)	AMBERG	Wireless
	Piezoresistive total pressure cells	Precompacted blocks (60/40)	Pressure (0 to 4 MPa)	AMBERG	Wired
	Capacitive type hygrometers	Precompacted blocks (60/40) and GBM	Relative Humidity (0 – 100%)	AMBERG	Wireless
	Automatic tensiometers	Precompacted blocks (60/40) and GBM	Pressure (0 to – 1000 kPa)	AMBERG	Wired
	FDR type water content sensors	Precompacted blocks (60/40) and GBM	Volumetric water content VWC) – > 0.05 VWC	AMBERG	Wired
	Wescor psychrometers	Precompacted blocks (60/40) and GBM	Relative Humidity (RH) - 95% RH to 99.9% RH	ARQUIMEA	Wireless
	TDR	GBM	Moisture content	University of Strathclyde	Wired
Control sensors	Displacement sensors	Cement plug	Displacement (mm)	AMBERG	Wired
	Hydraulic pressure sensors	Precompacted blocks (60/40) and GBM	Pressure (0 to 5 bars)	AMBERG	Wired
	Weight sensor	Tunnel	Water volume in tank (0-50 kg)	AMBERG	Wired
	PT100	Precompacted blocks (60/40) and GBM	Temperature (0 – 100°C)	AMBERG	Wired

Acronym: TDR: time-domain reflectometry.

In addition to wired sensors that were directly cabled to a single data acquisition unit, three wireless data transmission systems were also used to transfer data measured inside the bentonite buffer to receivers placed outside the buffer. Two units each of two different types of wireless data transmission system were installed inside the bentonite buffer; these were designed to transmit data recorded from within the buffer to wireless receivers located in the adjacent gallery. One type (developed in WP3.2, see Section 3.2.2) used high-frequency transmission (2.2 MHz), while the other type used low-frequency transmission (below 10 kHz). A third wireless transmission system (also developed in WP3.2, see Section 3.2.2), was also installed with the aim of achieving long-range wireless data transmission from the LTRBM to the surface. For this purpose, a transmitter was installed in the main access tunnel of the Tournemire URL, and a receiver was installed on the plateau above.

4.3.3 Hydration of the bentonite buffer

Following installation of the sensors and instrumentation within and around the bentonite buffer, artificial hydration of the bentonite buffer commenced. This was achieved using two types of hydration systems (Figure 4.18). The first consisted of three 5-cm-thick hydration mats, two located on either side of the precompacted bentonite blocks and one located between the GBM and the precompacted bentonite block. This hydration system contained a circular, rigid plastic reinforcement mesh covered by a geotextile mat. The rigid mesh allowed each mat to contain around 10 litres of water, thus enabling a substantial amount of water to be available within the buffer, and therefore facilitating quicker hydration of the buffer. The second type of hydration system consisted of two independent hydration mats, each one 1-m long, lining half of the bottom borehole within the GBM section. Each hydration mat was connected to a hydration panel located on the gallery wall next to the main borehole mouth, and each mat could be used separately.

Figure 4.18: Photos of the hydration mats used to hydrate the bentonite buffer. (A) shows the first type of hydration mat. (B) shows the second type of hydration mat. From Dick *et al*. (2019).

4.3.4 Performance assessment of new sensors

All the new sensors and equipment were thoroughly checked, either onsite or before their shipping to the Tournemire URL, before installation to ensure that they were fully functional. Following their installation in the buffer and connection to the data acquisition system, data was successfully received from all wired sensors except the THM integrated sensor, from which no data was recorded. The reason for the failure of the sensor will be established once the experiment is decommissioned.

New sensors

At the time of writing, four months after their installation in the buffer, the new wired sensors (the chemical electrodes and total pressure sensors) were all working and are recording realistic values, with the exception of the pH and Cl electrodes, which were no longer recording any data variation. It is not yet clear whether the problem originates from the sensors or the data acquisition system; and additional diagnostic tests are planned to establish the origins.

Data obtained so far from the new total pressure sensors show that the sensors have identical trends to those measured by the standard commercial ones. However, the values recorded by these sensors are much lower than the predicted values, and are surprisingly similar to those measured by the pore pressure data. The low pressures measured by the new and standard sensors may indicate that the sensors are no longer attached to the buffer and that consequently they are not measuring the swelling of the buffer. On the other hand, another of the new total pressure sensors (S101) seems to still be attached to the buffer, as the measured pressures continue to increase significantly following the first hydration phase. The remaining new pressure sensor measured a decrease in total pressure since the beginning of the first hydration phase; this anomaly could either be due to stress relaxation within the buffer or a problem with the sensor.

The pore pressure sensor data recorded from the two wireless units installed in the precompacted bentonite blocks and GBM material show that the data from both sensors agree with the results from the standard pore pressure sensor installed in the GBM.

A summary of the performance of new sensors (developed in Modern2020 WP3 and elsewhere) is given in Table 4.4.

Table 4.4: A preliminary assessment of the performance of new sensors installed in LTRBM. Data quality is defined as follows: 1 - measured data comparable to those obtained from the standard sensors; 2 - measured data comparable to those found in laboratory experiments; 3 - measured data significantly different from those obtained from the standard sensors; TBD - data quality needs to be determined.

	Sensors	Buffer	Monitoring Period	Data Quality	Data Transmission
New measuring instruments from WP3 to be tested:	pH	Precompacted blocks (60/40)	July 2018 – February 2019	2	Wired
	Eh	Precompacted blocks (60/40)	July 2018 – February 2019	TBD	Wired
	Cl-	Precompacted blocks (60/40)	July 2018 – February 2019	TBD	Wired
	Thermocouple Psychrometers	Precompacted blocks (60/40) and GBM	NW	---	Wireless
	Integrated THM sensor	Precompacted blocks (100/0))	NW	---	Wired
Other new measuring instruments to be tested:	Porewater sensors (vibrating wire based)	Precompacted blocks (60/40)	July to November 2018	1	Wireless
	Porewater sensors (vibrating wire based)	GBM	July to November 2018	1	Wireless
	Total pressure S101 (fibre-optics based)	Precompacted block 1 (60/40)	July 2018 – January 2019	3	Wired
	Total pressure S102 (fibre-optics based)	Precompacted block 3 (60/40)	July 2018 – January 2019	1	Wired
	Total pressure S103 (fibre-optics based)	Precompacted block 3 (60/40)	July 2018 – January 2019	1	Wired
	Total pressure S104 (fibre-optics based)	Precompacted block 3 (60/40)	July 2018 – January 2019	3	Wired

Wireless data transmission

The two wireless units embedded in the buffer yielded different results; the low-frequency wireless units reliably managed to record and send data to the receiver in the adjacent gallery, but the high-frequency units were never able to send any readable signal to their receiver, despite careful testing in the WTB (see Section 3.2.2). Thus, it was impossible to assess the performance of all the sensors connected to these units (particularly the new thermocouple psychrometers).

4.3.5 Combined data transmitter

As part of the LTRBM, an integrated, two-staged solution that links wireless sensors situated in the LTRBM with the earth's surface by a combination of short- and long range WTDs (see Section 3.2.2) was demonstrated. For this demonstration, a long range transmitter was linked to wireless sensor units. All data recorded by the wireless sensor units in the LTRBM borehole between July and November 2018 were successfully transmitted to a short range receiver. After processing, about 280,000 bits of data from both wireless sensor units were transmitted using the long range transmitter through 275 m of overburden at 8.6 kHz with a transmitter power of 110 mW.

Figure 4.19: Data receiver on top of the surface plateau (top) and data transmitter in the Tournemire tunnel (bottom). From Dick *et al*. (2019).

For the analysis of the long range data transmission tests, three types of transmission errors were distinguished:

- Identified transmission errors, where the original data could be restored.
- Identified transmission errors, where the data could not be restored (i.e. missing data).
- Unidentified transmission errors (i.e. erroneous data values).

For the five transmission tests performed, bit error rates of <0.03% were acchieved.

4.3.6 Summary and conclusions

The LTRBM Experiment was explicitly set-up to demonstrate the new innovative sensors and wireless data transmission units developed in the project. The LTRBM is fully operational and work is still ongoing. Implementing the test set-up took longer than expected due to the level of care that was required during each step of the installation.

The test was designed to take into account the needs of each sensor, and offer fast hydration and realistic swelling pressures within the bentonite buffer. Hydration of three out of four boreholes was efficient, however leaks in the fourth borehole hampered hydration in the upside stream of the buffer; this is due to be repaired to allow hydration from the bottom mats by mid-2019. A second leak observed from the main borehole could have been prevented if a double retaining wall filled with resin had been used between the cement plug and the GBM. Plans to build a new resin-based retaining wall in front of the cement plug is underway this should be implemented by mid-2019.

The preliminary assessment of the new sensors and wireless data transmission units shows encouraging results. Seven months after the installation, and following the first hydration phase, all but one of the new wired sensors are working and the results from these sensors are in general close agreement with those measured from the standard commercial ones. Furthermore, their data quality is comparable to those of the standard sensors and to experimental studies.

Two out of four of the wireless transmitters placed inside the bentonite buffer worked continuously during the monitoring period. These results indicate that the assessment of the sensors should be carried out during each step of the installation in order to prevent possible dysfunctions due to improper handling. The long-range wireless system successfully transmitted data from the LTRBM main tunnel across 275 m of shale and limestone to the Earth's surface.

The LTRBM experiment illustrates the difficulties in testing new sensors under realistic conditions (embedded in the rock or buffer), as if they fail no solutions are currently available to remove them to repair the defect. The proposed qualification methodology developed in WP 3.6 (Section 3.7) should greatly improve the required development process.

4.4 The FE Experiment in Mont Terri, Switzerland

This section provides a summary of the work done at the Mont Terri Underground Rock Laboratory in Switzerland during the FE Experiment to demonstrate monitoring technologies. Further details can be found in the Modern2020 Project Deliverable D4.4 (Fisch *et al.*, 2019).

The FE Experiment is a long-term heating experiment with the aim of investigating THM coupled effects on the Opalinus Clay host rock at full-scale and to verify approaches for emplacing the EBS. Based on the Swiss disposal concept, the Experiment simulates the construction, emplacement, backfilling, and THM evolution of a spent fuel and HLW repository tunnel in a realistic manner. Nagra (2019) provides a comprehensive summary of the design, construction and first 18 months of operation of the Experiment.

Heat transport and deformation processes within the EBS play a central role in safety analyses. Monitoring these processes, if undertaken, might require precise *in situ* methods for measurement of temperature and strain on a scale of tens to hundreds of metres, and potentially even kilometres. Fibre optic monitoring systems for measuring temperature and strain distribution currently offer a reasonable spatial resolution for this measuring range. Therefore, distributed fibre optic monitoring systems were installed in the FE Experiment to gain experience of using them under repository-like conditions, to demonstrate their feasibility for monitoring in these conditions, and to evaluate their performance.

4.4.1 Experimental set-up of the FE Experiment

The FE Experiment was designed to represent the construction and short-term behaviour of a geological repository based on the Swiss disposal concept (see Section 2.3.1 for a description of the Swiss concept). For this purpose, an experimental tunnel, 50 m long and approximately 3 m in diameter, was constructed in the Mont Terri URL (Figure 4.20). At the closed end of the tunnel there was a 12 m long Interjacent Sealing Section (ISS), within which a 2 m long bentonite block wall was constructed. The tunnel was supported by shotcrete everywhere except at the ISS, where steel sets provided support (Müller *et al.*, 2017).

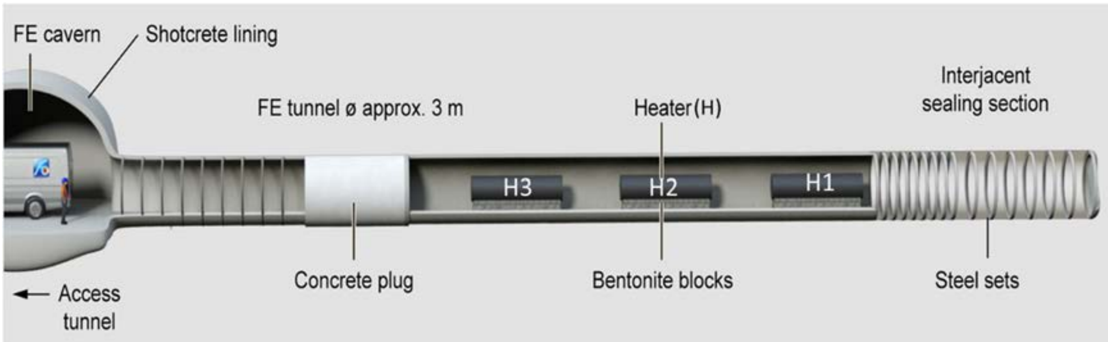


Figure 4.20: Experimental layout of the FE Experiment. The main parts of the FE cavern and FE tunnel are shown here without backfill. From Müller *et al*. (2017).

The waste canisters and their heat output are simulated by three identical heaters with dimensions similar to those of the waste canisters (4.6 m long, 1.05 m diameter) and a comparable heat output (currently 1350 W for each heater). The heaters were emplaced centrally in the FE tunnel, situated on top of bentonite block pedestals. The heater emplaced closest to the ISS was referred to as H1 (heater 1), the middle heater as H2, and the one closest to the concrete plug as H3. Upon completion of the instrumentation and installation of the monitoring equipment, the remaining space was backfilled with GBM with a prototype five-auger backfilling machine. The machine was designed to achieve a dense and homogeneous packing of the GBM (Köhler *et al.*, 2015). Lastly, the experiment tunnel was sealed with a concrete plug (Müller *et al.*, 2017).

The heating phase started in 2014 and is expected to continue for 10 – 15 years.

4.4.2 Instrumentation

The entire experiment implementation and the post-closure THM evolution was monitored using a network of several hundred sensors. The monitoring system included standard sensors and measurement systems, and new monitoring technologies including fibre optic sensors. The main parameters monitored by these sensors are temperature, pressure, deformation and humidity/water content. A summary of the measurements and sensors installed on the tunnel wall and in the bentonite buffer close to the tunnel wall is given in Table 4.6.

Table 4.5: A summary of the measurements and sensors installed on the tunnel wall and in the bentonite buffer close to the tunnel wall (Firat Lüthi, 2018).

Parameter	Sensor	Criteria for Selection / Purpose
Temperature	PT1000	Conventional, *
	Thermocouples	Conventional, *
	Integrated T sensors in RH and TP sensors	Integrated *
	FO for distributed temperature sensing (DTS)	To withstand corrosion, to obtain a T profile *
Humidity/water content	Relative humidity (RH) sensors (monolithic and capacitive)	Conventional
	Time-domain-reflectometers (TDR) and Frequency-domain-reflectometers (FDR)	Rock moisture monitoring in hotter sections to withstand long-term use under high T
Total pressure	Total pressure (TP) sensors	Monitor the potential swelling of the bentonite buffer
Deformation	Convergence measurements with total stations	Monitor any tunnel wall deformation after tunnel construction
	Displacement sensors	Monitor tunnel wall deformation after backfilling and during heating
	FO for distributed strain sensing (DSS)	
Thermal conductivity	Thermal conductivity sensors (KD2 -TR 1 probes)	To monitor the change in thermal conductivity
Geophysical monitoring	Gas-tight pipes	Provides long-term access thorough the concrete plug
	Acoustic sensor arrays	Permanent installations allow to capture subtle changes in acoustic waveforms
Gas composition	Hydrogen concentration sensor	Conventional
	Oxygen concentration sensor	Conventional
	Gas sampling lines	Continuous gas monitoring by mass spectrometry as well as periodic gas sampling
Corrosion monitoring	Sample holders with different metal compositions (carbon, steel, wrought copper, electrodeposited copper and cold sprayed copper)	To investigate *in-situ* corrosion phenomena in the case of potential future dismantling

* *spatial-temporal temperature distribution and evolution of the tunnel wall and of the bentonite buffer*

Sensors were installed in the near-field and far-field host rock (prior to the construction of the FE tunnel), on the tunnel lining, in the bentonite buffer, and on the heaters. Two fibre optic systems were implemented: distributed temperature sensing based on Raman backscattering, and distributed temperature and strain sensing based on Brillouin and Rayleigh scattering. Both systems have different resolutions and accuracies and therefore different advantages. Several fibre optic cables were installed on the tunnel wall within the EBS as well as in boreholes. The instrumentation set-up allowed for the comparison of different cables and different fibre optic measurement principles. Furthermore, prototype time-domain reflectometry probes were also installed in the rock and in the GBM to monitor the water content.

Since most of the sensors are installed in the backfilled FE tunnel, they cannot be replaced if they fail or malfunction. In view of this, careful selection of monitoring systems, including sensors, housing materials and cables, was necessary. Furthermore, the monitoring equipment had to withstand the harsh FE environment; temperatures of 130-150°C at the heater surface and 60-80°C at the tunnel wall are expected, in addition to high porewater salinities in excess of 35 mS/cm, which could accelerate corrosion of metallic sensor components in the rock and partially-saturated bentonite buffer close to the tunnel.

As of August 2018, the overall degree of sensor failure in the FE Experiment was low, particularly with regard to FO sensors and point temperature sensors (Firat Lüthi, 2018). However, most relative humidity sensors and total pressure cells around the heaters either provided unreliable data or had failed. On the tunnel wall and in the rock mass, more than 90% of temperature sensors were still operational, and on and around the heaters, more than 80% of temperature sensors were still operational. A similar pattern of higher failure rates for sensors close to the heaters compared to those on the tunnel wall or in the rock mass was also seen for relative humidity sensors and total pressure cells.

4.4.3 Dynamic calibration of the DTS units

At the start of installation and operation of the FE DTS system in September 2014, the default calibration of the DTS units were used. This default calibration provides good measurement accuracy under stable operating conditions, however the temperature measurements obtained from a Raman-spectrum-based DTS can be affected by multiple factors, such as the operating temperature and conditions of the machine, the quality of the incident laser pulse, the physical conditions and the cleanliness of the connections, the presence of strain or sharp bends at any location along the fibre, and the consistency of the power supply.

Therefore, although the DTS units can provide high accuracies at the time of installation, dynamic calibration which is applied to each measurement and includes the use of baths, the temperature of which are known exactly, is essential to obtain improved and consistent accuracy. To this end, the dynamic calibration system of the FE DTS temperature monitoring system was put in operation by the end of March 2018.

This dynamic calibration system consisted of two water tanks (each with a capacity of approximately 220 litres) - one ambient temperature bath (CB1), which was unheated and continuously equilibrated with the ambient air temperature, and a heated bath (CB2), the temperature of which was controlled by an electric heating element and kept constant to within ±0.1°C. The baths were designed such that "external factors", such as temporary temperature changes in the niche or a temporary power interruption (affecting heat supply) would have only minimal effect on the bath temperatures.

A single-ended FO measurement configuration is used as shown in Figure 4.21. Each FO cable runs through the ambient temperature bath (CB1) and then through the heated bath (CB2) before entering the tunnel. In the return section, cables enter first the warm bath (CB2) then the ambient bath (CB1). Two calibrated high precision sensors are connected to the precision thermometer and record the bath temperatures with an accuracy of ±0.03 °C. Calibrated temperatures at four measuring points within the cable section passing through CB1 (on cable return) are then compared to the reference temperature of CB1. The calibration procedure involves averaging of Stokes and anti-Stokes values from representative measuring points in the bath sections. The FE information system (see Section 4.4.6) calculated the "dynamic" coefficients for each FO cable measurement based on the Raman spectra backscatter measurements, equations described by Hausner *et al.*, (2011), the calibration bath temperatures, and signal step losses. The measurement accuracy after calibration was estimated to be ±0.1-0.3 °C.

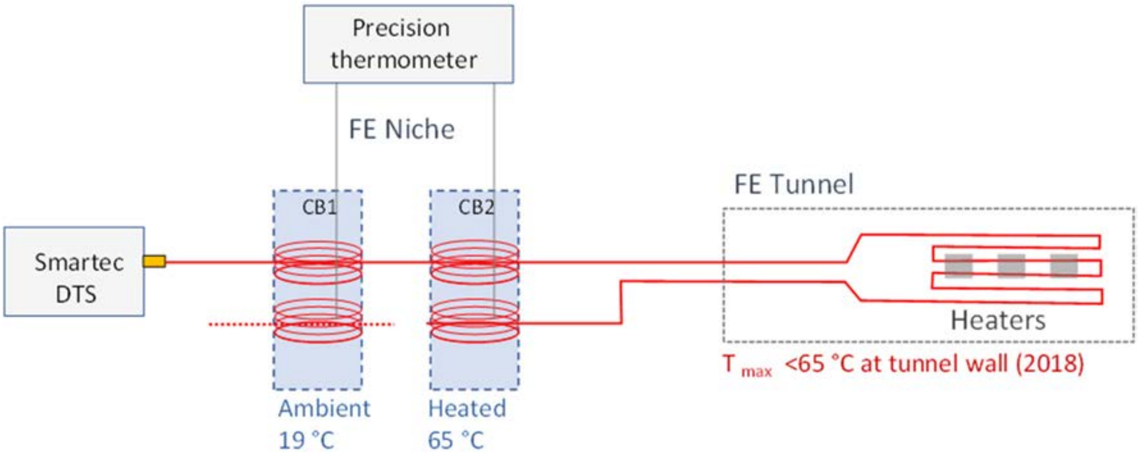


Figure 4.21: Single-ended configuration of the dynamic calibration system for DTS units. From Fisch *et al*. (2019).

4.4.4 Temperature evolution in the FE tunnel from 2014 to 2018

The evolution of the temperatures in the FE tunnel is shown in Figure 4.22 and Figure 4.23. The monitoring period shown extends over 4 years, from October 2014 to November 2018.

Figure 4.22 shows the evolution of the heater surface temperatures at top and bottom of each heater measured using point-type temperature sensors. The sensor positions are illustrated in the three cross sections on the right to the graph. In the cross-sections at positions H1, H2 and H3 (from top to bottom), the tunnel shotcrete profile, the heater circumference in the centre and the locations of the temperature sensor are shown.

The highest temperatures around the heaters were recorded at the top side of the heaters (00:00 position). This can be explained by the lower heat conductivities at the top section which is covered with GBM. On the bottom part of the heaters, on the other hand, the temperature is 4-5 °C lower due to higher heat conductive properties of the bentonite block pedestals resulting in an increased heat dissipation in downward direction from the heaters. Most of the temperature increase was recorded in the first six months after start of heating. During the last 12 months, the incremental increase for all sensors shown is less than 1°C.

Figure 4.23 shows in addition to surface temperatures of H2, the temperatures at the tunnel wall at various positions. The positions are shown in the tunnel cross section right to the graph window. The sensors at the wall are separated from the sensors at the heater surface by about 0.6 m – 0.8 m of bentonite buffer material. The temperature increase at the tunnel wall during the last 12 months varies between 0.9 and 1.5 °C.

Additional results relating to the temperature evolution in the ISS section, BFEA011 borehole, and comparison of DTS and point-type temperature sensors can be found in the task deliverable, D4.4 (Fisch, *et al.*, 2019).

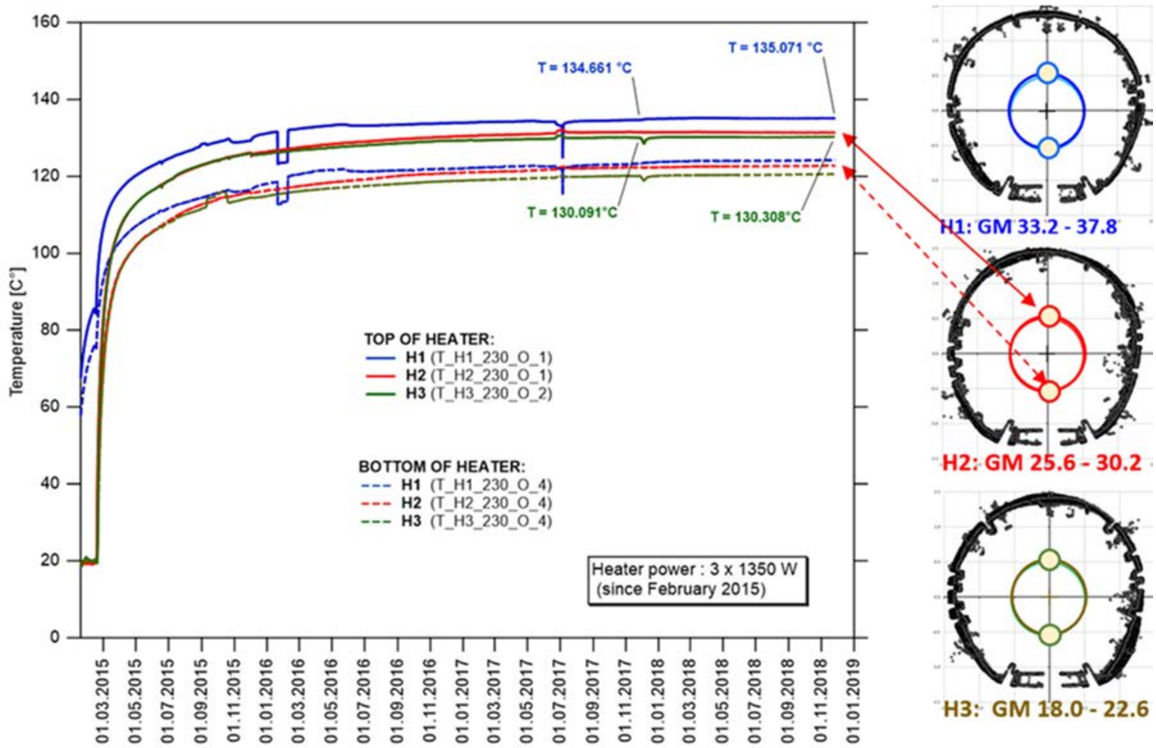


Figure 4.22: Evolution of the temperatures at the bottom and top side of each heater from 2014 to 2018. From Fisch *et al*. (2019).

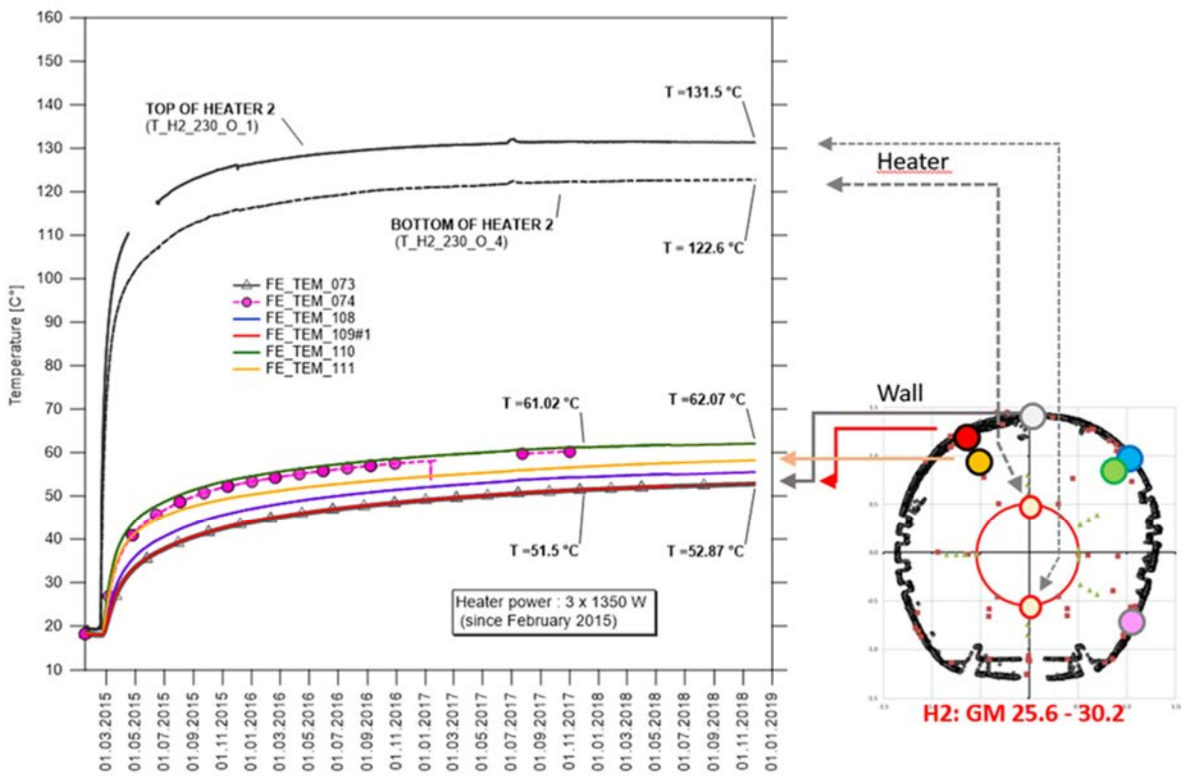


Figure 4.23: Evolution of the temperatures at the heaters and at the tunnel wall from 2014 to 2018. From Fisch *et al*. (2019).

4.4.5 Geophysical monitoring

In addition to collecting data using sensors placed *in situ* within the FE Experiment, geophysical methods were also used to monitor changes in the bentonite buffer in a quantitative manner with minimal adverse effect on the backfilling procedure or the THM evolution.

Two gas-tight pipes were installed approximately 1.7 m apart in the roof of the FE tunnel to a) perform single-hole measurements (GPR, gamma-gamma density and neutron porosity logs), and b) obtain tomographic images of the backfill material from cross-hole measurements between the two pipes, using GPR and seismic techniques.

Between February and May in 2018, seven geophysical measuring campaigns were carried out. The gamma-gamma density and neutron porosity logs appeared to be highly repeatable, the latter indicating modest saturation changes between successive experiments. The GPR single-hole data showed considerable variations between experiments, which can be attributed to changes in temperature and moisture content.

Joint inversions of the cross-hole GPR travel-time and amplitude data allowed reliable and consistent images of the electromagnetic properties to be determined. The quality of the seismic cross-hole data was initially poor, which was attributed to poor coupling of the measurement pipe to the relatively dry backfill. However, this improved during the course of the experiment. Tomographic inversions of these data sets showed progressively increasing velocities, likely caused by compaction and swelling of the bentonite backfill. Further research will be dedicated to the conversion of geophysical parameters into physical parameters such as temperature and water content/saturation. Once such relationships are established, geophysical data can be used to extrapolate the temperature and water content data collected by *in situ* sensors to larger areas.

4.4.6 Data management

The implementation of the FE Experiment has been monitored in detail since 2011, and more than one million data are acquired daily during the experiment. Different measurement devices are connected to different data acquisition systems. The FE information system (FEIS) was developed to collect and store all data acquired from the different sensor suppliers and installation companies under one roof (Figure 4.24). The FEIS allows all data sets to be easily accessed and compared, and the quality of the recorded measurements to be controlled. For this, an open-source object-relational PostgreSQL database is used together with PostGIS and a statistical analysis tool written in the programming language R. Currently, the FEIS collects more than one million measurements per day (Firat Lüthi, 2018).

A well planned and executed, and therefore reliably functioning, database facilitates data completeness from the first until the last day of monitoring. Even after the successful implementation of the FEIS, much work is still required to maintain a permanent data flow from all suppliers and to keep the database in an ordered state. Further developments of the FEIS, e.g. towards a mobile version, potentially combined with an augmented reality display of results when visiting on-site, are currently under discussion.

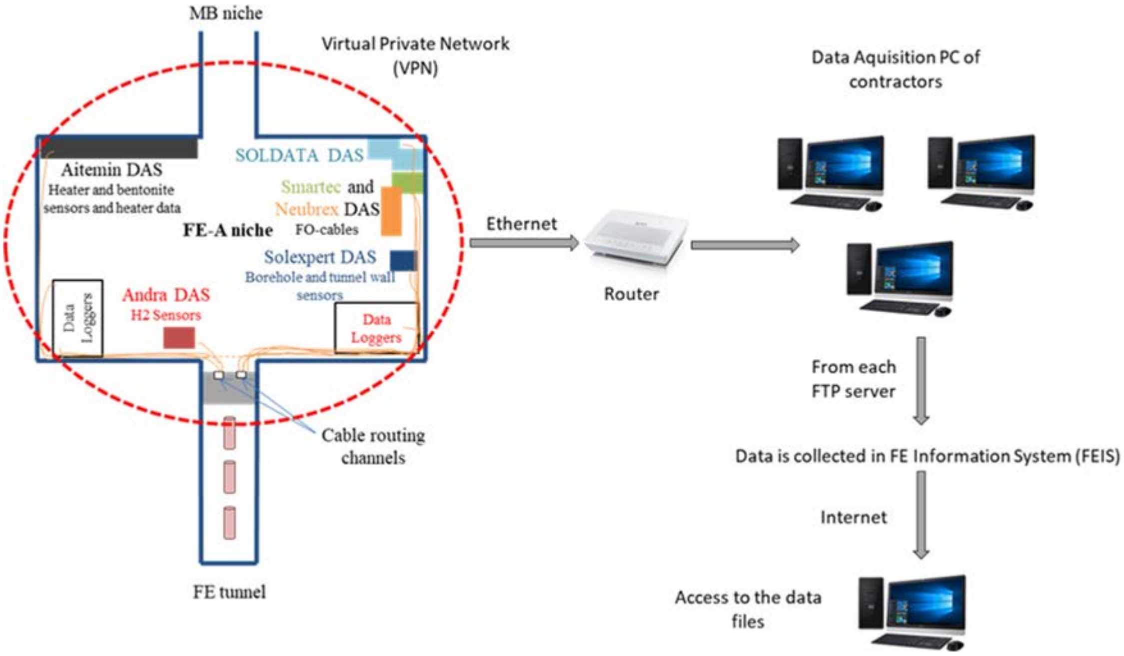


Figure 4.24: Illustration of the data acquisition systems installed at the FE experiment (left) and the workflow for data collection from all data acquisition systems (right). From Firat Lüthi (2018)

4.4.7 Conclusions

The initial design of the monitoring programme for the FE Experiment was based on experience from previous and similar underground experiments and their findings regarding long-term sensor behaviour. Valuable information also came from exchanges with the scientific community and from EC-supported research programmes. Before implementation, THM scoping calculations were performed to optimise the spatial distribution of sensors and to specify their measurement range and operating conditions.

To date, the monitoring programme for the FE Experiment has been successful as it demonstrably allows monitoring of the THM evolution of the EBS and the host rock. Monitoring began with measurements of the baseline conditions prior to construction and continued through all experimental phases. In terms of spatial discretisation, the heating phase is monitored using a series of similarly instrumented cross-sections within the FE tunnel complemented by measurements in boreholes drilled into the host rock. This setup allows not only a comparison of the THM response for each of the three heaters, but also a comparison of sensor performance and reliability.

Together with the FO systems, the sensor density in the FE Experiment is large enough to plot measurement results in unaliased cross- and longitudinal-sections, as well as on 3D planes such as the tunnel surface, for any point in time.

The FE Experiment offers a great opportunity to identify issues, to implement developments and to gather experience related to long-term monitoring under repository-like conditions. It also allows the evaluation and comparison of different sensor types and monitoring techniques in a more general sense. The lessons learned from the FE Experiment will be important for developing the monitoring concept of the future Swiss repository and can be used for development of monitoring programmes in other countries.

4.5 Summary and conclusions from demonstrators

The work carried out in WP4 is of direct relevance for the practical implementation of monitoring programmes. In addition to testing the reliability and real-world applicability of different monitoring technologies (some of which were developed in WP3), it demonstrates the integration of several components of a monitoring system, implemented in a range of different disposal concepts.

The outcomes of each demonstration are summarised below:

- The development of an EBS monitoring plan for ONKALO in Finland was carried out as a desk-based study. The work aimed to demonstrate the applicability of a monitoring plan which focused on showing compliance with the safety case and primarily covered long-term monitoring aspects.
- Development and qualification of a monitoring programme was conducted through practical demonstrations during HLW disposal cell demonstrators at Bure URL in France. Appropriate parameters for monitoring were selected, and evaluation of the monitoring system for a HLW disposal cell was conducted during experiments in two demonstrators – AHA1604 and ALC1605. These experiments provided useful information on the practicalities of installing a monitoring system, and what parts of the system worked and failed.
- Demonstration of monitoring at the LTRBM at Tournemire URL has tested new monitoring technologies (developed within the Modern2020 Project in WP3, and elsewhere) *in situ* and allowed their performance in repository-like conditions to be assessed. Additionally, demonstration of wireless data transmission from the LTRBM borehole to the ground surface above (a distance of 275 m through rock) was successfully demonstrated. The LTRBM is fully operational and work is still ongoing.
- The FE Experiment was conducted at Mont Terri URL in Switzerland to demonstrate the implementation of monitoring. The construction, emplacement, backfilling, and THM evolution of a spent fuel and HLW repository tunnel was simulated in a realistic manner, and the induced THM effects in the host rock and EBS was investigated through a full-scale multiple heater test. The test demonstrably allows monitoring of the THM evolution of the EBS and the host rock. Information on sensor performance and reliability was also gathered.

Evaluation of the experience gained from these demonstrations provides a pool of information that is useful for developing monitoring programmes, such as what aspects of repository monitoring are already achievable and have succeeded, and conversely where current difficulties lie. The practical experience gained (e.g. installing extensive instrumentation, and managing and evaluating data) also enables better preparation for implementing monitoring systems in actual repositories.

In situ demonstrations such as these also provide valuable information about the sensors used, such as their longevity in representative conditions, and allows a comparison of the performance of different sensor types. This information helps develop a better understanding of the reasons for sensor failure, which can feed back into the development process of the sensor design and monitoring equipment.

In summary, the *in situ* demonstrations in URLs conducted as part of WP4 show that it is feasible to monitor parameters such as those identified in WP2 of the Modern2020 Project. However, implementing a complete monitoring strategy in a real repository is not completely analogous to implementing one in a URL and additional work is also required to fully demonstrate that monitoring system design does not jeopardize long-term safety.

5 Modern2020 WP5: Stakeholder Engagement in Repository Monitoring RD&D

This chapter provides a summary of the work carried out in WP5 of the Modern2020 Project on stakeholder engagement in repository monitoring RD&D. Work focused specifically on the challenge of involving local public stakeholders in research at an early stage in the development of repository monitoring programmes and in an international setting. The focus was on people in local communities, potential repository host communities, or communities in which a URL is operating. They are the most directly involved, and the closest representatives of the general public with regard to the future deployment of monitoring strategies and monitoring technology.

The chapter is structured as follows:

- Section 5.1 summarises the understanding of the value of stakeholder engagement in repository monitoring RD&D prior to the Modern2020 Project.
- Section 5.2 describes the objectives of WP5.
- Section 5.3 describes the methods employed to interact with stakeholders during the Modern2020 Project.
- Section 5.4 explores the specific challenges encountered when attempting to engage local stakeholders in repository monitoring RD&D.
- Section 5.5 discusses the lessons learned from an online survey conducted as part of WP5.
- Section 5.6 describes the process by which a Stakeholders' Guide (Modern2020 Project Deliverable D5.2; Meyermans *et al.*, 2019) was developed.
- Section 5.7 describes the conclusions from WP5 regarding the expectations that citizen stakeholders have of repository monitoring, in particular, the expectations regarding accessibility and transparency of monitoring data.
- Section 5.8 states the overall conclusions from the work in WP5, and includes a list of key recommendations for the effective involvement of stakeholders in repository monitoring planning, based on experiences gained during the WP5 work.

More information can be found in three project deliverables:

- Deliverable D5.1 (Lagerlöf *et al.*, 2017)
- Deliverable D5.2 (Meyermans *et al.*, 2019)
- Deliverable D5.3 (Bergmans *et al.*, 2019)

5.1 Understanding of stakeholder engagement in repository monitoring RD&D prior to the Modern2020 Project

Repository monitoring is a subject of interest for a wide range of stakeholders. Within the context of a structured, transparent and step-wise process of developing and implementing geological disposal (as suggested, for example, in NEA, 2001), repository monitoring is generally expected to play a major role in reassuring the public and in building public confidence in the repository (IAEA, 2001; EC, 2004). The reasoning behind it, is that monitoring during the operational period which shows that the repository is behaving as expected might increase stakeholders' confidence in the post-closure safety case. Monitoring programmes may also play a role in decision-making processes involving the public, or their representatives, with the aim of attaining broader societal support for a disposal plan. This was explored as part of previous work on public stakeholder involvement in relation to repository monitoring undertaken within the MoDeRn Project (MoDeRn, 2013a). This work consisted on the one hand of in-depth interviews with monitoring experts and a literature review on the topic of citizen and stakeholder engagement with monitoring (Bergmans *et al*. 2012). On the other hand, a set of exploratory workshops with citizens from communities hosting existing radioactive waste facilities and with prior experience as participants in radioactive waste management projects of a varying nature in Belgium, Sweden and the United Kingdom were conducted (Bergmans et al. 2013). This exploration made clear that repository monitoring is a subject of interest for a wide-range of stakeholders. In particular, the MoDeRn Project concluded that some local citizen stakeholders expect monitoring to provide continuous information on repository performance. As such, it was concluded that early involvement may improve their confidence in the monitoring programme, as well as make clear what their concerns and expectations regarding such a programme are. With that in mind, a dedicated work package (WP 5) on societal concerns and stakeholder involvement was integrated in the set-up of Modern2020.

5.2 Objectives

The specific objectives of WP5 were:

- To actively engage local public stakeholders in repository monitoring RD&D within the Modern2020 Project, and to analyse the impact this has on both the participating stakeholders' and the project partners' understanding of, and expectations regarding, repository monitoring.
- To define more specific ways for integrating public stakeholder concerns and expectations into specific repository monitoring programmes.
- To learn how local stakeholder groups could be engaged effectively with RD&D programs and projects at an EU level.

5.3 Approach

The stakeholder engagement activity was organised in direct relation to the RD&D work undertaken in WP2, WP3 and WP4. At various stages in the Project, exchange meetings or workshops were set up, during which interaction between researchers and participating local citizens took place. The selection of local communities was to a large extent determined by waste management programmes and related governance processes. With varying success, citizen stakeholders were invited from countries where a local organisation of stakeholders around RMW sites is already established: in Finland (Municipality of Eurajoki), France (CLIS de Bure) and Sweden (Municipality of Östhammar). In addition, Belgian local stakeholders were incorporated. Geological disposal in Belgium is still in a research phase, but the municipalities of Dessel and Mol, and their local partnerships STORA and MONA, are hosts and neighbours to the centralised storage facility for HLW and to the HADES URL. Therefore, the local stakeholders that attended Modern2020 Project meetings had in common their long-term involvement in dialogue as representatives of local stakeholder groups. The level of technical knowledge among them varied: some possessed specialised knowledge while others had no specific scientific background.

The group of citizens that participated in the project cannot be seen as representative of the community at large, neither at the local, national, nor European level. Therefore, the set-up of the engagement activity in Modern2020 remained to a large degree experimental and exploratory. The research furthermore generated qualitative data, the analysis of which cannot be claimed to provide a representative categorisation of different opinions regarding repository monitoring and how to communicate about monitoring plans, activity and data with various stakeholder groups, again either at the programme-specific or European level. Nevertheless, it does provide insight into the understandings, concerns, reasoning and preferences of some members of WMOs, technical experts in the field, and involved citizens, which can be seen as indicative of the opinions and expectations of particular groups in society.

Involvement of the stakeholders in the Modern2020 Project used a range of approaches:

- A small core group of engaged community representatives (two from Finland, two from Belgium and one from Sweden) regularly attended technical Modern2020 Project meetings and workshops organised at the European level.
- Workshops (or so-called ‘home engagement sessions’) were set up in the home communities of the interested public stakeholders in order to discuss their concerns and opinions about monitoring in nuclear waste repositories. These sessions included feedback from the representatives that attended the technical Modern2020 Project meetings and workshops.
- The broader group of local stakeholders reached during the home engagement sessions was also given the opportunity to enter into discussion with technical representatives from Modern2020 in a workshop specifically designed to address the topic of stakeholder engagement in repository monitoring.
- Furthermore, the participating local stakeholders were offered the possibility to further share experiences and opinions about their involvement in the project, as well as their views on repository monitoring through an online survey in two rounds(a so-called “delphi’ survey) to which all Modern2020 partners were also invited to participate.
- Lastly, the local stakeholders were regularly consulted for feedback on a ‘Stakeholder Guide’ (Deliverable 5.2: Meyermans *et al.*, 2019), as well as on other outputs produced in the Project (such as workshop and research reports).

An overview of the ‘project level’ engagement activities and ‘home engagement sessions’ can be found in Deliverable 5.3 (Bergmans *et al.*, 2019) in their respective sections. This includes the dates, places and number of participants to these meetings. More information about the organisation of the online ‘Delphi’ survey and what specific topics were addressed can also be found in Deliverable 5.3 (Bergmans *et al.*, 2019).

5.4 Exploring specific challenges for engaging local stakeholders in monitoring RD&D

Work carried out within Task 5.1 of WP5 (reported in the Modern2020 Project Deliverable D5.1: Lagerlöf *et al.*, 2017) sought to enable a better understanding of how monitoring the underground plays and can play a part in the governance of radioactive waste repositories from a social science perspective. Mainly through literature review, participating stakeholder groups were investigated in relation to their national decision-making structure and processes regarding radioactive waste management; and with regard to their interest and experience in discussing issues related to geological disposal, repository safety, environmental monitoring and repository monitoring. The practical aim was to help the participating citizens to understand similarities and differences between the contexts of their (national) situations. For that purpose, Task 5.1 focused on how four WMO’s (Andra, ONDRAF/NIRAS, SKB and Posiva) plan to monitor future geological repositories for long-lived waste. Furthermore, the extent to which stakeholder concerns are taken into account in other cases of monitoring infrastructures and underground disposal facilities was studied in order to further the understanding of the specificity of the type of monitoring addressed. This was done by looking at the role and framing of underground monitoring in the case of carbon capture and storage as a comparative example. On this basis, some specific challenges for considering and organising local stakeholder engagement in Modern2020 were identified.

It was confirmed that monitoring is not a uniform concept, owing to the different contexts under which programmes operate. This variable character of monitoring may render it a good candidate for public participation, as this renders it to some extent “negotiable” or at least shows that different interpretations of the same thing can co-exist. It also provides opportunity to discuss the specificities of each disposal programme context and create greater understanding and appreciation for it.

However, Task 5.1 concluded that the possibility of engaging local stakeholders in monitoring development is conditioned by the maturity of the technological concept in the different programmes. Therefore, it would be difficult to unconditionally discuss the importance of monitoring and what monitoring can achieve when many decisions concerning technology and safety have already been taken. In any case, the subject of monitoring as such does help to open up the notions of passive safety, control, transparency and responsibility, thus encouraging a reflective dialogue which includes various stakeholders with a range of knowledge bases and interests. The role of repository monitoring in this transdisciplinary dialogue was further explored throughout local stakeholder engagement activities in the Modern2020 Project as described below.

5.5 The role of local stakeholders in Modern2020

Throughout the Modern2020 Project, it became clear that the participating citizen stakeholders considered themselves to be watchdogs over the development of monitoring, with regard to the wellbeing of future generations, and that they saw themselves as possible brokers between the technical experts involved in repository monitoring, and broader public groups. The involved citizens were of the view that much of the technical expertise involved in monitoring a repository was beyond their knowledge, but also held the opinion that some of the technical experts often framed risk in terms of technical details without considering broader context (e.g. knowledge related to other socio-political or socio-economical domains, and how specific monitoring technologies fit into the broader monitoring system and into the mega-project of geological disposal at large). However, it should be acknowledged that many of the technical experts working in the Modern2020 Project were focused on specific technology developments, and therefore would not be expected to have complete understanding of, or expertise in, all aspects of geological disposal. The participation of citizen stakeholders in the Modern2020 Project was not established to have an impact on the technical research, and it is challenging to identify any such impact. It would be challenging in any technical research project for citizen stakeholders to have direct impacts on the work, although the stakeholders did participate in the development of the Modern2020 Screening Methodology (see below). However, the public stakeholders engagement activities were of great interest from a social science perspective, and for the citizens and project partners involved.

Results from the online survey confirmed that the motivation for local citizen stakeholders to participate in the project was driven by social responsibility, for example, to play the roles of bridge-builders and knowledge brokers between the general public and WMO staff. They acknowledged that to achieve this, improved understanding of all aspects of repository monitoring would be required.

It appeared from the survey that approximately 60% of both the technical project partners and the citizen stakeholder participants cling to the so called “deficit model”, stating that the purpose of stakeholder engagement is primarily to provide technical information , i.e. to perform one-directional communication from experts to citizens. However, where this drives the majority of the technical project partners to conclude that local citizen engagement is most appropriate at stages when TRLs are 5 to 9 (i.e. from large scale prototype testing to full commercial application), the citizen group finds involvement appropriate at all levels, putting an emphasis on TRLs of 0 to 7 (i.e. from the idea of technology formulation to demonstration in an operational environment). This implies that local citizens want to be included earlier in the process and in more technical depth than recognized by technical experts.

Throughout their responses to the survey and reactions during meetings, it was clear that stakeholders did have trust in the technical capability of scientists and technical experts, but also that they wanted to keep these groups to be alert and answerable for what they were doing. In order to develop trust in research and technology development, the citizens in the Project did not count solely on receiving the final results of an RD&D project; they wanted to follow the process, develop an understanding of what the new technology could and could not achieve, and they wanted to be able to ask questions. Such questions were identified as being “why should we do this?”, “what are the benefits and for whom?”, “what are the limitations?”, and “why are programmes assessing monitoring differently?". These questions go far beyond the "deficit model" and give citizens a more active role in relation to experts. It is recognised that technical experts ask these questions routinely in the course of their work, and such questioning is part of the Modern2020 Screening Methodology discussed in Section 2.7.

Some of the technical project partners (but definitely not all) tend to frame the need to feed information to citizen stakeholders as filling the knowledge gap (reduce the deficit), assuming that, with the same level of information/ knowledge, they will come to the same conclusions as the experts and 'accept' the proposed approach to repository monitoring during the operational period. This approach might be adequate in some contexts and for some local stakeholders, however, most citizen stakeholders in this Project described their need for information as a necessary step in enabling them to ask critical questions, which cannot solely be answered from a technical perspective - questions relating to issues such as whether, or how, social and environmental impact had been taken into account, what other options had been considered, why those options had been screened out, and how the potential for further technological development had been taken into account. Over 70% of the participating citizens to the online survey indicated that they had learned relevant things regarding monitoring and other waste management programmes by participating in the project. 50% of the group indicated they appreciated open communication about uncertainties, unexpected outcomes, difficulties, mistakes or accidents.

To conclude, analyses of the various engagement activities and the responses to the survey showed that, overall, the participating community representatives were positive about the chance to be involved, even if their immediate impact on the technical level is likely to remain limited.

Honesty abides to admit that engaging citizens in an expert-driven technical research project was not always easy, especially because it was explicitly decided to have these local public stakeholders participate in the actual project, in direct interaction with the (technical) researchers. This was in part due to the fact that divergent expectations existed (in both groups, so not just between local stakeholders and technical experts) of how local stakeholder involvement in RD&D should be tackled. An additional factor was that the project partners and local stakeholders were inevitably driven by different agenda. The choice to approach specifically local citizens implicated in national waste management programmes, meant that we had to take into account developments at the national level. This for example led to a late entrance of French stakeholders in the Project, and to a temporary hold in participation of the Swedish stakeholders at the time of the Environmental Court hearings and related decision-making process concerning the Swedish project on geological disposal. These were clear and explicit examples of the fact that the pace of a research project does not necessarily coincide with the agendas of the local communities and the availability of their representatives. Lastly, the nature of the project made many discussions and project related documents very technical. Both of these aspects had a clear impact on the extent to which community representatives could attend Modern2020 Project meetings of various work packages and the time and ability as well as interest they had in reading up material beforehand or provide feedback on minutes of meetings or (draft) reports.

Nevertheless, some rich interactions have taken place, the Project has brought the topic of monitoring to the attention of local citizens and communities, and instigated some debate there. The interactive survey furthermore showed that the participating community representatives were overall positive about the chance to be involved at an early stage in this technology development even if their immediate impact on the technical level is likely to remain quite limited. The appreciation for, and estimated value of, the engagement activity among project partners was quite divergent, but the survey data does allow us to conclude that there is some positive correlation with the frequency and intensity of the interaction with the stakeholder participants.

5.6 Development of a "Stakeholder Guide"

As part of WP5, the sociologists affiliated with the Modern2020 Project coordinated the production of a local stakeholder guide to repository monitoring in the context of geological disposal of radioactive waste ("Monitoring in Geological Disposal and Public Participation: A Stakeholder Guide", referred to as the "Stakeholder Guide" below, the Modern2020 Project Deliverable D5.2; Meyermans *et al.*, 2019). The purpose of the Stakeholder Guide was to communicate the state-of-the-art on geological disposal and repository monitoring to a non-scientific audience, and, through this, facilitate discussion between scientists and a variety of public groups (for example, citizens, policy-makers and journalists) about various, often interrelated, technological and social concerns. It is envisaged that the Stakeholder Guide will be used as a tool to stimulate further interaction between public stakeholders and those implementing geological disposal and repository monitoring programmes, and create awareness of the variation in concerns and expectations with regard to the governance of disposal processes in different contexts.

The production of the Stakeholder Guide was an exercise in stakeholder participation that aims to clarify the different societal perspectives, interests and concerns surrounding repository monitoring. In this collaborative process, project partners and local stakeholders discussed the purpose, content and form of this particular Modern2020 Project product. During the writing process, the social scientists acted as scribes, provided with technical information by the technical experts, and participating local citizen stakeholders raised the issues and questions that they thought would be useful to address. An editorial board, composed of the Project Coordinator, WP leaders and one community representative, quality-checked the writing process. Feedback from a broader group of project partners and community representatives was also obtained during a workshop partially dedicated to the production of the Stakeholders' Guide. In this workshop, project partners provided feedback on the technical accuracy of the information in the document, whereas the citizen stakeholders primarily focused on the clarity and usefulness of information provided.

Through the joint writing process, the nature of the Stakeholder Guide evolved from being focused on the technical details of repository monitoring, to giving a broader view on monitoring in the context of repository governance and the role of public participation. The main challenges encountered when producing the Stakeholders' Guide were finding ways of addressing the differences between national contexts (in terms of geology, the stage of technology development, legislation, legacies of stakeholder involvement, *etc*.), developing a shared conceptual framework on monitoring, and dealing with the complexity and long, uncertain timeframes of geological disposal programmes. As a consequence, the Stakeholders' Guide evolved from having a manual-like structure (offering the state-of-the-art on geological disposal and repository monitoring for a non-expert audience) to a more open, reflective document, providing basic information on geological disposal and repository monitoring, whilst also highlighting uncertainties and knowledge gaps, and explaining the reasons for the differences between national programmes.

The production of the Stakeholders' Guide was itself a valuable exercise in stakeholder participation, which helped to clarify the different social perspectives, interests and concerns of citizen stakeholders and technical experts surrounding repository monitoring.

5.7 Citizen stakeholders' expectations of repository monitoring programmes, including the accessibility and transparency of monitoring data

Throughout the engagement activities, it appeared that opinions and expectations regarding monitoring were sometimes divergent between the participating local stakeholders and the technical experts involved in Modern2020. Their opinions seemed to vary with regards to why, what and how to monitor as well as about how accessibility and transparency of monitoring data could be achieved in practice.

It is a challenge for technical experts to communicate the post-closure safety case to local citizen stakeholders and to explain how uncertainties are managed in the safety case. In the previous MoDeRn Project (MoDeRn, 2013a), one of the main findings was that local stakeholders view the role of monitoring as a means of checking up on the repository's safety (where safety is not already assumed), whilst some technical experts perceived monitoring as a means of confirming safety (where, prior to the start of the operational phase, safety is already demonstrated through the submission of a safety case as part of the licensing/permitting process and through acceptance of the safety case by the authorities). However, this result has been refuted by the new data gathered in the Modern2020 Project, showing that both of these functions of repository monitoring were deemed as equally important by both local stakeholders and technical experts. The results also show that most participants see these two functions as working on a different level and in a different way: whilst the confirming function of monitoring refers to whether the acquired data fit to models used to predict the repository environment, monitoring as checking works at a somewhat 'lower level' referring to the ability of monitoring data to alert and understand if any unexpected or extraordinary situation would appear.

Most participants agreed that monitoring data could play an important role in supporting the dialogue between technical experts and local stakeholders; it could offer the opportunity for local stakeholders to closely follow and check the implementation and performance of the geological repository. This would have the potential to support a long-term dialogue between technical experts and local stakeholders, through which further confidence and trust could be built.

Feedback was also received on who the participants thought should be responsible for managing the data collected through monitoring, and how the data could be made transparent and accessible. Even though local stakeholders often deem the national regulatory body to be the most suitable actor for managing monitoring data – more so than technical experts – most participants agreed that the monitoring itself and the subsequent gathering of data should be performed by the responsible WMO, under control and supervision of the national regulator or, as mentioned by some, an independent research institution. They also held the view that it should be the national regulators who decide whether or not, how, and to what extent the monitoring data can be used by other actors, for instance, in order to accommodate independent expertise. If monitoring data are to be available to the wider public, all participants agreed that the monitoring data should first be synthesised by the responsible monitoring body/organisation.

5.8 Conclusions and recommendations

In a research project such as the Modern2020 Project, where much of the work was focused on technology, it is challenging to engage citizen stakeholders in the research itself. However, that does not mean they could not be engaged in the research process. Even if it is a more observatory role, we saw throughout this project a process of mutual understanding and trust building. This came about precisely because of the open atmosphere and the ability for stakeholders to see the diversity in opinions held by technical experts, and the uncertainties and remaining unanswered questions in repository programmes.

We explicitly chose the challenging route of engaging with local stakeholders during the early stages of developing and implementing a monitoring programme, before well-delineated, targeted communication of obtained monitoring results was possible (indeed, even before detailed monitoring programmes focused on monitoring during the operational period to build further confidence in the post-closure safety case have been developed). This put some strain on technical project partners and was also demanding of the citizen stakeholders themselves. But it added tremendously to the latter's feeling of authenticity. It does of course point to several limitations for this type of approach, which cluster around crucial issues of motivation, language, time, planning and resources – both from the perspective of the local stakeholders, and from the perspective of the Project.

Below are the key conclusions from the work carried out on citizen stakeholder engagement in the Modern2020 Project, based on observations made throughout the project, and on responses from the local stakeholders and technical partners to the online survey on how the former's role and engagement in the project was assessed:

- Local stakeholders felt that their role in the project was not to influence the course of the technical research, but to understand what it was for and how it could affect the waste management programmes.
- Local stakeholder participants were not prepared to legitimise the research outcomes, but wanted to ask critical questions in order to increase understanding and give feedback.
- Local stakeholders wanted to be engaged in the research process but not in the research itself in order to:
  - See how it is done and what it is for, to witness debate among researchers, and to get a sense of the knowledge and the knowledge gaps.
  - Confront the researchers with the real world outside the laboratory; to keep them alert and answerable and ensure they take local stakeholders' remarks and comments into account.
  - Gather information and knowledge in order to play the role of bridge-builder between broader public groups and stakeholder groups.
- To be involved early in the process and in close contact with researchers implies "messiness" in interaction, but this showed authenticity and stimulated trust.
- A focus on reaching consensual strategies would risk concealing national differences and political interests, which may become disguised as technical issues.
- From the results of the online survey, important differences were identified between the views held by technical experts and local stakeholders concerning whether or not stakeholders should be involved at the technical/engineering level of RD&D projects concerning repository monitoring - 85% of technical experts thought that they should not be involved, while 44% of local stakeholders thought they should. In addition, 35% of local stakeholders and 9% of technical experts considered citizen stakeholder involvement to have the potential to improve the design of monitoring systems. To conclude, a substantial part of the local stakeholders wanted to be involved at the technical level, and some also thought they could improve this type of work, while technical experts tended to be sceptical of this.

These results led to the formulation of the following key recommendations (and issues to think about) on how to integrate citizen stakeholders' concerns in RD&D projects more generally:

- Choose accessible meeting places and make planning adaptable (in view of the availability of stakeholder participants).
- Be realistic about how much stakeholder involvement can be realised with available resources:
  - Suggestions of having more regular interactions with local stakeholders (e.g. organising discussion before and after every workshop) have to remain workable for both the technical experts and local stakeholders.
  - Be aware of the extent to which technical experts are able to invest time in 'translating' their work into accessible and understandable information for 'lay stakeholders'.
  - The planning for the current work of WP5 assumed that all of the work would be undertaken by social scientists. What room is there in the future for a closer collaboration between social scientists and technical experts in planning the work?

- Find ways to overcome the language barrier (international RD&D projects use English as working language). Projects need to consider costs for both RD&D and interaction (e.g. translation).
- Carefully assess the reasons for citizen stakeholder engagement, and the appropriate times and topics for these interactions. Without clear direction for the discussion, stakeholder engagement risks becoming 'tokenistic'.
- Acknowledge that there will always be different expectations between invited stakeholders and project partners (but also among both categories) at the start of a project. This cannot be overcome by 'prepping' everyone beforehand. However, by being alert to this, and making adjustments (e.g. by providing additional information, and organising subsequent meetings differently) a process of mutual learning can be fostered.
- Pay attention to realising clear outcomes of stakeholder engagement within RD&D projects (by validating the engagement activities clearly into the project results), in order for both technical experts and local stakeholders to see how their efforts have paid off.
- Be sensitive about pushing too strongly towards agreeing a consensus; instead, acknowledge what is not agreed upon.

As an overall comment, we would lastly like to recommend that a wide range of views and considerations (in this case from local stakeholders) are taken into account when making decisions regarding the monitoring of repositories during the operational phase.

6 Conclusions

The Modern2020 Project has enhanced our ability to implement, both strategically and technically, repository monitoring during the operational phase to build further confidence in the post-closure safety case and to develop a broad consensus of how monitoring during the operational phase in support of building further confidence in the post-closure safety case would be beneficial. The integrated strategic, technical and sociological work undertaken provides the platform for developing site-specific repository monitoring programmes. In programmes close to licensing, specific monitoring programmes for the operational phase are required, some aspects of which are already developed, and the results of the Modern2020 Project provide a broad set of tools, methods and guidance, and innovative technological approaches that can underpin the monitoring programmes included as part of the safety cases. The outcomes of the Modern 2020 Project will be useful in supporting the completion of these programmes through development of plans for monitoring in support of building further confidence in the post-closure safety case. In Switzerland, Article 13 (1c) of KEG (2003) requires a concept for the monitoring period and the closure of the installation for the granting of a general licence. Nagra intends to submit general licence applications around the year 2024, and the outcomes of the Modern2020 Project will be an important input to this application.

In addition, the information from Modern2020 will also support the programmes identified in Section 1.1 that are at earlier stages of licensing (Belgium, the Czech Republic, Germany, the Netherlands and the UK). For example, understanding the approach to monitoring at an early stage in the process may identify designs that specifically take account of monitoring requirements at an early stage. All programmes have challenges in public acceptance, although developing trust and acceptance by the public may be more challenging for programmes in the earlier stages of licensing. For these programmes being able to explain general plans for monitoring and expectations for monitoring during the operational phase might play a role in meeting these challenges.

The strategic work in the Modern2020 Project has provided a common international understanding of generic monitoring programme strategies, parameter-selection methodologies and generic plans for responding to monitoring results. The understanding has been captured in the Modern2020 Monitoring Workflow. Deciding on monitoring parameters is a value judgement, with a range of strategies identified for monitoring using different approaches. The process for responding to monitoring results and generic responses to different types of results have been identified. It is recognised that responses should not be prescribed ahead of monitoring and that monitoring has the ability to contribute to the successful stepwise implementation of the repository programme as well as checking for compliance with the safety case.

WP2 of the Modern2020 Project has evaluated the role of repository monitoring within the safety case. The challenges of monitoring have been explicitly recognised, whilst, at the same time, building broad agreement that such monitoring is of value and should be undertaken. In particular, the test cases focused on the selection of monitoring parameters have explicitly looked at the safety case and identified instances where specific monitoring may provide additional value to the ongoing implementation of geological disposal.

As each monitoring programme must respond to the national context (consisting of the relevant regulations, the waste characteristics, the geological environment, the disposal concept and repository design, and the socio-political environment), the next step is for specific waste management programmes to progress specific monitoring programmes.

The Modern2020 Project has undertaken R&D on a range of novel monitoring technologies and has contributed to resolving technical issues by improving the technology readiness level of a range of monitoring technologies that are likely to be significant for monitoring the EBS and near-field rock during the operational phase in support of building further confidence in the post-closure safety case. These include wireless data transmission systems, long-term power supply, monitoring using optical fibre systems, non-contact displacement monitoring, water chemistry monitoring using ion-selective electrodes, new sensors for temperature, pressure and relative humidity, and geophysical methods. Development of site-specific monitoring programmes will provide specifications for the further development of these technologies so that they can be deployed in operating repositories in the near future. In addition, Modern2020 has contributed to the deployment of monitoring systems by evaluating four integrated demonstrators (Posiva's EBS Test Case; Andra's HLW disposal cell demonstrators; the LTRBM demonstrator; and the FE Experiment), and by providing a generic qualification approach.

Following the research into stakeholder engagement at an early stage in the RD&D process and on an international basis, the views of stakeholders in the context of the remit of Modern2020 are now better understood, as are the methods and advantages of engaging with stakeholders during, for example, the development of repository monitoring technologies. New methods for including citizen stakeholders from the onset of RD&D programmes have been developed and tested. Early involvement of citizen stakeholders was improved by understanding that the purpose was not to change the outcome of the meetings but to witness the open and honest debate of alternatives by the technical experts. The involvement in the preparation of communication material was improved by including the citizen stakeholders in the identification of objectives, structure and required content of the Stakeholder Guide.

Monitoring provides a platform for a range of stakeholders to be actively involved in a repository programme over a long period. This consistent involvement allows greater understanding to be developed and increases the ability for citizen stakeholders to be actively engaged. The methods developed during the Modern2020 Project are particularly well-suited to increasing the democratic quality of the implementation process. In particular, in the Modern2020 Project a wide range of stakeholders, including representatives from WMOs, TSOs, research organisations and citizen stakeholders were gathered together and participated in joint RD&D on repository monitoring.

Although there have been significant advances in the strategic, technological and sociological aspects of repository monitoring within the Modern2020 Project, international collaborative efforts should continue so that there are adequate resources available for technological development and so that the learning gained from practical application of the guidance, tools and approaches developed in the Project can be shared on an international basis and each programme can benefit from the lessons learned elsewhere.

The Modern2020 Project was undertaken by a wide range of organisations with expertise in geological disposal of radioactive waste and the post-closure safety case, monitoring technologies, and stakeholder engagement related to geological disposal. This group met frequently throughout the Project, sometimes in small group meetings and workshops, and also in Project-wide events such as the General Assemblies, the international conference and the training school. Many of the participants in the Modern2020 Project had previously been involved in the MoDeRn Project or were responsible for the development of specific repository monitoring programmes. This allowed the outcomes of the MoDeRn Project to be communicated to a broader audience and for an extension of knowledge and competence on repository monitoring. Hence, the Modern2020 Project has been successful in maintaining and enhancing knowledge and competence with respect to repository monitoring, and continued collaboration is encouraged.

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