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Monitoring During the Staged Implementation of Geological Disposal: The MoDeRn Project Synthesis

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Executive Summary

MoDeRn Project Objectives and Scope

The ***Mo****nitoring* ***De****velopments for Safe* ***R****epository Operation a****n****d Staged Closure* (MoDeRn) Project was a four-year collaborative research project within the Seventh European Community Framework Programme (FP7). MoDeRn considered how monitoring can contribute to the safety strategy and engineering design of geological disposal facilities for long-lived radioactive waste, as well as contribute to public understanding of, and confidence/trust in, geological disposal of radioactive waste.

The overall objective of the MoDeRn Project was to develop and document the collective understanding of repository monitoring approaches, technologies and stakeholder views to provide a reference point to support the development of specific national repository monitoring programmes. The MoDeRn Project included:

- Consideration of monitoring objectives and strategies, and the development of guidance on the design and implementation of repository monitoring programmes that takes account of the technical and societal context, the staged implementation of geological disposal, the capabilities of monitoring technologies, and the requirements of stakeholders (including regulators and public stakeholders), and is suitable for supporting decision making.
- Development and demonstration of innovative monitoring technologies that enhance the ability to monitor repositories, supported by a description of technical requirements and the state-of-the-art in monitoring technologies.
- Development of case studies that illustrate the process of mapping monitoring objectives and strategies to the processes and parameters that need to be monitored in a given context, the possible design of monitoring systems, the use of monitoring to check compliance with the safety case, and possible approaches to prevent and detect failures in the monitoring system.
- Development of a better understanding of the views of public stakeholders on the role of monitoring in geological disposal, in order to provide information and guidance that could support the future development of repository-specific monitoring programmes, and, in particular, stakeholder involvement in the development and implementation of monitoring programmes.

Monitoring is a broad subject, and can encompass many different objectives and activities within a radioactive waste management programme. The MoDeRn Project focused on repository monitoring, in particular monitoring of the near field to check the assumptions in the long-term safety case and to support decision making. Repository monitoring for other reasons, e.g. for operational safety, for safeguards and for compliance with environmental impact assessment requirements has not been the focus of the technical work in the MoDeRn Project.

This report is the synthesis of the MoDeRn Project. The objectives of this report are:

- To present the key results and conclusions from the MoDeRn Project.
- To provide an overview and access point to more detailed project reports.
- To provide guidance on the development of repository monitoring programmes.
- To identify the current status of knowledge and capabilities regarding repository monitoring and to identify future research requirements.

Objectives and Strategies

The work on consideration of monitoring objectives and strategies included elaboration of a generic structured approach to the development and implementation of a monitoring programme, the MoDeRn Monitoring Workflow. The MoDeRn Monitoring Workflow (Figure E.1) describes a step-by-step process for identifying what is required from monitoring and developing those requirements into a defined programme through analysis of the disposal system, in particular the safety functions of the engineered and geological barriers. The Workflow identifies three key stages in developing and managing a monitoring programme:

1. Objectives and Parameters: Identification of the objectives and sub-objectives of the monitoring programme, and relating these to processes and parameters to identify a preliminary parameter list for monitoring. Processes and parameters may be identified through an analysis of the safety case, for example through consideration of safety functions and/or features, events and processes (FEPs) that may have an impact on the safety functions of specific disposal components, or may address key programme requirements, for example demonstrating an ability to retrieve waste.

2. Monitoring Programme and Design: An analysis of performance requirements, available monitoring technology and overlaps/redundancy to screen the preliminary parameter list and to facilitate design of the monitoring programme. The programme design will define how, where and when data will be collected, and will specify performance levels, trigger values and potential risk mitigation measures that could be implemented in response to certain monitoring results.

3. Implementation and Governance: Conducting a monitoring programme and using the results to inform decision making. Whilst the monitoring programme is undertaken, there will be a need to evaluate the results both on a continuous and a periodic basis. Continuous evaluation will focus on the assessment of individual monitoring results, whereas periodic evaluation will consider the overall influence of monitoring results on the safety case and on programme decisions.

Monitoring Technologies

Technologies exist for monitoring the parameters that are likely to be of interest in understanding the evolution of repository systems, but monitoring the repository environment, especially the near field, has challenges that are specific to repository programmes. The repository environment is likely to be more aggressive to some monitoring equipment than environments for which such equipment was originally designed, and could exceed the design basis. Monitoring of the repository near field must also respect the passive safety of the multiple barrier system, and, in part because the rate of transient processes acting in the near field is expected to be slow, must address compromises between access for data transfer and energy supply, versus the challenges of providing *in situ* power over long periods. When considering the long timescales involved in monitoring, issues like drift of measuring devices and the need for calibration, reliability/longevity and the possibility for repair or replacement (without creating undue disturbances) must also be considered. Development of repository monitoring technologies and the strategies to apply these technologies would be required where there is a desire to monitor the repository near field following waste emplacement.

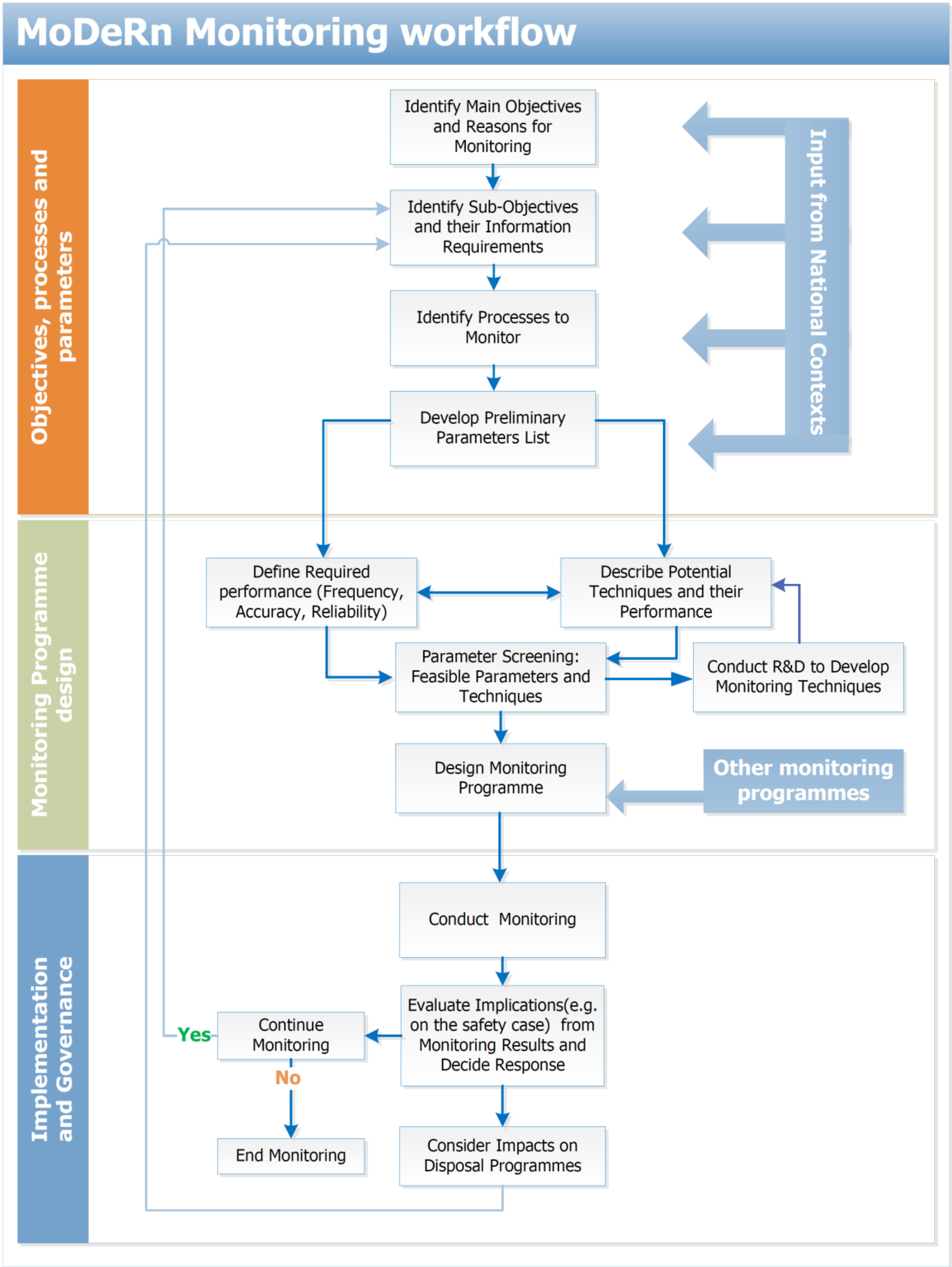

Figure E.1: The MoDeRn Monitoring Workflow.

Innovative engineered barrier system (EBS) monitoring technologies have been the focus of research and technical development (RTD) work within the MoDeRn Project, and this work has brought the technical readiness of a range of potential technologies closer to that required for deployment within repository projects:

- New algorithms for full waveform elastic inversion of seismic tomography data have been developed and practical methods for acquiring tomographic data have been developed through testing at Mont Terri and Grimsel. These developments enhance the ability to monitor a range of processes (e.g. saturation, and gas generation and migration) that affect the velocity structure of the near field.
- A new seismic hammer for application in microseismic monitoring has been developed. The hammer will enhance the ability to generate strong S wave signals, and thereby to improve the feasibility of conducting shear wave monitoring of the near field. This will improve the potential to provide information on changes to the excavation disturbed zone (EDZ), e.g. the mechanical response to heating.
- A high-frequency wireless node that allows measurement of several parameters (e.g. pore pressure, total pressure and water content), and transmission of the measured data over distances of a few metres has been designed, developed and tested. The node is expected to have a lifetime of 20-25 years. A patent application for the wireless node has been submitted as an outcome of this work.
- A low-frequency data transmission system, capable of transmitting data through 225 m of an electrically highly-conductive geological medium, at frequencies up to 1.7 kHz has been designed, developed and tested at the HADES underground research laboratory (URL), and the conditions under which low-frequency data transmission may be applied have been evaluated. This potentially provides a method for wireless transmission of monitoring data from a repository to the surface following repository closure.
- Research into distributed monitoring using fibre optic sensors has been undertaken in the HADES and Bure URLs. Sensors have been successfully installed and tested at both URLs and have successfully measured displacement around experimental tunnels in response to tunnel excavation.
- Digital Image Correlation (DIC) and acoustic emission (AE) monitoring have been successfully used to detect crack initiation and growth during a half-scale test of the Belgian Supercontainer.
- Corrosion sensors that can measure *in situ* corrosion rates have been developed and tested in surface facilities.

These developments have been incorporated into a compilation of the state-of-the-art in repository monitoring, which includes information on the experience of monitoring from radioactive waste research, in particular research in URLs, and from other industries.

Illustrative Monitoring Programmes

Within the MoDeRn Project, illustrative monitoring programmes have been developed for the three main types of host rock considered suitable for the geological disposal of radioactive waste. The illustrative monitoring programmes have demonstrated, on a theoretical basis, that near-field monitoring programme designs can be established based on a structured analysis of the FEPs considered in the safety case, and to address pre-closure information requirements prescribed in regulations (e.g. to demonstrate reversibility).

Several strategies for overcoming well-known challenges to repository monitoring have been identified and proposed in the illustrative monitoring programmes. These include the use of different types of monitored disposal cells, for example sacrificial cells that will be decommissioned and from which waste will be retrieved during closure of the repository; monitoring strategies that focus on the monitoring of wastes emplaced during the first stages of operation, which allows information to be gathered and used in decision making during the subsequent stages of operation; and the monitoring of disposal galleries that do not contain real waste. The use of dummy canisters, i.e. canisters with the same material properties, mass, dimensions and heat output as canisters containing waste, but which can be instrumented to avoid any potential impact on the passively safe disposal of waste, is proposed in two of the illustrative programmes.

The development of the illustrative monitoring programmes has allowed testing of the MoDeRn Monitoring Workflow using existing safety cases and other national context information. The illustrative programmes were developed using a process consistent with the MoDeRn Monitoring Workflow, i.e. a process that includes identification of the main objectives and reasons for monitoring, identification of sub-objectives, processes and parameters through an evaluation of the safety case and other drivers (e.g. assumptions on the requirements of stakeholders), and the development of a monitoring system design based on an understanding of the performance requirements and techniques available. Therefore, the MoDeRn Monitoring Workflow can be considered an appropriate structured approach for developing a monitoring programme.

Stakeholder Involvement

Research was undertaken on public stakeholder involvement in relation to repository monitoring. This was directed at a better understanding of views on the role of monitoring in geological disposal, and the governance of repository development and staged closure. By improving this understanding, information and guidance has been identified that can be used to support the future development of repository-specific monitoring programmes.

Consideration of participatory processes in repository monitoring was conducted through a range of activities:

- Interviews were conducted with specialists employed by European waste management organisations (WMOs).
- A workshop with stakeholders was held in which representatives of other types of organisation (mainly regulatory agencies, with a limited number of participants from advisory bodies and public stakeholder groups) discussed the research activities of the MoDeRn Project and provided insights into stakeholder views on repository monitoring.
- Workshops involving public representatives from nuclear facility host communities were held in Belgium, Sweden and the United Kingdom (UK). The participants in these workshops had varying degrees of engagement with, and knowledge of, radioactive waste management projects.
- A visit to the Mont Terri URL and the Grimsel Test Site in Switzerland was undertaken with a subset of the public representatives that participated in the host community workshops.
- Discussions on the role of stakeholder involvement in repository monitoring programmes were held during the end-of-project international conference on monitoring in geological disposal of radioactive waste.

The national workshops and Swiss URL visits demonstrated that it is possible to discuss in a detailed manner monitoring issues with interested local stakeholders, even at an early stage in a repository programme. These activities furthermore revealed a mutual interest between participating technical experts and local stakeholders, leading to fruitful discussions considered beneficial and of interest by both parties.

The main conclusions from the work on stakeholder involvement in monitoring programmes are as follows:

- The opinion that monitoring should be a checking process rather than a confirmatory process was expressed by many stakeholders. Monitoring programmes are therefore likely to be viewed by some stakeholders as being more trustworthy if it is clearly communicated that they are designed from the perspective of challenging that repository behaviour is as expected, and if stakeholders are able to access clear information on how each aspect of repository performance is checked.
- Public stakeholders expressed a view that the checking of repository performance should be comprehensive and linked to an overall science programme. A continuation of research and development on repository monitoring techniques was expected. WMOs could ensure that this view is addressed by discussing with their stakeholders the role of monitoring during different phases of repository implementation, and by communicating the manner in which operational and long-term safety is assured.
- As anticipated, some public stakeholders do have expectations regarding post-closure monitoring, mainly in view of being able to prepare for (and respond to) unanticipated events or evolutions. Individual programmes will need to decide on ways to respond to this expectation. Additionally, communication of the understanding of remaining uncertainties, and a preparedness to allow options for monitoring to evolve and to respond to changes in the expected evolution of the repository (e.g. closure being postponed) could be beneficial to addressing stakeholders' expectations regarding long-term monitoring.
- Monitoring can be characterised as a socio-technical activity and could potentially contribute to building the confidence of public stakeholders in the safety of a particular repository project, though not by itself. Of course, many other factors will also play a role in building stakeholder confidence, such as the approach to decision making, and the level of public and stakeholder engagement. Monitoring can contribute to repository governance if it can address expectations from stakeholders, if it is expressed as a practical commitment to maintain a watch over the repository performance, and if there is transparency about the limits of monitoring, including what could realistically be expected in terms of evolution in monitoring techniques.

MoDeRn Project Concluding Statement

The partners in the MoDeRn Project have undertaken a wide-ranging work programme that has developed a better understanding of repository monitoring, has provided developments in the technologies that can be used to monitor the repository near field, and that provides a reference framework against which national programmes can be developed.

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List of Acronyms

3D:	Three-dimensional
AE/MS:	Acoustic emissions and microseismics
BER:	Bit error rate
CEMRC:	The Carlsbad Environmental Monitoring and Research Center
CRInSAR:	Corner reflector interferometric synthetic-aperture radar
DIC:	Digital image correlation
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation disturbed zone
EIA:	Environmental impact assessment
EIS:	Electrochemical impedance spectroscopy
ESDRED:	Engineering Studies and Demonstration of Repository Designs
FEPs:	Features, events and processes
FP7:	Seventh European Community Framework Programme
HLW:	High-level waste
HST:	Half-scale test
IAEA:	International Atomic Energy Agency
ILW:	Intermediate-level waste
LED:	Light-emitting diode
LL-ILW:	Long-lived intermediate-level waste
LLW:	Low-level waste
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
NEA:	Nuclear Energy Agency
R&D:	Research and development
RTD:	Research and technological development
SNR:	Signal-to-noise ratio
SOTA:	State-of-the-art
UK:	United Kingdom
URL:	Underground research laboratory
US:	United States
UT:	Ultrasonic test
WIPP:	Waste Isolation Pilot Plant
WMO:	Waste management organisation
WSNs:	Wireless sensor networks

Glossary

This glossary provides definitions of terms that are used within this report and which are either specific to monitoring or have a specific meaning/definition within the MoDeRn Project.

Deviating Behaviour: Repository evolution that is inconsistent with the assumptions in the safety case.

Disposal Cell: The excavation in which waste is emplaced, as envisaged in the French concept for disposal of HLW.

Drift: Drift is the slow change in the response of a sensor over time owing to physical and chemical phenomena affecting the way that the sensor responds.

Engineered Barrier System (EBS): The man-made components of the repository, typically comprising the wasteform, the waste container, the buffer, the backfill, and the plugs and seals.

Extrinsic Sensor: A sensor that acts as a means of relaying signals from a remote sensor to the electronics that process the signals.

Features, Events and Processes (FEPs): Features are distinct parts or characteristics of the system. Events are changes to a system that may be characterised by a frequency of occurrence. Processes are on-going chemical and physical changes in a system.

Intrinsic Sensor: A sensor that acts as the sensing element.

LIDAR: A technology that measures distance by illuminating a target with a laser and analysing the reflected light.

Main Objectives: The specific, high-level goals of a monitoring programme. The MoDeRn Reference Framework recognises four high-level goals for monitoring: to support the basis for repository performance evaluations, to support operational safety, to support environmental protection, and to support nuclear safeguards. Supporting the basis for repository performance evaluations includes the two different aspects of supporting the basis for the long-term safety case and supporting pre-closure management of the repository.

MoDeRn Reference Framework: Information and guidance provided by the MoDeRn Project, which can be used to support the development of a comprehensive monitoring programme. The MoDeRn Reference Framework describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders in the development and implementation of a monitoring programme. The MoDeRn Reference Framework is represented by the published reports from the MoDeRn Project.

MoDeRn Monitoring Workflow: A structured approach to the development of a specific monitoring programme.

Monitoring System Failure: An instance when the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena occurring in the repository.

Node: A device for measuring a parameter and transmitting the measured data to a receiver.

Overarching Goals: High-level statements that define the contribution of monitoring to the implementation of geological disposal. The MoDeRn Reference Framework recognises two overarching goals that all monitoring programmes will contribute towards: to support confidence building and to support decision making.

Pilot Facility: A region of the underground repository used to emplace and monitor a small but representative fraction of the waste. A pilot facility would be developed early in the operational phase of repository implementation, in order to provide information on the behaviour of the barrier system and check predictive models, and to allow early detection of any undesirable characteristics. It will also serve as a demonstration facility that provides input for decisions regarding closure of the entire facility. The waste in the pilot facility would be retrieved following operation of the facility and would be disposed of in the main repository. The pilot facility would be developed in a separate region of the repository to the main waste emplacement areas.

Parameters: Numerical indicators of properties related to FEPs.

Preliminary Parameter List: A list of possible monitoring parameters for which data could be collected to meet specific sub-objectives.

Pt100: A Pt100 sensor is a temperature sensor, in which temperature is calculated by measuring the resistance of a platinum element.

Repository Monitoring: Monitoring can have a wide interpretation. In this report, repository monitoring is used to refer to monitoring of the natural and man-made systems at a repository site.

Sub-objectives: Precise statements of the purposes of monitoring that allow the identification of processes and parameters to be monitored.

Sacrificial Cell: A sacrificial cell is an area in a repository in which real waste is emplaced and monitored for a specific period, after which the waste is retrieved and disposed of separately. Sacrificial cells are developed within the main body of repository alongside normal disposal cells for waste where there is no intention to retrieve waste.

Stakeholder: An actor with an interest in monitoring in relation to geological disposal of radioactive waste. Can include, but is not limited to, members of a WMO, regulatory organisations, advisory bodies, and members of the public and/or their representative bodies.

Trigger Values: Pre-defined results from a monitoring programme, which, if measured, would invoke further action.

List of MoDeRn Project Partners

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

Aitemin: Association for Research and Industrial Development of Natural Resources.

ANDRA: L'Agence nationale pour la gestion des déchets radioactifs.

DBE TECHNOLOGY: DBE TECHNOLOGY GmbH.

Enresa: Empresa Nacional de Residuos Radiactivos.

ETH Zurich: ETH Zurich.

Euridice: European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment.

Galson Sciences: Galson Sciences Limited.

Nagra: Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle.

NDA: Nuclear Decommissioning Authority.

NRG: Nuclear Research and Consultancy Group.

Posiva: Posiva Oy.

RAWRA: The Radioactive Waste Repository Authority.

RWMC: Radioactive Waste Management Funding and Research Center.

Sandia: Sandia National Laboratories.

SKB: Svensk Kärnbränslehantering AB.

The University of Antwerp: The University of Antwerp.

The University of East Anglia: The University of East Anglia.

The University of Gothenburg: The University of Gothenburg.

1 Introduction

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for its long-term management assume disposal in geological repositories. The successful implementation of geological disposal of radioactive waste relies on both the technical aspects of a sound safety strategy, and scientific and engineering excellence, as well as on societal aspects such as stakeholder acceptance and confidence/trust. A key argument in international guidance and national programmes has been that monitoring can provide a significant contribution to both technical and social aspects of successful repository implementation.

This report is the synthesis of research undertaken in the ***Mo**nitoring **De**velopments for Safe **R**epository Operation a**n**d Staged Closure* (MoDeRn) Project, which was a four-year collaborative research project within the Seventh European Community Framework Programme (FP7). MoDeRn considered how repository monitoring can contribute to the technical safety strategy and quality of the engineering of geological disposal facilities for long-lived radioactive waste, as well as contribute to public understanding of, and confidence/trust in, geological disposal of radioactive waste.

The overall objective of the MoDeRn Project was to develop the international consensus on monitoring to a level of description that is closer to the actual implementation of monitoring during a staged approach to geological disposal, thereby demonstrating that monitoring can provide the contribution envisaged in international guidance and by national programmes.

> The MoDeRn Project aimed to further develop the understanding of the role of monitoring in the staged implementation of geological disposal and to provide examples, guidance and recommendations that may be useful to waste management organisations (WMOs) for their development of a monitoring programme and their understanding of how it could be implemented and used as part of repository implementation.

The objectives of this report are:

- To present the key results and conclusions from the MoDeRn Project.
- To provide an overview and access point to more detailed project reports.
- To provide guidance on the development of repository monitoring programmes.
- To identify the current status of knowledge and capabilities regarding repository monitoring and to identify future research requirements.

1.1 Monitoring Geological Repositories for Long-lived Radioactive Waste

Monitoring is a broad subject, and monitoring within a radioactive waste management programme can encompass many different objectives and activities. These objectives and activities include technical and non-technical aspects, such as monitoring changes in the inventory, changes in waste treatment and conditioning practices, and changes in the societal context. Repository monitoring is a more narrow discipline within this wider context, and is related to monitoring the features, events and processes (FEPs) affecting the behaviour of a geological disposal facility.

The MoDeRn Project defines the term monitoring in the context of geological disposal of radioactive waste as:

Continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/characteristics, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment - and thus to support decision making during the disposal process and to enhance confidence in the disposal process.

The geological disposal of radioactive waste is envisaged as a staged process that will take many decades to implement. During the long period over which a repository will be sited, constructed, operated and closed, future operators, and current and future generations will need to make decisions about how, when and if to implement various steps in the development of the repository system. Decisions at each stage of repository implementation can be supported by information provided by monitoring results (IAEA, 2001; EC, 2004).

The post-closure safety of a geological repository is demonstrated in a safety case (IAEA, 2012). This is defined as a set of arguments and analyses used to justify the conclusion that a specific repository system is safe. It includes a description of the system design and safety functions, illustrates the performance of engineered and natural safety barriers, presents the evidence that supports the arguments and analyses, and discusses the significance of any uncertainty or open questions. The safety case also presents the evidence that all relevant regulatory safety criteria can be met.

A key objective of a monitoring programme is to provide information to support the post-closure safety case:

- During the early stages of repository implementation, monitoring can strengthen the understanding of system behaviour used in developing the post-closure safety case and to allow further testing of models of long-term behaviour (IAEA, 2001).
- During the operation of the repository, monitoring can be undertaken to demonstrate that the assumptions in the safety case are valid (EC, 2004) and to check compliance with licence conditions.

Although monitoring is a means to assist in checking or confirming that key assumptions regarding the post-closure safety-related features of the disposal system are valid (EC, 2004), post-closure safety is ensured by passive means inherent in the characteristics of the site and the facility, and those of the waste package. Post-closure safety does not depend on monitoring and monitoring should not compromise the passively safe design (IAEA, 2011).

In addition to supporting the post-closure safety case, monitoring can support other aspects of repository implementation, including operational safety, environmental impact assessment (EIA), and safeguards. Some of the monitoring that could be undertaken for operational safety, EIA, and safeguards could overlap with monitoring undertaken in support of the post-closure safety case.

Monitoring information can be used to give stakeholders and 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 (EC, 2004). Therefore, monitoring potentially has an important role in stakeholder engagement throughout a repository implementation programme. The use of monitoring as a method for building stakeholder confidence requires the implementer to consider adoption of particular approaches to monitoring, and to consider monitoring specific events and processes.

1.2 Background to the MoDeRn Project

1.2.1 MoDeRn Project Objectives and Scope

The overall objective of the MoDeRn Project was to develop and document the collective understanding of repository monitoring approaches, technologies and stakeholder views to provide a reference point to support the development of specific national repository monitoring programmes. The MoDeRn Project included:

- Consideration of monitoring objectives and strategies, and the development of guidance on the development of repository monitoring programmes that takes account of the applicable technical and societal context, the staged implementation of geological disposal, the capabilities of monitoring technologies, and the requirements of stakeholders (including regulators and public stakeholders), and is suitable for supporting decision making.
- Development and demonstration of innovative monitoring technologies that enhance the ability to monitor repositories, supported by a description of technical requirements and the state-of-the-art in monitoring technologies.
- Development of case studies that illustrate the process of mapping monitoring objectives and strategies to the processes and parameters that need to be monitored in a given context, the possible design of monitoring systems, the use of monitoring to check compliance with the safety case, and possible approaches to prevent and detect failures in the monitoring system.
- Development of a better understanding of the views of public stakeholders on the role of monitoring in geological disposal, in order to provide information and guidance that could support the future development of repository-specific monitoring programmes, and, in particular, stakeholder involvement in the development and implementation of monitoring programmes.

From a technical point of view, monitoring of the engineered barrier system (EBS) is one of the biggest monitoring challenges faced by implementers. It is unique to geological disposal owing to the long timescales involved and the requirement that monitoring does not affect the passive safety of the disposal system. While the project partners recognised the importance of monitoring for operational safety, EIA and nuclear safeguards, these specific monitoring programmes are expected to call for monitoring activities and technologies similar to those already in use in tunnels and mines, at other nuclear installations, and in association with environmental protection, and it is assumed that their implementation can be planned and further developed based on prior experience. Therefore, the main focus of the technical work in the MoDeRn Project has been the monitoring of EBS performance.

In addition to the technical challenges of EBS monitoring, the other key challenge recognised at the outset of the MoDeRn Project was the development of an integrated monitoring programme (i.e. a programme that integrated a range of monitoring activities potentially derived from different perspectives). An integrated monitoring programme would reflect the range of drivers for undertaking monitoring and the multiple ways in which monitoring data could be used to support confidence and decision making during repository implementation. This includes the integration of routine operational safety, environmental or safeguards monitoring with monitoring of the EBS in support of the safety case, and, in particular, the role of monitoring in stakeholder engagement.

1.2.2 MoDeRn Project Activities

Eighteen partners were involved in the MoDeRn Project, representing organisations responsible for radioactive waste management (WMOs) in seven EU countries (ANDRA, DBE TECHNOLOGY, Enresa, NDA, Posiva, RAWRA and SKB), Switzerland (Nagra) the US (Sandia) and Japan (RWMC) as well as organisations with specialist expertise in monitoring (Aitemin, Euridice, NRG, and ETH Zurich) and a specialist radioactive waste management consultancy (Galson Sciences Limited). Three partner organisations offer specialist experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organisations, industry) in highly technical issues (the University of Antwerp, the University of East Anglia and the University of Gothenburg).

The programme of work included:

- Eight partner workshops.
- Several meetings of smaller partner groups on focused topics.
- A workshop (the Troyes Monitoring Technologies Workshop) involving participants with technical expertise in monitoring in other industries such as oil and gas, mining and civil construction, including involvement in other EC projects that are considering monitoring issues (MoDeRn, 2010a). The principal objective of the workshop was to identify techniques that could enhance the ability to monitor a repository,
- A workshop with stakeholders, which aimed to gain feedback on monitoring from regulators and advisory bodies (MoDeRn, 2011a).
- An international conference on monitoring in geological disposal of radioactive waste (MoDeRn, 2013a).
- Engagement with public stakeholder representatives from Belgium, Sweden and the UK, including a joint event with a number of these stakeholders at two underground research laboratories (URLs) in Switzerland.

Work in the MoDeRn Project was undertaken in a comprehensive and coherent programme of research structured into six interrelated work packages:

- **Work Package 1: Monitoring Objectives and Strategies:** Work Package 1 aimed to provide a clear description of monitoring objectives and strategies that (i) appear suitable in a given physical and societal context, (ii) may be implemented during several or all phases of the radioactive waste disposal process, (iii) appear realistic with respect to the capabilities of available monitoring technology, (iv) take into account feedback from both expert and public stakeholder interaction, and (v) provide information to support decision-making processes, while developing the licensing basis.

  Within the MoDeRn Project, programme challenges have been addressed by preparing a *reference framework* for monitoring activities in geological repositories. The reference framework identifies and discusses relevant issues that need to be considered during the development of a comprehensive monitoring programme, and describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders. The reference framework includes a structured approach to the development of a monitoring programme; this is referred to as the *MoDeRn Monitoring Workflow*. The reference framework aims to support radioactive waste management organisations (WMOs) in Europe and beyond as they further progress towards implementing geological repositories (MoDeRn, 2013b).

The MoDeRn Reference Framework is represented by the published reports from the MoDeRn Project. The published reports from the MoDeRn Project are illustrated in Figure 1.1 and are listed in Table 1.1. Three levels of reports are recognised. Level 1 reports consist of the Project Synthesis (this report). Level 2 reports consist of summaries of the work on objectives and strategies (MoDeRn, 2013b) and technological development (MoDeRn, 2013e). Level 3 reports contain details of the technical work undertaken in the project.

As part of WP1, previous (national and international) work addressing monitoring in geological disposal was reviewed and the different national contexts of the participating partners was described, taking into account a variety of physical and societal contexts, and the different stages of the national disposal programmes (MoDeRn, 2010b). In addition, research into stakeholder engagement on monitoring has gathered feedback from both expert and non-expert stakeholder interactions, obtained through workshops, and other forms of dialogue (MoDeRn, 2012; 2013c).

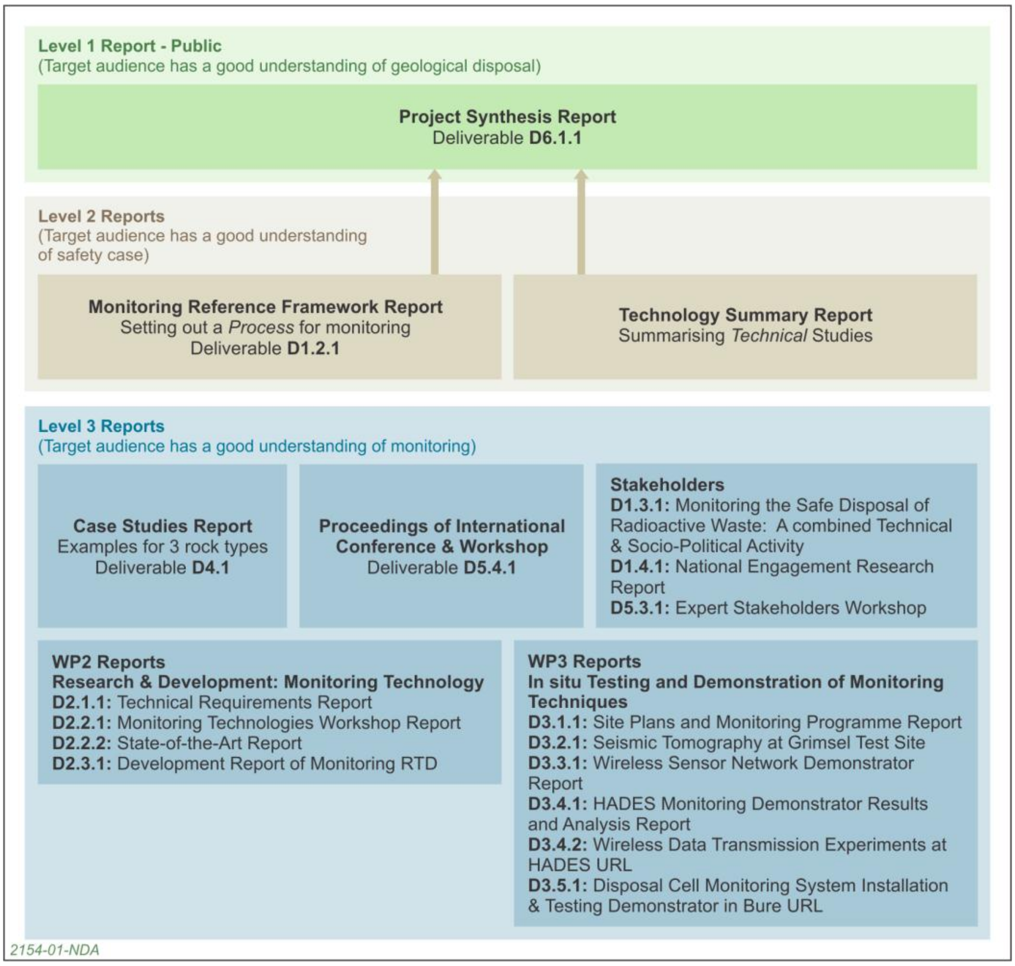

Figure 1.1: Hierarchy of published reports from the MoDeRn Project.

Table 1.1: Publicly available reports produced during the MoDeRn Project.

Deliverable Number	Deliverable Title	Reference
Level 1: Project Synthesis		
D-6.1	Monitoring During the Staged Implementation of Geological Disposal: The MoDeRn Project Synthesis	This report
Level 2: Strategic Reports		
D-1.2.1	Monitoring Reference Framework Report	MoDeRn, 2013b
None	Technology Summary Report	MoDeRn, 2013e
Level 3: Technical Reports		
D-1.1.1	National Monitoring Contexts Summary Report	MoDeRn, 2010b
D-1.3.1	Monitoring the Safe Disposal of Radioactive Waste: A Combined Technical and Socio-Political Activity	MoDeRn, 2012
D-1.4.1	Monitoring and the Risk Governance of Repository Development and Staged Closure: Exploratory Engagement Activity in Three European Countries	MoDeRn, 2013c
D-2.1.1	Technical Requirements Report	MoDeRn, 2011b
D-2.2.1	Monitoring Technologies Workshop Report	MoDeRn, 2010a
D-2.2.2	State-of-the-Art	MoDeRn, 2013d
D-2.3.1	Development Report of Monitoring RTD	MoDeRn, 2013f
D-3.1.1	Site Plans and Monitoring Programmes Report	MoDeRn, 2010c
D-3.2.1	Seismic Tomography at Grimsel Test Site	MoDeRn, 2013g
D-3.3.1	Wireless Sensor Network Demonstrator Report	MoDeRn, 2013h
D-3.4.1.	HADES Demonstrator	MoDeRn, 2013i
D-3.4.2	Wireless Data Transmission Demonstrator: from the HADES to the surface	MoDeRn, 2013j
D-3.5.1	Disposal Cell Monitoring System Installation and Testing Demonstrator in Bure Underground Research Laboratory	MoDeRn, 2013k
D-4.1	Case Study Report	MoDeRn, 2013l
D-5.3.1	Expert Stakeholders Workshop	MoDeRn, 2011a
D-5.4.1	Monitoring in Geological Disposal of Radioactive Waste: Objectives, Strategies, Technologies and Public Involvement. Proceedings of an International Conference and Workshop	MoDeRn, 2013a

- **Work Package 2: State-of-the-art and RTD of Relevant Monitoring Technologies:** The second work package focused on a description of the technical requirements on monitoring activities as well as an assessment of the state-of-the-art of relevant technology responding to these requirements (MoDeRn, 2011b, and MoDeRn, 2013d). It included the Troyes Monitoring Technologies Workshop (MoDeRn, 2010a). Technical research has been undertaken into innovative monitoring technologies that could address key challenges with EBS monitoring.

- **Work Package 3: *In situ* Demonstration of Innovative Monitoring Technologies:** The third work package aimed to develop *in situ* demonstrations of innovative monitoring techniques and provide a description of innovative monitoring approaches specifically responding to some of the design requirements of a repository. *In situ* demonstrations were undertaken in URLs in Belgium, France and Switzerland (MoDeRn, 2013c).

- **Work Package 4: Case Study of Monitoring at All Stages of the Disposal System:** The fourth work package was dedicated to a series of three case studies illustrating the process of mapping objectives and strategies onto the processes and parameters that need to be monitored in a given context, the possible design of corresponding monitoring systems, the use of monitoring to check compliance with the safety case, and possible approaches to prevent and detect failures in the monitoring system

- **Work Package 5: Dissemination of Results:** The fifth work package aimed at providing a platform for communicating the results of the MoDeRn Project. Two international meetings were managed through this work package: the stakeholders workshop with safety, regulatory and advisory authorities (MoDeRn, 2011a); and the international conference on repository monitoring (MoDeRn, 2013a). The work package also included implementation and maintenance of a project web site.

- **Work Package 6: Reference Framework:** The final work package consolidated results from the other work packages and provided a shared international view on how monitoring may be conducted at various stages of the disposal process.

1.3 Target Audience for this Report

The 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, to whom the report can provide guidance on how to develop, implement and use monitoring in support of decision making.
- Safety authorities likely to place requirements on the monitoring approach and who may impose some monitoring as part of license conditions.
- Designated advisory boards likely to inform national decision makers on waste management issues.

However, owing to the technical context under which monitoring work must be undertaken, a good understanding of geological disposal of radioactive waste is assumed, including a general understanding of the development of post-closure safety cases.

1.4 Structure of the Report

Following this introduction, this report is presented in a further five chapters:

- Chapter 2 provides a summary of the MoDeRn Monitoring Workflow and introduces the MoDeRn Reference Framework for repository monitoring.
- Chapter 3 discusses the technical aspects of repository monitoring, including a discussion of the current state-of-the-art of monitoring technology, and the outcome of specific research and demonstrator work undertaken at several URLs within the MoDeRn Project.
- Chapter 4 provides a summary of the case studies that have been performed to test the MoDeRn Monitoring Workflow and to illustrate the application of monitoring technologies within such a framework. Chapter 4 also presents a consideration of the use of monitoring to check compliance of repository performance with the safety case, and discusses the ability to detect monitoring system failures.
- Chapter 5 provides a summary of the research into stakeholder participation in monitoring programmes within the MoDeRn Project.
- Chapter 6 presents the conclusions from the MoDeRn Project.

2 Reference Framework for Repository Monitoring

This chapter provides a summary of the MoDeRn Reference Framework. More detailed information is available in the MoDeRn Reference Framework report (MoDeRn, 2013b).

2.1 Introduction to the Monitoring Reference Framework

Prior to the MoDeRn Project, guidance on the development of monitoring programmes at the international level included general requirements and described how monitoring can support the implementation of geological disposal in a broad sense (IAEA, 2001; EC, 2004). The MoDeRn Project identified a need to develop more detailed information and illustrations, and to develop and propose a structured approach to provide guidance to national programmes on how to implement and use a monitoring programme. The information and the structured approach would build upon the existing general guidelines, but would be more focused on the actual implementation of a monitoring programme. It would also incorporate lessons learnt from those national programmes having already conducted monitoring or commenced development of a monitoring programme.

The MoDeRn Project provides advice on how monitoring might be integrated within a repository programme by proposing a *Monitoring Reference Framework*. The reference framework identifies and discusses relevant issues that need to be considered during the development of a comprehensive monitoring programme, and describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders. The advice is illustrated by the *MoDeRn Monitoring Workflow* (Figure 2.1) a structured approach to developing, implementing and operating a monitoring programme. The themes developed more specifically in the MoDeRn Project are:

- How monitoring objectives may be developed and their role in the disposal process understood. In particular, how to develop the Main Objectives of a monitoring programme into clear information requirements related to key safety functions, and which can then be used to propose processes and parameters to be monitored.
- How monitoring systems may be designed and what strategies may help in meeting the monitoring objectives. These will include strategies to address technical limitations, with an outlook for further research and development (R&D), and, more generally, strategies to develop the potential for added value from a monitoring programme as well as an assessment of its limitations for supporting decisions on the implementation of geological disposal.
- How monitoring should be addressed as part of the overall governance of the repository implementation process, guidance on how monitoring results would inform and thus contribute to management decisions, how they would be evaluated against prior expectations, and how monitoring results deviating from such prior expectations could be addressed.
- How monitoring might contribute to stakeholder confidence – to discuss how the evidence expected from testing the validity of the licence basis prior to closure, the process overall and the roles different stakeholders may play could contribute to enhancing confidence in the repository implementation process.

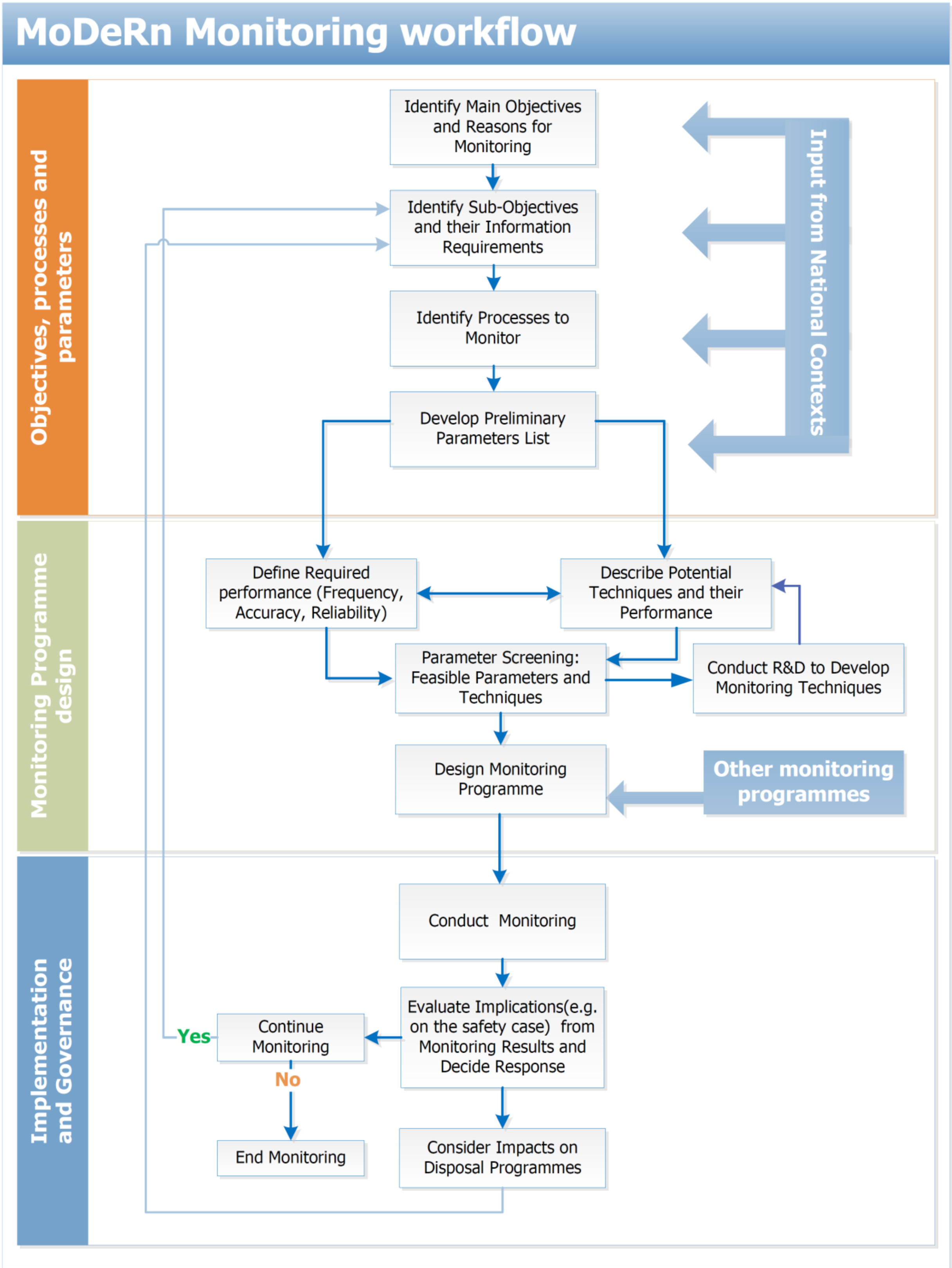

Figure 2.1: The MoDeRn Monitoring Workflow.

The MoDeRn Reference Framework identifies and discusses relevant issues that need to be considered during the development of a comprehensive monitoring programme, and describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders. The *Monitoring Reference Framework* provides advice to WMOs that can be used to support development of a monitoring programme that is consistent with their national repository programme, is realistic to implement, and would provide information suitable for decision making.

The Monitoring Reference Framework develops the themes highlighted above in more detail and provides recommendations on how to develop them within the context of a national repository programme. This should enable implementers to build upon previously established understanding of monitoring, and the process should take full advantage of the more detailed understanding already developed in certain national repository programmes.

The Monitoring Reference Framework does not provide a description of a reference monitoring programme. Indeed, the project clearly recognises the diversity of national contexts and, as a result, the diversity of monitoring solutions that are likely to be developed. However, examples are provided to illustrate how the information developed in the MoDeRn Project can support development of a monitoring programme.

The MoDeRn Monitoring Workflow (Figure 2.1) describes a step-by-step process for identifying what is required from monitoring and developing those requirements into a defined programme through analysis of these requirements. The Workflow identifies three key stages in developing and implementing a monitoring programme:

1. Objectives and Parameters: Identification of the Main Objectives and Sub-objectives, and relating these to processes and parameters to identify a Preliminary Parameter List for monitoring.
2. Monitoring Programme and Design: An analysis of performance requirements, available monitoring technology and overlaps/redundancy to design a monitoring programme.
3. Implementation and Governance: Conducting a monitoring programme and using the results to inform decision making.

The MoDeRn Monitoring Workflow envisages a top-down approach to the development of a monitoring programme, where a top-down approach is defined as one that starts from a high level (i.e. the Main Objectives), including engagement with all interested parties, and uses these to develop more detailed monitoring requirements. A top-down approach can be used to ensure comprehensiveness, transparency and traceability. Developing this top-down process should also help to ensure that a monitoring programme is properly focused on priorities. A bottom-up approach, i.e. a process that starts by defining detailed approaches and attempts to link these to higher level considerations, is not recommended, as it can often be driven by technical preferences rather than programme needs and may not necessarily focus on priorities.

The MoDeRn Monitoring Workflow represents an idealised structure for development of a monitoring programme. The Workflow is broken down into a series of linear steps to communicate the processes more clearly, but development of a monitoring programme is expected to be iterative, i.e. result from several cycles of evaluation of the safety case.

Early development of monitoring programmes applying the process described in the Workflow should help the implementer and stakeholders to understand the approach to monitoring and provide a basis for engagement on monitoring programmes. The three key stages of the Workflow process are discussed in more detail below (Sections 2.2-2.4).

2.2 Identifying Objectives and Parameters

The first stage in developing a monitoring programme, as envisaged in the MoDeRn Monitoring Workflow, is the specification of the monitoring programme objectives and identifying the processes/events and parameters that could be monitored to meet these objectives. The outcome is a Preliminary Parameter List, which is used as the basis for developing the monitoring programme design.

Four steps are recognised:

- Identify Main Objectives and reasons for monitoring.
- Identify Sub-objectives and their information requirements.
- Identify processes and events to monitor.
- Develop Preliminary Parameter List.

These steps are described below. The MoDeRn Reference Framework recognises that the identification of sub-objectives, processes/events and parameters is a closely-linked and iterative process. Therefore, we describe these three steps together, after first discussing the identification of Main Objectives and reasons for monitoring.

Identifying Main Objectives and Reasons for Monitoring

The key drivers for conducting a monitoring programme should be clarified at the start of the process. These are referred to as Main Objectives in the MoDeRn Monitoring Workflow. Key drivers and safety requirements have been recognised in international work on monitoring (IAEA, 2001, 2011 and 2012) and (EC, 2004).

Main Objectives are statements describing the goals that call for the development, implementation and use of a specific monitoring programme. The MoDeRn Project recognised four fundamental Main Objectives (Figure 2.2):

- To support the basis for repository performance evaluations.
- To support operational safety.
- To support environmental protection.
- To support nuclear safeguards.

Monitoring is an activity of interest to, and could support the confidence of, a range of stakeholders. While it is important to consider stakeholder requirements through the development and conduct of a monitoring programme, the MoDeRn Reference Framework views these requirements as being contained within the four Main Objectives. Monitoring related to these four Main Objectives would therefore encompass any activities undertaken in support of stakeholder confidence.

By defining the specific goals of monitoring, implementers could develop specific activities related to each goal. This would make the process of developing the monitoring programme more focused and efficient. For instance, all monitoring activities carried out to support the basis for repository performance evaluations could be grouped in a dedicated monitoring programme, just as all monitoring activities carried out to evaluate environmental impact could be grouped into a separate, dedicated monitoring programme.

There are two overarching goals that all monitoring programmes will contribute towards: *to support decision making* and *to support confidence building*. *To support decision making* is associated with the use of information derived from monitoring in the context of a stepwise repository implementation process. Here, monitoring provides information to support management decisions required throughout the process. *To support confidence building* is associated with some of the more general added value that can be expected from monitoring. Monitoring provides a tool to verify and evaluate the actual evolution of a repository and the surrounding environment, with the intent of checking that the disposal facility behaves within the bounds assumed in the safety case and that protection goals are met.

As noted in Chapter 1, the MoDeRn Project has considered how monitoring programmes may be developed to support a post-closure safety case, including the different aspects of supporting the basis for the long-term safety case and supporting pre-closure management of the repository. While both rely on the repository components to perform specific functions and the associated robustness of the design, pre-closure management can be influenced through active management and direct monitoring, while the basis for long-term safety relies on the passive system response to any FEPs that may govern its long term evolution, and, most importantly, any monitoring of this long term evolution must not affect passive safety.

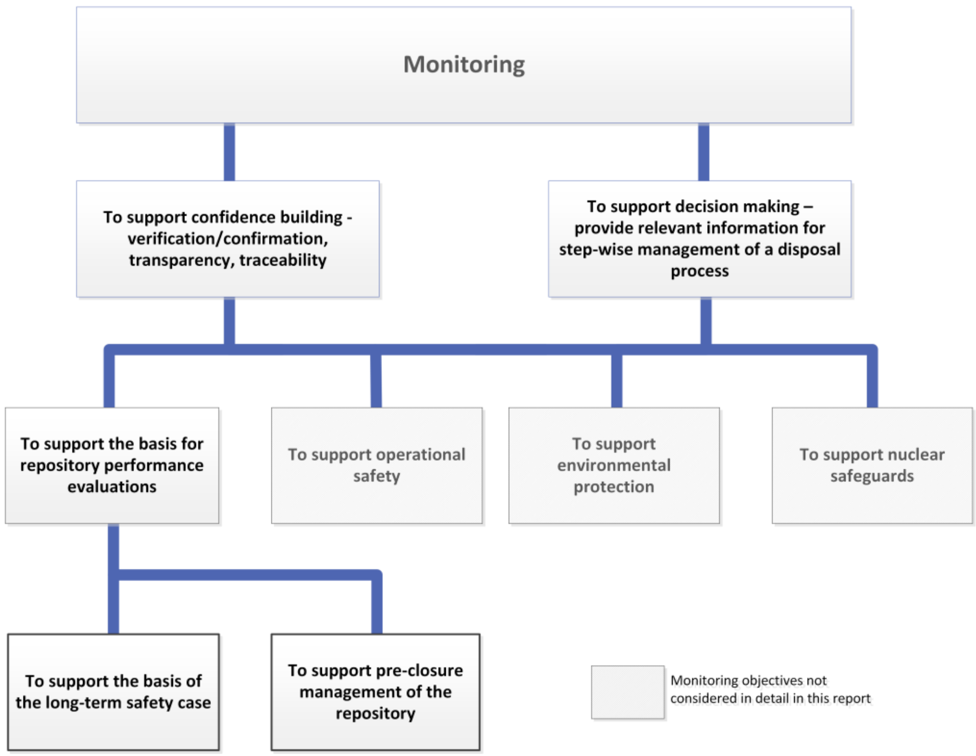

Figure 2.2: Overarching goals and main objectives for monitoring.

Identifying Sub-objectives, Processes/Events and Parameters

Whilst the Main Objectives are important in setting out the key drivers for a monitoring programme, they cannot directly be used to identify parameters to be monitored, because they are not linked to specific aspects of the disposal system.

Sub-objectives are precise statements of the purposes of monitoring that allow the identification of processes and parameters to be monitored. Sub-objectives are derived from other work in the disposal programme, including development and analysis of the safety case, repository design, regulations and stakeholder concerns. Sub-objectives take account of the national context; this could include specific legal and regulatory requirements, and stakeholder views, and will also be specific to the particular waste type, geological environment, disposal concept and overall implementation strategy. The national context may also define an overall strategic approach to the monitoring programme, including the general locations in which monitoring should be undertaken, e.g. in the actual repository or in a pilot facility.

The long-term safety of a disposal concept is frequently expressed in terms of the *safety functions* that define the contribution of the individual barriers and the overall multiple barrier system to isolation and containment. Processes and events that influence these safety functions could be subject to monitoring. Processes are on-going chemical and physical changes in a system, whereas events are changes that may be characterised by a frequency of occurrence. Parameters are the numerical indicators of processes and events, and may be linked to specific monitoring techniques or sensors. Therefore, a list of parameters, referred to here as the *Preliminary Parameter List*, related to relevant safety functions of a disposal concept, is seen as the key link between setting the objectives for a monitoring programme and designing it.

The identification of the Preliminary Parameter List would be facilitated through cross-disciplinary discussions, with representatives from the safety case, repository design, stakeholders and experts in monitoring technology. The Main Objectives would be considered, and existing safety cases[1] and existing outcomes of safety assessments could be used as the basis for identifying processes and events with a significant impact on the safety case. The cross-disciplinary discussion would also allow identification of monitoring activities that could contribute to additional confidence building, provide meaningful evidence to support safety case assumptions, or could be used for additional checking of the consistency of repository performance with the safety case. Sub-objectives could be identified through an analysis of each FEP considered within a safety case, each parameter included in the quantitative safety assessment or through consideration of safety functions and performance criteria.

The MoDeRn Monitoring Workflow envisages a staged approach in which a Preliminary Parameter List is developed before the final list of parameters is developed during the design of the monitoring programme, to allow the design of the monitoring programme to consider issues of redundancy, accuracy, technical feasibility etc. This allows different specialists to provide focused outputs during different stages of the development of the monitoring programme.

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[1] The safety case would include the assumptions regarding waste type, geological environment and repository design.

The selection of a process/event and a parameter needs to be linked to a justification that states why the parameter should be included in the monitoring programme or not. Experts in safety case development, design and stakeholder engagement are best placed to develop these justifications. The justification could be a statement describing the assumptions behind expert judgement, a link to a specific section of a report or a link to a particular model result, and a statement explaining how monitoring of the parameter addresses a specific sub-objective.

Transparency in selection of monitoring parameters would be achieved through the structured approach to identification of processes and parameters. Transparency is also about communication, and, therefore, parameter lists should be archived and linked to information that provides the evidence on which the justification for the parameters inclusion in the modelling programme is based. This archive could be subject to external review and further refinement throughout the programme. The archive could also be supplied to, and reviewed by, stakeholders.

2.3 Monitoring Programme Design

Following the development of a Preliminary Parameter List, the list should be consolidated and the monitoring programme designed. In the MoDeRn Monitoring Workflow, the stage of design of the monitoring programme recognises that a practical number of monitoring parameters should be included, that the technical requirements and specification for the monitoring of each parameter need to be defined, and that suitable techniques need to be available for undertaking the required monitoring. This may be considered as part of the original development of the parameter list. However, in the MoDeRn Monitoring Workflow, specification of the requirements for monitoring each parameter is recognised as a separate step for clarity/visibility and to illustrate the link with available technologies, which would be considered in parallel.

The Preliminary Parameter List represents a list of possible monitoring parameters for which data could be collected to meet specific sub-objectives. The Preliminary Parameter List does not contain details of the technical requirements nor does it define the monitoring technologies to be used. As recognised above, there is also the need to screen the Preliminary Parameter List to ensure that the monitoring programme is appropriate, i.e. efficient and reliable. Finally, the monitoring programme must be designed, i.e. an implementable monitoring programme must be developed.

Technical Requirements and Potential Techniques

In order to select final monitoring parameters, the information needs for each of the entries in the Preliminary Parameter List must be defined. Through analysis of the origins of the parameter, including the stated sub-objective, the frequency, accuracy and reliability of information collected on the parameter are specified. This information may, for example, be derived from a consideration of the safety case. This task is undertaken in parallel with work on understanding the capabilities of monitoring techniques, as this will inform the specification of the required performance.

For each parameter, there is a need to identify one or more techniques of suitable maturity (technical readiness) available to monitor the parameter. This requires an information source against which to compare requirements against capabilities. In the MoDeRn Project, a state-of-the-art report on monitoring technology has been developed as a description of available monitoring technologies (see Section 3.1) and the state-of-the-art report represents such an information source. The information source should include an assessment of the operating conditions under which the technology can perform, and a description of the expected performance and reliability under repository conditions.

Where there are currently no sufficiently mature technologies that meet the specified performance requirements, further R&D could be undertaken to improve existing techniques (e.g. to improve performance under repository conditions) or to develop new techniques. Therefore, R&D on monitoring technologies can be an integral part of a monitoring programme that allows the options for repository monitoring to be increased. An early analysis of monitoring requirements and available technologies would help to identify where R&D on monitoring techniques could be progressed for the benefit of future monitoring programmes. Developments in monitoring technologies achieved through this R&D would be incorporated in an update of the information source describing the capabilities of monitoring technologies (see above).

Where no technique is available for monitoring a parameter, and there is no prospect of R&D delivering a suitable technique in the required timeframe, the parameter would be rejected during application of the screening process (see below). This might lead to reconsideration of the accompanying sub-objective, or may result in additional research as part of the overall science programme and may result in changes to the repository design.

Parameter Screening

Once the technical requirements and potential techniques for monitoring each parameter have been defined, the Preliminary Parameter List can be screened to determine which parameters are to be included in the monitoring programme.

This screening is motivated by three needs for the implementation of an efficient and reliable disposal process:

1. The first need is a pragmatic one of limiting monitoring activities in the repository to the essential requirements. This would prevent imposing any activities that might interfere with operations and the expected repository evolution unless it can be demonstrated that there is some benefit from undertaking the monitoring (e.g. the monitoring links to an identified uncertainty not addressed elsewhere or links to a specific commitment made by the implementer).
2. The second need is one of clarity of information. A monitoring programme with clear links between monitoring results and the basis to evaluate expected performance is needed to inform decision making.
3. The third need is for the process of screening to consider the importance of monitoring a specific parameter for safety (e.g. the significance of the parameter in the safety case), and the feasibility of monitoring the parameter. Screening could thus be referred to as both (i) a progressive refining of "what needs to be monitored"; and (ii) an iterative assessment that describes what options for technical implementation of monitoring are available.

The feasibility considerations in the screening process will ensure that the parameters in the monitoring programme can be monitored whilst:

- Avoiding damage or disturbance to the safety functions provided by each component of the multi-barrier system.
- Being able to operate effectively in harsh environments (temperature, humidity, radiation and induced stress).

- Achieving the required accuracy where the basis for safety is often related to small changes over long timescales.
- Ensuring the monitoring information from selected locations is demonstrably representative.
- Implementing an appropriately reliable and durable monitoring system, particularly over the long timescales envisaged.
- Acknowledging that access to *in situ* sensors is not possible without disturbing barriers.
- Acknowledging that there may be challenges in identifying or interpreting errors in the monitoring system.

Although these issues will also be addressed during the design stage by engineers, it is important that they are considered during the screening stage, as this will also allow safety assessors an input into the specification of the monitoring system, for example by defining what monitoring of the near field would be, and what would not be, acceptable for the post-closure safety case, especially in terms of maintaining the passive safety of the disposal system.

The screening process proposed here needs to be implemented in a complementary manner to the original selection of the processes/events and parameters in the Preliminary Parameter List. Part of the process could involve further engagement with stakeholders to check that important objectives from their perspective are appropriately addressed during the screening process.

Design monitoring programme

For each of the technically feasible parameters identified through the screening step, more detailed plans need to be developed for their monitoring. The design of the monitoring programme would consider:

- Selection of specific monitoring locations, including consideration of redundancy and ensuring that the selected locations would provide representative information.
- Management of uncertainty in the performance of the chosen monitoring techniques, as captured within the performance description for the method.
- Data management.
- Processing of primary sensor data, data validation, quality assurance and data management.
- How the results of the monitoring would be used in data analysis, interpretation and communicating monitoring information, to ensure that the monitoring system design met requirements.
- Trigger values and/or repository performance criteria for the monitoring programme. A trigger value is a response from an individual monitoring activity that would invoke further action, and repository performance criteria are expectations regarding the overall performance of the facility. Trigger values and repository performance criteria will be a combination of limiting values, ranges, and observations of repository evolution that can be related to the assumptions and arguments in the safety case. Where feasible, trigger values and repository performance criteria should be defined

so that if monitoring data lie outside the values specified, this does not necessarily imply unsatisfactory performance of the facility. Instead, trigger values and repository performance criteria should be set to provide a warning that expected performance may not be occurring and that further action is required (risk management). Responding to data values that exceed a trigger value or are inconsistent with repository performance criteria is part of the overall governance programme, but, during the design stage, it is necessary to define response plans to ensure that appropriate risk mitigation actions are feasible and have been considered prior to monitoring commencing.

- Integration of the repository monitoring programme with other monitoring programmes that might be collecting data of relevance (e.g. groundwater quality monitoring programmes).

Design of the monitoring programme also requires an understanding of possible implementation strategies, i.e. the possible approaches to instrumenting the repository in order to provide information which adequately contributes to meeting a specific monitoring objective. This includes strategic decisions on where the monitoring will be undertaken (e.g. in a sacrificial cell or in a disposal gallery that does not contain real waste). These decisions may be determined by a strategy already in place, e.g. a requirement for a specific type of monitoring provided through regulation. It is expected that several options for the monitoring programme may be identified and each option would be evaluated with respect to the required performance. Such an evaluation would consider the potential for (i) providing representative results; (ii) providing adequate information on processes that evolve over long timescales; (iii) circumventing technical challenges of direct *in situ* monitoring; and (iv) not significantly interfering with the performance of the repository.

Although it is theoretically possible to perform monitoring on all components of the repository, this approach is unlikely to prove appropriate. The added value from exhaustively monitoring all of the components of the repository and all processes contributing to repository implementation needs to be balanced against the added complexity that this would introduce into operations (including the impact on operational safety), the added financial burden and the lack of focus on key issues that such an approach would bring. Therefore, monitoring will probably only be conducted in selected locations and on specific components of the repository.

Monitoring needs to be representative, and an evaluation of proposed sensor locations and measurements to demonstrate that they are representative of the whole repository is therefore a relevant aspect of design. For a given host formation and engineered system, the number of sensors and their spatial distribution should be chosen in a way that the scope of monitoring provides the required information.

To ensure that monitoring system designs can be accommodated within the overall design of the repository, these need to be developed in the early stages of design and could influence the overall repository design configuration. An example considered in the MoDeRn Project is how the potential for low-frequency data transmission would benefit from inclusion in the repository design of excavations in which a large radius loop antenna could be sited underground (see Section 3.2.4).

2.4 Implementation and Governance

As part of the specification of a monitoring programme, it is important that a process is developed for collecting monitoring information, evaluating and communicating that information and responding to the findings as appropriate. This process for evaluation and decision making should be developed in consultation with stakeholders to ensure that the monitoring process meets regulatory guidance and is accepted as transparent.

Evaluation of monitoring data is likely to be undertaken on both a continuous and a periodic basis. Continuous evaluation will focus on the assessment of individual monitoring results, whereas periodic evaluation will consider the overall influence of monitoring results on the safety case and on programme decisions.

Following the acquisition of monitoring data, the first action would be to verify the quality of the data, which will include the use of methods to detect failures in the monitoring system as discussed in Section 4.5. Evaluation of individual monitoring results is likely to be undertaken on a continuous basis as data are acquired. In the first instance, the design of a monitoring system should provide for redundancy and for alternate techniques for monitoring. For a long-term monitoring programme, reliability and sensor drift may be relevant issues to be addressed in data quality verification, and this needs to be factored into any analysis, including the development of criteria for identifying and rejecting spurious results. This could be achieved, for example, by comparison against other monitoring data collected by the same technique or by other techniques.

It is not envisaged that all instruments will fail at the same time. Redundant equipment, or equipment using alternative technology that continues to operate reliably, would provide a basis for analysis of inconsistent data. It is important to be able to effectively analyse whether such an event is failure of instrumentation rather than unacceptable performance of the repository. Where the operating life for a monitoring system is known to be limited, then a key requirement is that measurements are taken more frequently than the expected rate of equipment failure. Further discussion of detecting monitoring system failure and errors is provided in Section 4.5.

From the moment a licence basis has been established and a licence is granted, monitoring plays a role in evaluating the actual repository evolution compared with that licence basis. Comparisons with the licence basis will be undertaken periodically. Confirmation or discrepancies arising from monitoring results provide important information. However, the real basis for decision making is not the individual monitoring result, but its implications, if any, on the safety case. If the monitored parameter is established as a performance indicator, i.e. as providing a measure directly related to the safety case, then the monitored value might directly trigger a need for decision and action on behalf of disposal process management.

It is expected that monitoring will either provide information that is confirmatory of prior understanding or provide information that will refine or introduce new understanding. Making use of monitoring results requires an understanding of how the monitored parameters are related to the safety functions and the safety case. If prior steps in identifying objectives, deriving them from safety functions and linking them to the basis for evaluating expected performance, are followed as recommended by the MoDeRn Reference Framework, this should already be understood and documented.

If monitoring results are consistent with the assumptions and understanding in the safety case, they are expected to support decisions to continue the repository programme as planned or, if enhanced knowledge allows, to pursue a path of optimisation. If, on the other hand, monitoring results challenge prior understanding, this could call for a re-evaluation of the licence basis.

Monitoring might not merely serve to check expected behaviour, but also to reduce uncertainties by measuring parameters *in situ* (either remote monitoring of emplaced waste or monitoring in representative locations such as pilot facilities). With regard to the latter, *in situ* monitoring over long durations may contribute to enhanced understanding of slow processes (e.g. transient groundwater pressure, although the ability to monitor this parameter would depend on the hydraulic conductivity of the rock and the hydraulic head). These may allow predictions to be updated and a re-evaluation of the performance of the repository system to be undertaken. This reduction in uncertainty could allow trigger values to be relaxed and the intensity of monitoring to be reduced. This could also support optimisation of the disposal process. If monitoring results provide sufficient evidence to allow reduction of previously conservative assumptions, this might be used as a basis for considering the relaxation of design requirements, where these could be demonstrated to be overly conservative.

As discussed in the previous section, the MoDeRn Reference Framework foresees the definition of trigger values and repository performance criteria, which - if exceeded – would invoke risk management processes. A range of risk management approaches exist; examples include:

- Perform additional monitoring.
- Reassess the safety case/assumptions related to the parameter that exceeds the trigger value. This might be achieved by the re-running of performance assessment or supporting calculations.
- Engineering intervention.
- Retrieve the waste.

However, presentation of such risk management procedures should always be accompanied by a clear message that safety is demonstrated by the safety case.

2.5 Conclusions on the MoDeRn Reference Framework

This chapter has introduced the issues addressed in the MoDeRn Reference Framework and has presented the MoDeRn Monitoring Workflow. The MoDeRn Reference Framework describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders in the development and implementation of a monitoring programme. The MoDeRn Reference Framework is represented by the published reports from the MoDeRn Project. The Workflow provides a structured approach that can be used by a WMO to develop and implement a repository monitoring programme that is linked to the safety case.

However, more detailed information on the practicalities of monitoring is required to demonstrate how monitoring of the near field could be undertaken, and, in particular, how monitoring programmes can address technological, programmatic and stakeholder challenges. These challenges are addressed in the next three chapters, which consider monitoring technologies (Chapter 3), integrated monitoring programme case studies (Chapter 4) and the involvement of stakeholders in monitoring (Chapter 5).

3 Repository Monitoring Technologies

This chapter provides a summary of the technical research undertaken into monitoring technologies within the MoDeRn Project. More detailed information is available in the MoDeRn Technology Summary report (MoDeRn, 2013e) and underlying topic reports (MoDeRn, 2011b; 2010a; 2013d; 2013f; 2013g; 2013h; 2013i; 2013j; 2013k).

Section 3.1 provides an introduction to monitoring technologies by discussing some of the technical requirements and technical challenges posed by repository monitoring, and by summarising some of the lessons that can be taken from a consideration of the state-of-the-art in repository monitoring and in other related industries (e.g. oil and gas industry, carbon sequestration, mining and civil engineering). More detailed descriptions of the monitoring technologies can be found in the state-of-the-art report described in Section 3.1 (MoDeRn, 2013d).

Section 3.2 summarises RTD work undertaken on monitoring technologies as part of the MoDeRn Project. This has included RTD on:

- Seismic tomography (Section 3.2.1)
- Micro-seismic monitoring (Section 3.2.2).
- High-frequency wireless sensor networks (Section 3.2.3).
- Long range, low-frequency wireless data transmission (Section 3.2.4).
- Monitoring using fibre optic sensing (Section 3.2.5).
- Monitoring of concrete structures (Section 3.2.6).

A summary of the advancements made in the MoDeRn Project related to monitoring technologies is provided in Section 3.3.

3.1 Introduction to Monitoring Technologies

Technical Requirements and Technological Challenges

In Section 2.1, the MoDeRn Monitoring Workflow has been presented as an overall methodology for addressing the programmatic issues and challenges related to monitoring. There are also many practical issues and challenges related to the technology needed for monitoring. Technology is of key importance because it determines what can be measured, with what precision, and with what reliability over the long timescales and challenging conditions envisaged.

Monitoring technologies exist for monitoring the parameters that are likely to be of interest in understanding the evolution of repository systems. These parameters include temperature, mechanical pressure, hydraulic pressure, water content/saturation, salinity, radiation, displacement, deformation, humidity, gas concentration (oxygen, carbon dioxide, hydrogen and methane), gas pressure, pH, Eh, concentration of colloidal particles in solutions and alkalinity. However, the nature of the waste, geological environment and disposal concepts envisaged for disposal of radioactive waste place specific technical requirements on the capabilities of monitoring technologies that must be addressed before successful repository monitoring can be undertaken.

The environmental conditions in a repository are likely to be more aggressive to some monitoring equipment than in other applications, and are likely to exceed the conditions for which monitoring equipment was originally designed. This necessitates the development of specialised equipment to meet extremes in temperature, mechanical pressure, hydraulic pressure, water saturation, salinity, radiation and displacement.

Furthermore, as the rate of transient processes occurring in the near field is expected to be slow relative to the monitoring period, and because there is a requirement that monitoring should not compromise the passively safe design (IAEA, 2011), additional considerations need to be addressed in developing a monitoring programme, especially when the monitoring is concerned with near-field monitoring after the emplacement of waste and engineered barriers. These include developing compromises between access (boreholes, etc.) for data transfer and energy supply, versus the challenges of providing *in situ* power over long periods, for example to allow remote monitoring and wireless transmission of monitoring data. When considering the long timescales involved in monitoring, issues like drift[2] of measuring devices and the need for calibration, reliability/longevity and the possibility for repair or replacement (without creating undue disturbances) is a relevant aspect that must be considered for the application in repository monitoring.

Development of specialised monitoring technologies and equipment for application in repository settings expands the options available for developing a monitoring programme. Technologies for repository monitoring can be based on:

- Use of available technologies that respond to the needs of repository monitoring.
- Development of specific adaptations of available technologies (e.g. to enhance resistance to environmental conditions).
- Development of new technologies.

The strategy for developing a monitoring programme also influences the technical requirements on monitoring equipment. This includes the use of pilot facilities and/or sacrificial cells, which may be decommissioned prior to the closure of a repository; more intrusive monitoring may be appropriate for these strategies. Monitoring strategies and integrated monitoring programmes are discussed in Chapter 4.

State-of-the-Art in Monitoring Technologies

State-of-the-Art in Repository Monitoring

In order to provide an overview of the current capabilities of repository monitoring technologies, a state-of-the-art report has been compiled as part of the MoDeRn Project (MoDeRn, 2013d). The state-of-the-art report provides:

- A general introduction to the parameters potentially of interest for monitoring (the actual parameters of interest will depend on the specific monitoring programme), the components that might need monitoring, and the associated requirements and constraints.
- An overview of the state-of-the-art for technologies that may be used for repository monitoring, including a list of references for each monitoring technology considered.

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[2] Drift is the slow change in the response of a sensor over time owing to physical and chemical phenomena affecting the way that the sensor responds.

- A summary of the advantages and disadvantages of each technology, and identification of R&D requirements to address the disadvantages.
- A conclusion on the feasibility and limitations of the technology for repository monitoring.

In the report, emphasis was placed on sensors, signal and data transmission, and local energy sources, because these are the aspects of monitoring technologies identified as most relevant to EBS monitoring, which is the focus of the MoDeRn Project. The information in the state-of-the-art report built on the existing knowledge and experience of the project partners, including experience on the strengths and weaknesses of the different monitoring technologies developed in experiments and in technology development projects in URLs. In addition, information from the Troyes Monitoring Technologies Workshop (MoDeRn, 2010a), and the outcome of RTD and demonstration activities (see Section 3.2), all of which were undertaken as part of the MoDeRn Project, were incorporated in the state-of-the-art report.

Monitoring State-of-the-Art in other Industries

As part of the MoDeRn Project, the Troyes Monitoring Technologies Workshop was held at the Université de Technologie de Troyes (UTT), France on 7-8 June 2010. The workshop brought together 55 experts from a range of organisations, including industry, WMOs and research institutes (MoDeRn, 2010a). The general aim of the workshop was to bring together monitoring specialists from a range of disciplines to present and discuss their work and experience in applying state-of-the-art monitoring techniques. The specific objectives of the workshop were to:

- Review recent developments in monitoring technologies.
- Stimulate a mutually beneficial exchange of experiences, applications and views between the radioactive waste management community and monitoring technology experts from other fields.
- Facilitate knowledge transfer, e.g. identify EC projects with a monitoring component.

The outcomes of the Troyes Monitoring Technologies Workshop are summarised below and are described in more detail in the Workshop report (MoDeRn, 2010a). This includes identification, at the time of the workshop, of the technologies under development or being applied in other industries that may have applications in repository monitoring, noting that some of the technologies discussed at the workshop are already being applied or developed within national and international radioactive waste management projects.

Wireless sensor networks (WSNs) consist of spatially distributed autonomous sensors used to monitor structures and/or environmental conditions (Römer and Friedemann, 2004). WSNs find application in many industrial and civilian areas, including industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control. Transmission is generally considered through-air, with a lesser or greater ability to transmit through obstacles. Developments in WSNs and through-the-earth data transmission are of interest to repository monitoring as these technologies may support the transmission of monitoring data from the near field of the repository system without affecting the passive safety of the EBS. As such, research in this area has been undertaken within MoDeRn (see below).

A fibre optic sensor is a sensor that uses an optical fibre either as the sensing element (*intrinsic sensors*), or as a means of relaying signals from a remote sensor to the electronics that process the signals (*extrinsic sensors*) (Measures, 2001; Yin *et al*., 2008). A laser is currently used as the light source for all commercially available fibre optic sensors. Lasers have a relatively high power consumption compared to other light sources (e.g. light-emitting diodes). Optical fibres have a wide range of potential applications because they can operate under harsh environments, including environments with strong electromagnetic fields, high temperatures, explosive potential, aggressive chemical species or ionising radiation. Fibre optics have found particular application in civil engineering applications, where glass optical fibres can measure strains of 1%, and where polymer optical fibres have been demonstrated to measure strains up to 20% and can potentially measure strains up to 40%. The principal application for fibre optic sensors in repository monitoring is the measurement of parameters such as strain, pressure and/or temperature within the near field. Fibre optic sensors provide distributed monitoring and, as such would be suitable for monitoring the 3D parameter-field rather than the single location measured by traditional measurement devices.

Seismic interferometry uses cross-correlation techniques to map the velocity structure of the sub-surface, using background seismic signals (Campillo and Paul, 2002; Snieder, 2004; Snieder, 2006; Wapenaar and Fokkema, 2005). Changes in the velocity structure can be used to develop an understanding of the impact of processes on the physical properties of the sub-surface, and thereby to develop an understanding of the processes themselves. Developments in coda wave analysis allow for the monitoring of temporal changes in the average properties of a medium (e.g. pressure as a result of thermal expansion) of ~0.1% – 0.01%. Seismic interferometry is being developed within the oil and gas industry, but is mainly used in research and academic settings. Future developments could allow monitoring of physical changes in the sub-surface (e.g. gas generation and migration, and increases in temperature), although this would be highly dependent on the geological environment.

Seismic reflection surveys provide information on the velocity structure of the sub-surface by recording the reflection of a known seismic source. Time-lapse three-dimensional (3D) seismics can be used to image the movement of fluids within the earth (European Association of Geoscientists and Engineers, 2003), e.g. a gas plume, and have been used for monitoring CO_2 plumes resulting from carbon sequestration projects. The resolution of time-lapse 3D seismic monitoring is now such that estimates of the volume of CO_2 imaged on 3D seismic surveys of the Sleipner Field in the North Sea accounts for 85% of the injected CO_2. Seismic reflection could be used to monitor gas generation and migration, although this would be highly dependent on the geological environment and disposal concept.

Acoustic emissions and microseismic (AE/MS) surveys monitor fracturing in rock and man-made materials through measurement of the seismic signals emitted when materials fracture (Young and Martin, 1993). AE/MS monitoring has the potential to monitor the mechanical evolution of the EBS following closure of a disposal cell, prior to closure of the access ways and service areas within a repository (i.e. to be used as part of a staged closure process). AE/MS events have been monitored in response to changes in pressure (of 4 MPa) and changes in temperature (of 6°C) in underground research laboratories.

Geotechnical monitoring will be required in geological repositories to determine the physical nature of the rock mass, and the rock mass response to excavation, emplacement of waste and closure of the facility (Bell, 2007). Geotechnical monitoring will contribute to confirming the host rock response to construction and operation, and thus may contribute to the demonstration of operational safety. In terms of the state-of-the-art in geotechnical monitoring recognised at the Troyes Monitoring Technologies Workshop:

- Strain monitoring using extensometers and tell-tales can now monitor millimetre-scale displacements in tunnels.
- Stress monitoring can detect the impact of the excavation on the *in situ* stress up to 100 m from the tunnel.

Surface monitoring using air-based and satellite-based systems can be used to develop an understanding of the changes to the ground as a result of repository development and to monitor for unexpected activity. Satellite-based optical imaging technology is readily available with a 50 cm resolution, and satellite-based corner reflector interferometric synthetic-aperture radar (CRInSAR) provides millimetre-scale monitoring of changes in ground elevation.

3.2 RTD on Monitoring Technologies in the MoDeRn Project

In the MoDeRn Project, RTD was undertaken on several technologies that were considered to offer the potential to improve the ability to monitor the EBS in a variety of settings. The aim was to develop the technologies so that their range of applicability was increased and to demonstrate their potential applicability as novel repository monitoring technologies. This would widen the range of monitoring technology options that programmes could consider. Technological developments and demonstrations focused on EBS monitoring, to be consistent with the overall objectives of the project (see Section 1.3).

In this section, we describe the developments to seismic tomography, micro-seismic monitoring, high-frequency WSNs, low-frequency wireless data transmission, fibre optic sensing and concrete monitoring technologies made in the MoDeRn Project. Discussion of each monitoring technology includes a high-level summary of the technology, the potential application of the technology in repository monitoring, the work undertaken in the MoDeRn Project, the results from this work, and outstanding issues that affect the potential for the technology to be applied in repositories. Further details of the R&D undertaken in the MoDeRn Project is available in the Technology Summary Report (MoDeRn, 2013e) and underlying topic reports.

3.2.1 Seismic Tomography

More detailed information on the work on seismic tomography undertaken in the MoDeRn Project is reported in MoDeRn (2013g).

Seismic Tomography

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 (Figure 3.1).

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.

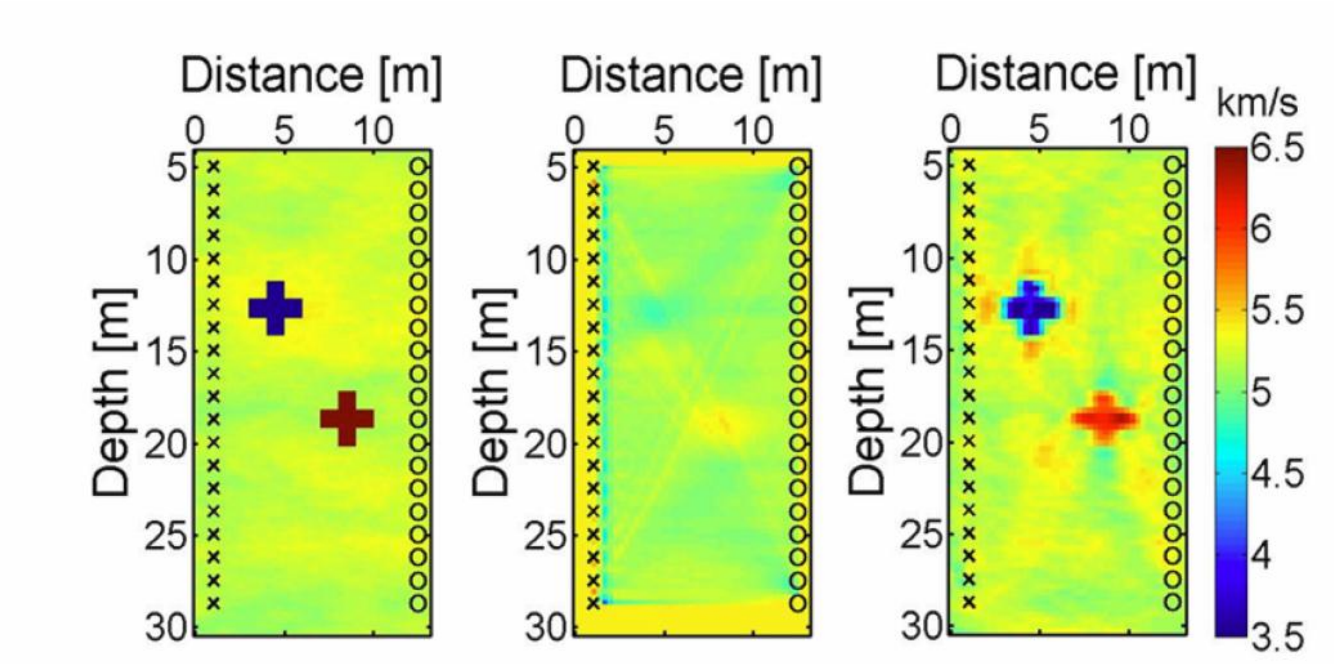

Figure 3.1: Three synthetic tomograms illustrating how seismic tomography can be used to image the elastic properties of the sub-surface. The tomograms are 2D plots of seismic velocity and show the locations of the theoretical signal sources (crosses) and receivers (circles). The image on the left is a velocity model in which two anomalies are emplaced, one low-velocity anomaly (in blue) and a high-velocity one (in red). The image in the middle is a tomogram based on travel-time tomography and the image on the right is a tomogram based on full waveform inversion.

Potential use of Seismic Tomography in Repository Monitoring

Regardless of the design of a repository, the seismic velocities within the EBS will probably be substantially lower than those of the surrounding host rock. As the EBS evolves, for example through resaturation, the generation and migration of gas, and, potentially, through displacement, the seismic signature will vary. Such variations could be detected through seismic tomography. Seismic tomography has, therefore, the potential to support the post-emplacement monitoring of the EBS.

Research into Seismic Tomography within the MoDeRn Project

In the MoDeRn Project, research into seismic tomography has focused on the monitoring of a saturation test in the Grimsel Test Site (Figure 3.2), investigations into a gas injection test in the Mont Terri URL (Figure 3.3), and theoretical developments (e.g. algorithm developments). At the Grimsel Test Site, cross-hole and hole-to-tunnel seismic methods have been employed as a means of monitoring induced changes in an artificially-saturating bentonite wall confined behind a low-pH shotcrete plug. The Grimsel test was originally constructed as part of the EC Engineering Studies and Demonstration of Repository Designs (ESDRED) Project (Bárcena and Garcia-Siñeriz, 2008). At Mont Terri, seismic tomography has been used to monitor a micro-tunnel constructed as part of an experiment assessing gas migration through the excavation disturbed zone (EDZ) (Trick *et al*., 2007, Manukyan, 2011).

The work undertaken in MoDeRn focused on full waveform inversion of seismic tomograms, because the low density of the EBS compared to the host rock means that travel-time-based methods are unsuitable - travel-time-based methods concentrate on the analysis of the first seismic waves to arrive at the receiver (first arrivals), which follow ray paths that do not intersect the EBS (as illustrated in Figure 3.1). The work included the development of techniques for improving the repeatability of the seismic measurements, developing a better understanding of the elastic properties of bentonite and the development of suitable tomographic inversion algorithms. These developments were applied to, and tested against, the experimental set-ups in Grimsel and Mont Terri.

Research Results

The research undertaken within the MoDeRn Project has significantly advanced the potential for using seismic tomography to monitor the EBS. The results can be summarised as follows:

- Experimental design: Criteria have been established for specifying the optimal spatial and temporal sampling strategies for EBS monitoring. In particular, the work has demonstrated that it is essential that the seismic signal used for tomographic imaging includes both low and high frequencies, and that these frequencies can be measured in the receivers. With regard to spatial sampling, the work concluded that the source and receiver spacing along the boreholes is not so critical for conducting elastic waveform inversions, but, instead, it is essential to have multi-component recording capabilities and, if possible, directed sources.

- Validity of the acoustic approximation: Extensive numerical experiments revealed that the acoustic approximation used to translate seismic waves into a velocity structure is not adequate for monitoring radioactive waste repositories. Elastic inversion schemes should be used instead. However, acoustic waveform inversions are the current state-of-the-art, and elastic inversions are the topic of current research and require further development.

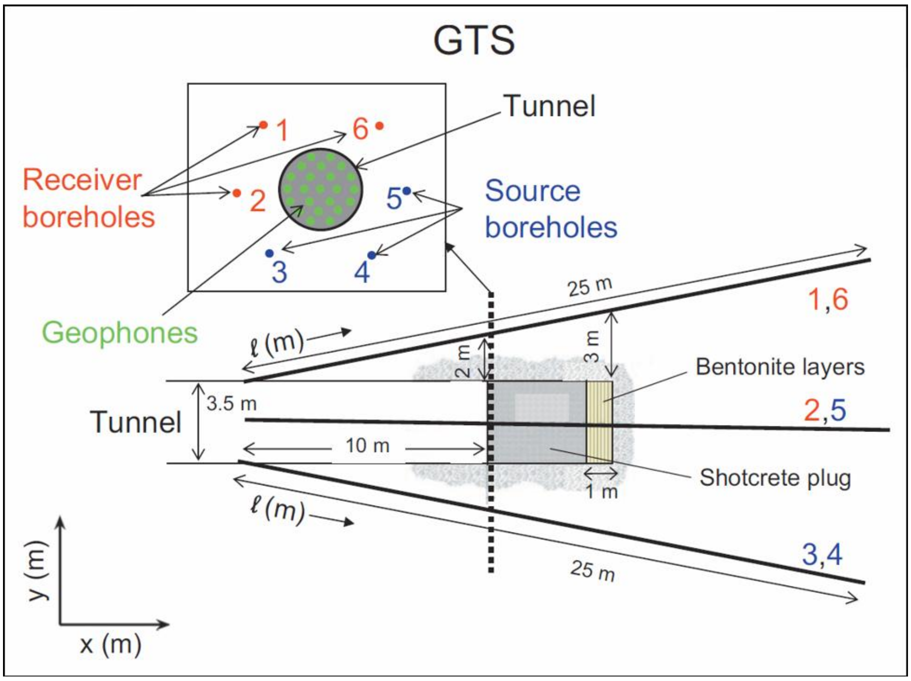

Figure 3.2: Experimental configuration of the seismic tomography test at the Grimsel Test Site. The cross-section perpendicular to the tunnel axis at the top left corner shows the relative orientations of the six boreholes (blue for source and red for receiver) and the distribution of vertical-component geophones (green dots) mounted on the outer wall of the shotcrete plug. The lower drawing shows the borehole inclinations and the relative positions of the tunnel, shotcrete plug, and bentonite layers.

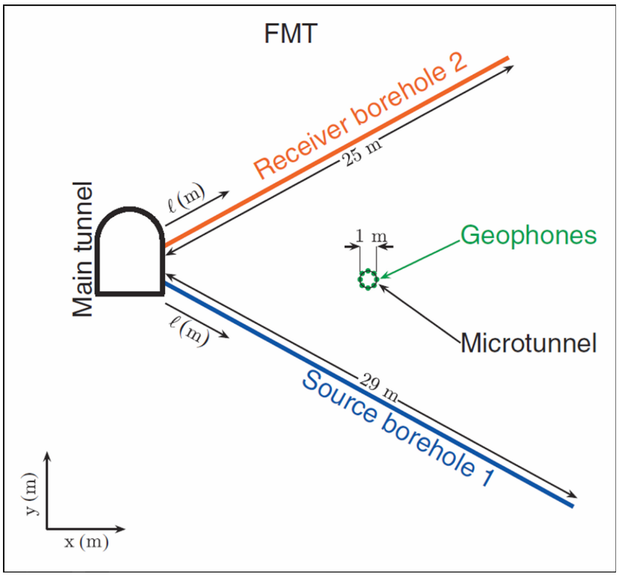

Figure 3.3: Experimental configuration of the seismic tomography test at the Mont Terri URL. Two boreholes extend from the side of the main tunnel (blue for source and red for receiver). Vertical component geophones (green dots) are rigidly mounted equidistant around the monitored micro-tunnel.

- Non-linearity issues: The mathematical formulation used to transfer the seismic waveform information into a velocity model is highly non-linear, and it is therefore challenging to develop algorithms to undertake the necessary calculations. The work in the MoDeRn Project has identified where currently-available algorithms are expected to be successful and when they are likely to fail. Furthermore, the potential for undertaking successful translation of the seismic waveforms to a velocity model depends on the availability of *a priori* information, i.e. a detailed velocity model for the area of interest acquired before the monitoring of changes is undertaken. Acquisition of a detailed velocity model is considered feasible for dedicated repository tomographic monitoring. It has been shown that non-linear effects increase when the contrast between the velocity of the EBS and the host rock is more pronounced. This means that non-linear issues are more challenging in a granitic host rock, compared with a clay environment, as the seismic velocity of granite is higher than clay.
- Anisotropic inversions: Suitable host rocks may exhibit a high degree of anisotropy, for example the layering within sedimentary rocks can impose a strong anisotropy parallel to bedding. The algorithms used to convert seismic signals to a tomographic image need to account for the anisotropy, and such algorithms were not available prior to the MoDeRn Project. Anisotropic and elastic waveform algorithms have been successfully developed, and initial synthetic inversions have been undertaken to demonstrate the suitability of using these new algorithms for monitoring sedimentary rocks using seismic tomography.
- Coupling problems: Sensor coupling to the host medium is a critical issue. An algorithm has been developed and successfully tested and can be used to reliably determine the coupling factors. In addition, practical work undertaken within Mont Terri has demonstrated that only firmly grouted geophones that are cemented into boreholes allow seismic signals to be captured with sufficient accuracy to allow full waveform inversions to be undertaken. Although the coupling problem persists when geophones are grouted into boreholes, the coupling factors are constant, and, therefore, the algorithm developed within the MoDeRn Project can be used to overcome this problem.

These results have been published in several journals, all of which are referenced in the detailed report on the seismic tomography work (MoDeRn, 2013g) and in two PhD theses (Manukyan, 2011; and Marelli, 2011).

Further Research Requirements and Potential Application

The work on seismic tomography in the MoDeRn Project has illustrated the potential feasibility of monitoring the EBS using full waveform elastic inversions of the recorded seismic waveforms. However, acoustic waveforms are the current state-of-the-art, and further development of the elastic method is required. At present, seismic tomography techniques have progressed sufficiently to be confident that velocity changes within an EBS can be monitored. However, further work is required to relate velocity changes to specific processes, i.e. to allow the measured changes to be related to saturation, gas generation, thermal expansion or other near-field processes. In addition, consideration would need to be given in the safety case for the possible influence of backfilled monitoring boreholes close to the EBS, i.e. whether there could be sufficient confidence in their sealing so that they would not be considered as a radionuclide migration pathway in the safety assessment. Further consideration of equipment reliability and durability is also required.

3.2.2 Micro-seismic Monitoring

More detailed information on the work on micro-seismic monitoring undertaken in the MoDeRn Project is reported in MoDeRn (2013i).

Micro-seismic Monitoring

Micro-seismic events are localised seismic phenomena that can originate spontaneously during stress release (or build-up) in the rock mass, for example after an excavation, and are the result of the mechanical response of the rock. They can also originate during the emplacement of the waste or be induced manually by generating small seismic oscillations using a hammer or another type of signal-generating source against the rock mass. Seismicity also results from the sudden release of accumulated strain energy during the initiation and propagation of discontinuities in rock (e.g. joints, fractures and faults). The frequency of the emitted seismic signals typically ranges from less than 1 Hz (infrasonic) to 1 MHz (ultrasonic), with the characteristic frequency of the events being dependent upon the scale of the event occurring at the rupture surface and the seismic properties of the rock mass.

Potential use of Micro-seismic Monitoring in Repository Monitoring

Micro-seismic monitoring may allow monitoring of the near-field response to waste and EBS emplacement. This monitoring could be undertaken prior to the closure of the access ways and service areas in the repository.

Research into Micro-seismic Monitoring within the MoDeRn Project

Around the PRACLAY Gallery in the HADES URL, a network of piezo-electric sensors (sources and receivers) has been installed to monitor the micro-seismicity in the Boom Clay rock mass. The sensors are installed both in the near field around the PRACLAY gallery and at the interface between the Boom Clay and the concrete lining (Figure 3.4). By monitoring the seismic properties of the host rock, this network enables the assessment of the host rock quality, and its evolution in response to different events (e.g. gallery excavation and lining construction, ventilation, resaturation and heating).

The existing monitoring network, which was installed in 2006, has generated and recorded microseismic signals on a daily basis since 2007 using a series of piezoelectric ceramic sensors as transmitters and receivers. These sensors operate at high frequencies, above 5 kHz, which are quite suitable to generate and record primary (P) waves but not the low frequency secondary (S) waves. These propagate predominantly in the frequency range between 1 and 1000 Hz. By including the shear waves in the analysis of the micro-seismic signals, more information on the rock quality would become available.

The new seismic hammer will generate predominantly low frequency signals in the range of 1 to 1000 Hz. These signals cannot be efficiently recorded with the currently installed piezo-electric receivers due to their characteristic high background noise at frequencies generally below 5 kHz. For this reason, a suitable type of piezoelectric transducer or accelerometers, which operate in the frequency range between 1 and 1000 Hz, will be installed to record the signals generated by the new seismic hammer.

Research Results

Within the MoDeRn Project, the new shear wave hammer was designed and a prototype developed and tested. Typical time series and frequency content measurements using the current setup in the HADES URL are illustrated in Figure 3.4. They clearly show the high frequency content spectrum of the measured signals obtained with the current piezoelectric sensors. Figure 3.5 illustrates signals generated in the Boom Clay using an impact hammer of the type similar to the one being developed for the new source. They clearly show the distinct S wave signal and the accompanying low frequency range obtained with the hammer system.

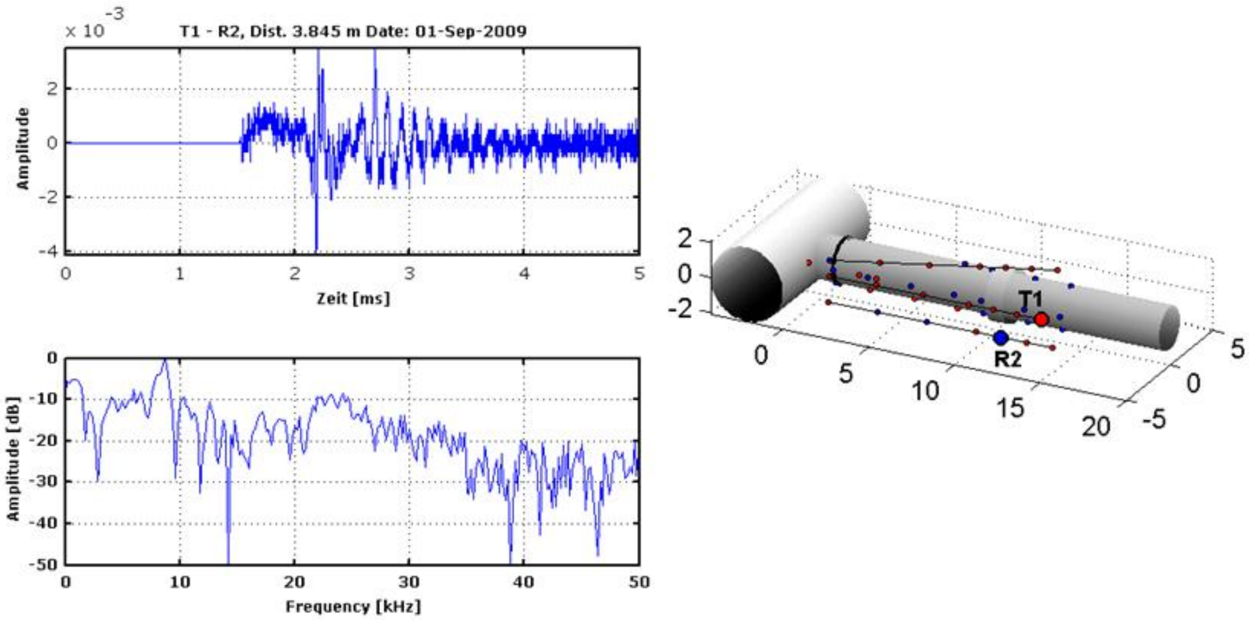

Figure 3.4: Typical time (top) and frequency spectra (bottom) obtained with current piezoelectric sensors in HADES between receiver R2 and transmitter T1. This illustration also shows the location of transmitters and receivers installed in 2006 in three boreholes around the PRACLAY test gallery, and in 2008 at the interface between the Boom Clay and the concrete lining of the PRACLAY gallery. Transmitters are coloured red and receivers are coloured blue.

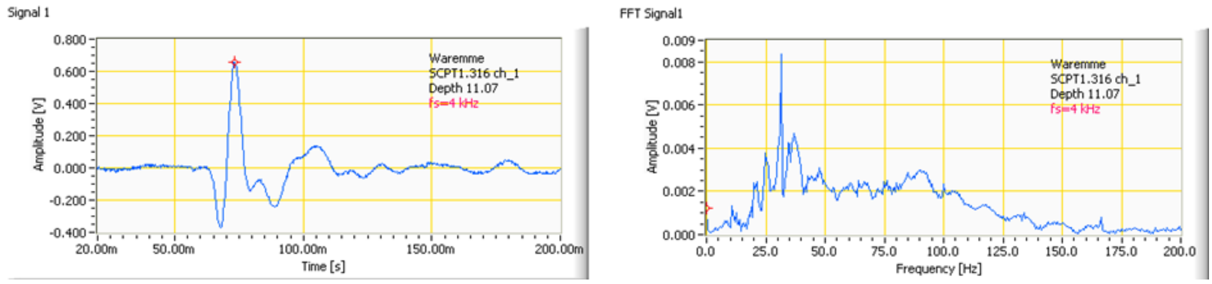

Figure 3.5: Typical time series (left) and frequency spectra (right) obtained in the Boom Clay with an impact hammer similar to the one developed for the new hammer.

Further Research Requirements and Potential Application

The micro-seismic monitoring programme will continue throughout the PRACLAY heater test programme and will provide valuable learning on the use of the newly designed seismic hammer. Continued experience with the recently developed seismic hammer will enhance the ability to generate strong S wave signals to improve shear wave monitoring and continue to provide information on changes to the EDZ as the heating experiment progresses.

3.2.3 High-frequency Wireless Sensor Networks

More detailed information on the work on high-frequency WSNs undertaken in the MoDeRn Project is reported in MoDeRn (2013f and 2013h).

High-frequency Wireless Data Transmission

Development of wireless data transmission methods would allow for data measured by sensors emplaced within the EBS to be relayed to receiving stations, and would, therefore, represent a method for monitoring the EBS without the need for data transmission using wires. The sensors that could be emplaced within the EBS would be based on traditional technologies, with adaptations to reflect the anticipated environmental conditions. Measurable parameters could include, for example, pressure, temperature and humidity.

There are several well-recognised limitations in applying wireless data transmission to repository monitoring. One important limitation, owing to the remote nature of the measurement devices and the long period required for monitoring repository systems, is the need to consider an autonomous power supply to the sensors and to the transmission units.

High-frequency wireless data transmission considers transmission of data in the very-high frequency (VHF) and ultra-high frequency (UHF) bands. These wave bands have a higher data rate capability than lower frequency wave bands, which results in shorter transmission times and lower power consumption. However, the penetration of data through rock at high-frequencies is much lower than for data transmitted at low frequencies. Low-frequency data transmission has also been a subject of research within the MoDeRn Project (see Section 3.2.4).

Potential use of High-frequency Wireless Data Transmission in Repository Monitoring

Given the low penetration rates achievable for the transmission of data through rock at high frequencies, the potential use of this technology is mainly focused on monitoring of the near field following emplacement of the waste and EBS, prior to the closure of the access ways and service tunnels. However, this technology could also be used following closure of the access ways and tunnels, provided appropriate methods for relaying the monitoring information were developed.

Research into High-frequency Wireless Data Transmission within the MoDeRn Project

Initial work under this programme focused on designing appropriate wireless nodes by evaluating, at different frequencies, the distances through which remote transmission could be achieved for a range of solid media, and the capacity and rate for transmitting data at those frequencies relative to energy requirements. A range of theoretical, laboratory and site-specific work was undertaken (see below).

The research and demonstration activities aimed at demonstrating, under realistic conditions, the potential for underground use of high-frequency wireless nodes as components of monitoring networks. The wireless nodes would incorporate conventional sensors and transmission units, which could potentially be placed within the EBS of the repository. The research and demonstration work also considered the supply of the corresponding energy needs for operating the wireless nodes in an inaccessible location over decades.

The aim was to develop high-frequency wireless data acquisition and transmission nodes capable of incorporating up to four conventional sensors, providing the integral power supply and gathering the data remotely from all of them. The data obtained by the high-frequency wireless nodes would be transmitted to an open gallery and integrated into an existing data monitoring and control system. The data trends would be reported and compared with conventional hard-wired monitoring systems that were already installed at the test site.

The wireless nodes were designed and tested on the same shotcrete plug at the Grimsel Test Site that was used for the demonstration of seismic tomography (see Section 3.2.1, Figure 3.2). This test comprised the installation of five high-frequency wireless nodes, two of them installed in the bentonite buffer through boreholes drilled in the shotcrete plug, and three more units located in boreholes drilled in the shotcrete plug and the rock mass. The parameters measured were pore pressure, total pressure and water content.

The primary purpose of the test was to evaluate the performance of high-frequency wireless networks in transmitting data from the sensors to the control system, and the expected data life when using batteries as an energy source under realistic conditions. Additionally, the feasibility of power harvesting to conserve the power source (battery) and to extend the period of monitoring was also evaluated.

Research Results

The transmission distances for high-frequency signals at four frequencies were tested in the laboratory, and in the field (at the El Cabril low-level radioactive waste disposal facility and the Tournemire URL). The frequencies tested were 2.4 GHz, 868 MHz, 433 MHz and 169 MHz. In laboratory tests, signals at 868 MHz and 433 MHz were capable of passing through 50 cm of bentonite, 25 cm of salty water and 40 cm of argillite rock; transmission distances at 2.4 GHz were lower. Field tests demonstrated that transmission distances at 169 MHz were greater, about 3.5 m in clay-based rocks and greater than 5 m in saturated bentonite, and this frequency was adopted for the demonstration tests in the MoDeRn Project.

Research into power supply considered energy harvesting using thermal gradients and high-performance batteries. Thermal gradients can be used as a power source, based on the Seebeck effect (van Herwaarden and Sarro, 1986), which describes the voltage created when there is a temperature gradient across two semi-conductors. A temperature difference of 15°C would be sufficient to provide a power of 1,100 µW, which is comparable to the long-term power requirements of high-frequency wireless nodes. However, data would be transmitted periodically in bundles, and, therefore, the energy required to transmit the data must be stored. Existing super capacitors have leakage rates of the same order as the power that could be generated. Therefore, harvesting of thermal gradients is not currently viewed as a feasible method for the supply of energy to wireless nodes. Instead, the wireless nodes developed for the MoDeRn Project used a Li-$SOCl_2$ battery combined with some high performance capacitors. The final design for the nodes used is for a small self-contained device with an expected lifetime up to 20 or 25 years. The node is illustrated in Figure 3.6.

In the tests carried out to date, the wireless nodes have acquired and transmitted the same amount and quality of data as sensors using traditional wires.

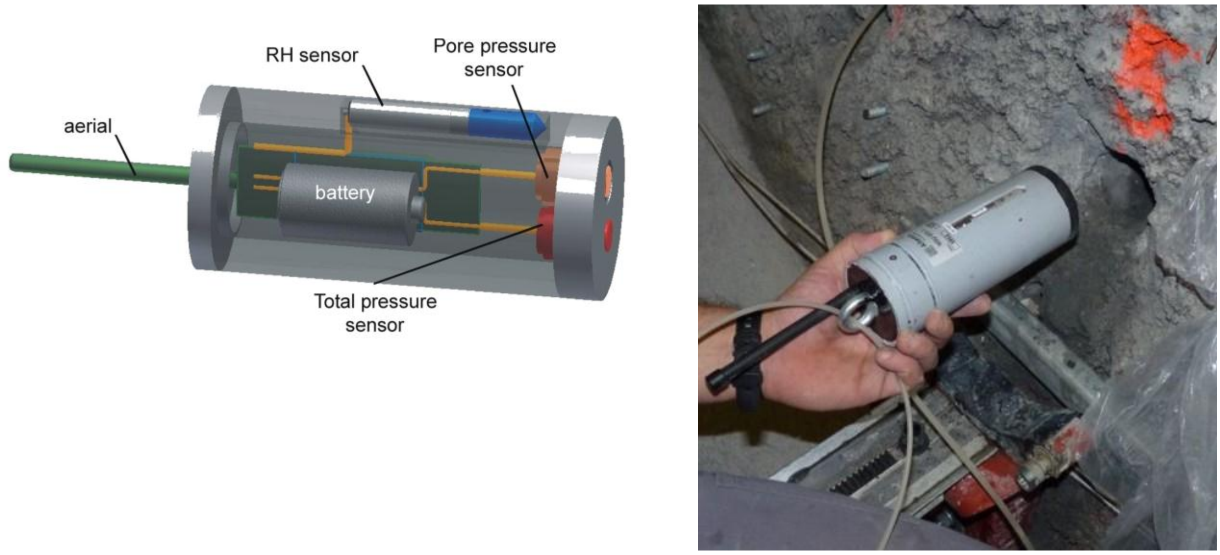

Figure 3.6: Illustration of the node developed for measurement of pore pressure, total pressure and water content, and high-frequency transmission of the measured data. The illustration on the left shows the design of the node, and the illustration on the right shows the installation of one of the nodes in the Grimsel Test Site.

Further Research Requirements and Potential Application

The acceptability of placing wireless nodes within the EBS would need to be assessed within the post-closure safety case before it could be regarded as a feasible technique. There are several issues that might need to be addressed, depending on the disposal concept. These might include consideration of the impact that corrosion products could have on the performance of engineered barriers (over and above the impact that corrosion of waste packaging material and repository infrastructure would have), and the ability to emplace the nodes without affecting the quality of the engineered barriers. As well as addressing these issues from a safety case perspective, technological developments such as miniaturisation and use of corrosion-resistant materials could be addressed in further work.

Other research requirements identified during the MoDeRn Project include specific technical developments:

- Investigation and development of new methods for harvesting and, importantly, storing energy, in order to extend the lifetime of high-frequency wireless nodes.
- Incorporation of additional types of sensors to the nodes to extend the range of parameters that could be monitored.
- Identification of any requirements for development of the use of wireless nodes in high radiation fields and provision of solutions for the identified requirements, e.g. provision of shielding if required.
- Improvement in the reliability and redundancy of some components to extend the expected lifetime of the nodes.

- Improvement of the transmission range and reliability by enhancing the approach to data transmission (for example improved transmission antenna, use of directional aerials for data receipt and optimised communication protocols).

These improvements could be extrapolated to similar short range data transmission systems such as the systems proposed in the KBS-3V case study (see Section 4.4).

In addition, there have been several theoretical solutions proposed for transmission of data from repositories to the surface. These include signal hopping (relaying data through media by using a series of appropriately placed wireless nodes) and coupling of high-frequency systems with long-range, low-frequency data transmission systems. Whilst, in theory, these approaches appear feasible, practical demonstration of these approaches has not yet been undertaken. Practical demonstration is required to identify problems limiting the practical use of such systems in operating repositories and to identify solutions to these challenges. Demonstration would also support optimisation of the approaches envisaged.

3.2.4 Low-frequency Wireless Data Transmission

More detailed information on the work on low-frequency wireless data transmission undertaken in the MoDeRn Project is reported in MoDeRn (2013j).

Low-frequency Wireless Data Transmission

Work on low-frequency wireless data transmission within the MoDeRn Project has investigated the transmission of data using low-frequency magneto-induction techniques. The use of low-frequency fields overcomes problems with strong signal attenuation by solid media that occur with high-frequency data transmission. In magneto-induction, magnetic fields are generated by a loop antenna that propagates in all directions through the host rock or elements of the EBS. This provides a potential method for transmitting signals through plugs, seals and dams, between different parts of a repository or from the repository to the surface.

Signal attenuation (and hence transmission distances) at low frequencies mainly depend on the electrical conductivity of the media through which the signal is transmitted; signal attenuation is higher for media with a high electrical conductivity as more eddy currents and secondary fields are induced. This is of importance when considering the application of this technology because the electrical conductivity of geological media can vary significantly. Typical values for electrical conductivity range from µS/m to mS/m in rock salt and crystalline rock, and from mS/m to S/m for argillaceous rocks. This variation is linked, in part, to the water-filled porosity of a geological media, which has a significant influence on the electrical conductivity (ground water conductivity is about 0.5 S/m).

Potential use of Low-frequency Wireless Data Transmission in Repository Monitoring

Low-frequency wireless data transmission techniques can potentially be used to transmit data over small, medium and large distances (i.e. from distances of several metres to distances of several hundred metres). The main advantage of using low-frequency techniques is the low attenuation of the transmission signal by the host rock or elements of the EBS. For post-closure monitoring, low-frequency wireless data transmission could be a key technology for transferring data from the repository to the surface.

As with high-frequency data transmission, application of such monitoring faces technical challenges, including optimisation of the energy efficiency achievable by the technique, the provision of energy for generating the signal, the use of suitable modulation and error detection methods for a certain frequency range, and the long-term durability and reliability of components of the system. Transmission of low-frequency electromagnetic fields also has the added challenge of overcoming localised sources of electrical interference.

Research into Low-frequency Wireless Data Transmission within the MoDeRn Project

In the MoDeRn Project, the development of low-frequency wireless data transmission technologies focused on testing the ability to transmit data over a large distance, i.e. from a repository to the surface, within the specific context of post-closure monitoring. Experiments were performed in the HADES URL (Figure 3.7), and were supplemented by desk-based analysis and small field tests. Because the supply of energy over long periods in the post-closure phase is assumed to be a limiting factor, the specific objective was to characterise and optimise the energy use of this technique. It was expected that this would allow an assessment of the general feasibility of long-term wireless data transmission from a repository to the surface through the Oligocene Boom Clay and overlying aquifers. Owing to the high electrical conductivity of the Boom Clay and the overlying aquifers at the Mol site, they were expected to attenuate the magnetic fields more strongly than other host rocks e.g. granite, salt rock or the Jurassic clays envisaged as repository host rocks in France and Switzerland. Therefore, the results from the work would be broadly applicable to a large range of potential repository sites. The research also aimed to understand what external factors (e.g. background noise) may need to be taken into account when using low-frequency wireless data transmission.

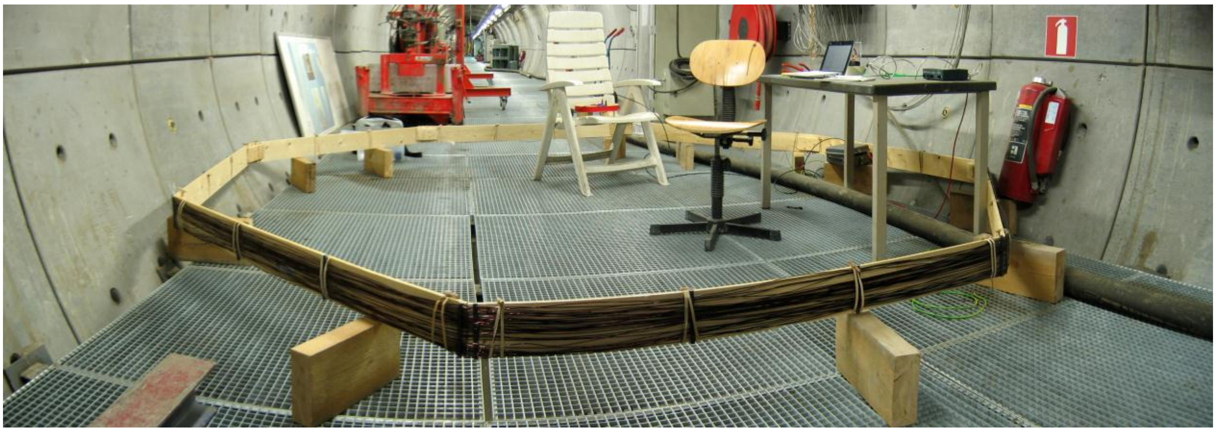

Figure 3.7: One of the transmitter antenna (the loop placed on the wooden blocks) used for testing low-frequency data transmission in the HADES URL.

Research Results

The key result of this part of the MoDeRn Project is that data transmission over long distances through the underground by magneto-induction techniques is possible. The research was successful in demonstrating wireless transmission of data through 225 m of an electrically highly-conductive geological medium, at frequencies up to 1.7 kHz, using antennae with a radius of approximately 3.5 m. The optimum data transmission channels were between 1.4 kHz and 1.7 kHz. Data transmission was achieved at several frequencies with data rates up to 100 sym/s and bit error rates below 1%.

Energy requirements for the experimental set-up were higher than what can be expected under more favourable circumstances, because experimental conditions at the Mol site were not optimal with respect to three features:

- The size of the transmitter antenna was limited to 3.5 m by the diameter of the HADES URL (Figure 3.7), leading to an antenna aperture far below optimum. In repository situations, incorporating a large loop antenna within larger diameter service areas, or across several tunnels, would significantly improve the performance of this technique.
- There are several on-site and off-site power lines in the vicinity of the HADES URL that could not be avoided through experimental set-up (the lateral distance to the power lines could not be increased to more than 50 m). These create strong electrical interferences on the surface above the HADES URL, and significantly affect data reception.
- Experimental work in the HADES URL is performed during the day, leading to additional strong transient interferences (e.g. by passing cars and operation of the shaft lift). It might be feasible to avoid such interferences in a repository following closure.

The lowest energy use realised in the HADES URL was about 1 Ws/bit, but in a real disposal situation the set-up could be significantly optimised, and it is expected that lower energy use could be demonstrated. For example, with a transmission antenna with a radius in excess of 75 m, an energy use below 1 mWs/bit should be achievable.

Estimation of the energy requirements for two application cases was performed: the generic Dutch disposal concepts in Boom Clay and rock salt, situated 500 m and 800 m below ground respectively. Based on the demonstrated performance and analyses of the underlying processes, it was estimated that transmission of monitoring data to the surface can be realized with about 1 mWs of energy per bit of transmitted data for both cases. This would allow transmission of 1,000 sensor readings, with 1% precision, on a weekly basis for 100 years with the energy equivalent of two cell phone batteries. Results of the quantitative analyses are transferable to other host rocks, as long as the subsurface can be assumed to be (only) horizontally stratified and no magnetic permeable layers are present (i.e. no strata containing significant quantities of iron).

Further Research Requirements and Potential Application

There are several issues that have to be considered and/or developed further to facilitate deployment of low-frequency data transmission as a standard data transmission technique:

- Estimation of the energy requirements of low-frequency data transmission systems would benefit from better estimates of the amount of data that may need to be transmitted post-closure, and clarification of the possible duration of post-closure monitoring. Planning and design would need to consider the energy requirements for both sensors and data transmission systems.
- Several techniques for supply of electrical power over extended periods of time (several decades) have been suggested (see Section 3.2.3), but there is no mature technology for long-term power supply at present. Further research is therefore required in this area with specific reference to the requirements for transmission of data using low-frequency magneto-induction techniques.

- Additional work is required to provide information on the long-term durability/reliability of components of transmission system. The work on low-frequency data transmission in the MoDeRn Project has been developed using an experimental set-up and the real application will require development of durable components and system, particularly with respect to the reliability of underground transmitters.
- The frequency range used in the experiments is vulnerable to natural and man-made electromagnetic interferences, and it will therefore be important to understand the site-specific impact of sporadic loss of data and the potential ability to employ countermeasures at any specific site, recognising the balance between system simplicity and data requirements.
- Envisaging wireless transmission of data over long distances as only one element of an overall conceptual monitoring infrastructure, several other open topics were identified, including:
    - How (different) wireless data transmission techniques on different scales can be coupled, and how energy supply to these units in the pre- and post-closure phase can be managed.
    - How energy distribution should be organised and how efficient 'hibernation' states can be achieved.
    - Whether data would be transmitted on demand or at predefined intervals.
- The advantages of providing a bidirectional data link between the underground repository and the surface should be considered, recognising the increased complexity of the monitoring system. A bidirectional link would allow the monitoring system to be controlled from the surface, for example, to change the data acquisition rate.

3.2.5 Monitoring using Fibre Optic Sensing

More detailed information on the work on monitoring using fibre optic sensing undertaken in the MoDeRn Project is reported in MoDeRn (2013i) and MoDeRn (2013k).

Fibre Optic Sensing

Fibre optic sensors have been described in Section 3.1. Optical fibres can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fibre so that the quantity to be measured modulates the intensity, phase, polarization, wavelength or transit time of light in the fibre. Data can also be collected from unmodified optical fibres from the backscattering of light out from the fibre. Three scattering modes can be used to monitor different parameters. Raman scattering (using multimode fibres) can be used to monitor temperature. Brillouin and Rayleigh scattering (using single mode fibres) can be used to measure strain and temperature over large distances (Rogers, 1999; Lanticq *et al.*, 2010).

The interpretation of data acquired using optical fibres is based on calibration against known responses to parameter changes. This requires determination of optical fibre characteristics (e.g. shifts in the intensity and frequency of the light as a function of change in temperature and strain), and assessment of installation-related issues. Each installation has its own characteristics, such as the way the fibre is fixed, the number and quality of splices (connections), and the type of connectors. Partly, the calibration can therefore be performed by the manufacturer before the installation, but to achieve the full potential of accuracy, an *in-*

situ calibration is required. This is usually performed by adding classical temperature sensors, such as Pt100 sensors[3] or thermocouples, next to the fibre at specific locations.

Potential use of Fibre Optic Sensing in Repository Monitoring

Optical fibres may be selected for monitoring because of the small size of the fibres and because of their inherent multiplexing capabilities - many sensors can be combined along the length of a fibre by using different wavelengths of light for each sensor, or by sensing the time delay as light passes along the fibre through each sensor. These qualities make optical fibres suitable for repository monitoring; they provide an efficient means of monitoring a range of parameters. The principal application for fibre optic sensors in repository monitoring is the measurement of parameters such as strain, pressure and/or temperature within the near field. Fibre optic sensors provide distributed monitoring and, as such, would be suitable for monitoring the 3D parameter-field rather than the single location measured by traditional measurement devices.

However, monitoring data acquired using optical fibres is typically transmitted using wires, but data acquired through the use of optical fibres following emplacement of waste and backfilling of emplacement areas should be transmitted by wireless systems to ensure pathways are not created through key parts of the EBS (e.g. plugs and seals), and specific strategies would require development to ensure that the deployment of optical fibres did not affect the safety functions of the barriers being monitored.

In addition, power is required to generate the light source used with the sensors. Laser-based fibre optic sensors have high power consumption and are therefore not generally considered useful for monitoring the EBS following waste emplacement. Light-emitting diodes (LEDs) have lower power consumption and are generally regarded as more appropriate for repository monitoring, even though commercially available fibre optics currently all use lasers.

Alternatively, optical fibres could be emplaced in repositories in which pre-closure management was used to keep the option for retrievability open, and monitoring of the emplaced packages was used to optimise the design applied later in the programme (see discussion of the illustrative programme for monitoring of HLW disposal cells in the French geological disposal concept in Section 4.3).

Research into Fibre Optic Sensing within the MoDeRn Project

Research into optical fibres within the MoDeRn Project has been undertaken within the research, development and demonstration programme associated with the PRACLAY Heater Test in the HADES URL in Belgium and during the development of technologies for monitoring the concrete Supercontainer[4].

The PRACLAY Heater Test is a demonstration at near-real scale of the thermal effects of emplacing high-level waste (HLW) in a gallery constructed in a clay host formation (the Boom Clay). The thermal-mechanical response of the PRACLAY gallery will be monitored using a distributed fibre optic monitoring system emplaced on the inside of the PRACLAY

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[3] A Pt100 sensor is a temperature sensor, in which temperature is calculated by measuring the resistance of a platinum element.

[4] In addition, the use of optical fibres has been demonstrated in an integrated monitoring test undertaken in the Bure URL in France. The test in Bure is reported in Section 4.3.

gallery (Figure 3.8). The main phase of the Heater Test – the heating itself – has not yet started as the gallery seal has not yet obtained the required hydraulic conductivity and swelling pressure owing to an unexpectedly slow rate of hydration and swelling of the bentonite.

The system inside the PRACLAY Gallery consists of a distributed temperature sensor (a 55-m-long fibre inside a capillary tube) and three 10-m-long fibre optic deformation sensors placed in series to measure the axial deformation of the PRACLAY Gallery. In addition, three boreholes drilled perpendicular from the PRACLAY Gallery (one upward, one horizontal and one downward) have been equipped with fibre optic sensors to determine the axial strain (due to thermal expansion caused by heating of the PRACLAY Gallery) along each borehole.

The fibre optic sensors are based on the SOFO gauge system (Inaudi *et al*., 1999). A SOFO gauge consists of two fibres inside protective tubing, with one fibre being attached to two anchor points at both ends of the tubing, and another fibre of similar length which is loose inside the tubing – it is expected that the length of the latter fibre will not be influenced by the change of length between the anchor points, but only by temperature, making the sensor inherently temperature compensated. The difference in strain measured along each fibre can then be calculated by interferometery.

Optical fibre gauges were selected because of the high water pressure and temperature near the gallery wall, and previous failures of conventional borehole extensometers inside a plastic clay environment. Two boreholes, both of which are 20 m long, contain three SOFO gauges (two 5-m-long sensors and one 10-m-long sensor at the far end of the borehole) to obtain multiple strain measurements. The other borehole, which is 10 m long, contains just the two 5-m-long SOFO gauges.

The aim of this work was to improve our understanding of the use of optical fibres for this technique and to investigate what adaptations might be required for this type of sensor.

Figure 3.8: Installation of a distributed fibre optic monitoring system inside the PRACLAY Gallery.

Monitoring of the Belgian Supercontainer during a half-scale test is described in the next section (Section 3.2.6). The use of fibre optics to measure strain in three orthogonal directions (parallel and perpendicular to the longitudinal axis of the Supercontainer, and tangential to it) as well as temperature in the concrete buffer and filler has been extensively applied in the second half-scale test. The methods include both distributed and semi-distributed Fibre Bragg Grating (FBG) fibres, each with and without fibre protective reinforcement.

Research Results

During the testing of the SOFO gauges, two of the nine sensors failed. One of the sensors failed during installation, and another during the subsequent works in the gallery. Both failures are however located in the connecting fibre, and not in the measurement part of the gauge. No installation procedures were available from the manufacturer for installation of the SOFO gauges in this type of setting, and, therefore, an in-house installation procedure had to be developed. This indicates that generic installation procedures need to be prepared for this novel type of sensor for repository monitoring.

The measurements that have been obtained so far using the SOFO gauges in the three boreholes show that these sensors are able to quantify displacements with a resolution of 1 µm. Based on other quality factors, such as repeatability, the expected accuracy of this system in general can be estimated to be less than 10 µm over 10 m. This would allow monitoring of strain with an accuracy assumed to be appropriate for repository monitoring.

The use of fibre optics to monitor temperature and strain in the three orthogonal directions in the half-scale test have demonstrated its potential as an *in-situ* monitoring technology that generates very little disturbance and limited intrusion to the surrounding concrete structure being monitored. However, the measurement instruments needed to interrogate the fibres require direct access to the fibres. This means that the fibres will need to penetrate the structure, a condition that could limit its applicability as monitoring technology in a repository.

Further Research Requirements and Potential Application

Regarding distributed sensing, the optical fibre monitoring techniques show a lot of potential. Optical fibre technology can be considered as mature – and fibres are now omnipresent in communication applications. When used for repository monitoring however, calibration appears to be the most relevant issue. In theory, high accuracies with elevated spatial resolution (typically far better than a metre) can be obtained, but this requires a comprehensive knowledge of processes that affect the response of the fibre to the target parameter. For the combined strain/temperature principles, distinguishing between both parameters can be problematic, as a stress-free installation usually cannot be guaranteed.

Research is currently very active in this domain, and efforts are underway to apply a hybrid Brillouin/Rayleigh system in order to try to obtain both temperature and strain from a single fibre.

There are many designs for the outer coatings of fibres. These should be adapted to the environment to offer sufficient ruggedness (e.g. strong enough to resist installation manipulations), without affecting the sensing characteristics. The performance of optical fibres will depend in part on the way it is installed. Further understanding of installation procedures is therefore required, not only to avoid damages of fibres and connectors during installation, but also to develop confidence in the measurement results.

3.2.6 Supercontainer Monitoring Technologies

More detailed information on the work on supercontainer monitoring technologies undertaken in the MoDeRn Project is reported in MoDeRn (2013i).

Monitoring of the Belgian Supercontainer

The Supercontainer is the Belgian reference concept proposed by ONDRAF/NIRAS, for the packaging of HLW and spent fuel (ONDRAF/NIRAS, 2009; 2010). It is based on a multiple barrier system that includes an outer steel envelope, a concrete buffer and a water-tight carbon steel overpack containing one or more waste canisters.

The long-term safety function of the overpack is to contain the radionuclides during the thermal phase, which will last several thousand years. One of the long-term functions of the concrete buffer is to provide a high-alkaline chemical environment that favours the formation of a tightly adhering passive oxide film on the external surface of the carbon steel overpack, which protects the underlying metal. The presence of the oxide film is believed to result in negligible and uniform overpack corrosion rates. In order for the safety functions to be achieved, the concrete buffer should not contain through-going cracks.

In order to demonstrate the feasibility of Supercontainer construction, one half-scale test (HST1) has been performed (Areias *et al.*, 2010) and another is being undertaken in 2013 (HST2). The half-scale tests have true diameter scale, but they are limited in height to approximately half of a real Supercontainer.

The second half-scale test is being extensively monitored, as illustrated in Table 3.1.

Table 3.1: Monitoring parameters and instrumentation in HST1 and HST2.

Instrumentation	Parameter	HST1	HST2
Thermocouple	Temperature	X	X
Strain gauges (including vibrating wire gauges)	Strain	X	X
LVDT (Linear Velocity Displacement Transducer)	Displacement	X	X
Anemometer	Wind velocity	X	X
Humidity TDR probe	Moisture content	X	X
DIC (Digital Image correlation)	Onset and evolution of cracking		X
AE (Acoustic Emission)	Crack formation		X
Total pressure sensor	Total pressure		X
Fibre optics	Temperature, axial and radial strain		X
Oxygen sensor	Oxygen flux		X
Reference electrode	Corrosion potential		X
Corrosion sensor	Corrosion rate		X

Monitoring of both of these experiments has partly been undertaken within the framework of the MoDeRn Project, in particular the development and testing of:

- Digital Image Correlation (DIC): DIC is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images. This is often used to measure deformation (engineering), displacement and strain, and is widely applied in many areas of science and engineering, for example Lecompte *et al.* (2009); Lecompte (2007); Sutton *et al.* (2009); and Aggelis *et al.* (2013).

- Acoustic Emission (AE) Monitoring: AE techniques are widely used in mining, tunnelling and hydro fracturing projects to monitor crack location, density, development and evolution. AE can track changes in the depth and mode of the cracks in concrete structures (Aggelis *et al.*, 2013) when sensors are located in a 3D pattern. Crack depth can also be measured by one-sided ultrasonic test (UT) measurements since the travel time of the excited wave increases due to the discontinuity created by the crack along the wave travel path (Doyle and Scala, 1978). Cases that demonstrate the use of AE to monitor the evolution of cracks in concrete include Doyle and Scala (1978) and Robeyst *et al.* (2009).

- Corrosion Sensors: Corrosion sensors typically detect metal corrosion through changes in the electrical current of the medium of interest. The corrosion rate can be estimated through measurement of the voltage or current between a reference electrode and the metal being monitored. Corrosion sensors are frequently applied in the field to measure corrosion activity of gas and oil pipelines and offshore structures, and to monitor corrosion activity of embedded reinforcement bars in concrete.

Potential use of Supercontainer Monitoring in Repository Monitoring

The techniques developed and tested within the framework of the MoDeRn Project have the potential to support repository monitoring in the following ways:

- DIC: This technique could be used to monitor for the onset and evolution of cracks in general and in particular within the supercontainer prior to backfilling, and, should spaces in the repository not be backfilled, over the long term. However, such monitoring needs access to the object being monitored and would need to be developed to be suitable for installation in the small annulus available around the Supercontainer when emplaced in a disposal tunnel or would require changes to the reference design (e.g. use of a larger annulus around the Supercontainer to provide space for DIC monitoring).

- AE Monitoring: AE could be used to detect micro-seismic activity, and crack location, density, initiation and propagation in concrete. This would require the placement of accelerometers in suitable locations around the emplacement tunnel, most probably in boreholes, but the accelerometers can also be cast directly into the concrete. In the case of boreholes, the potential impact of such boreholes on the containment functions of the near-field rock would have to be assessed before AE monitoring could be considered feasible.

- Corrosion Sensors: Corrosion sensors could be used to undertake *in situ* monitoring of the corrosion of disposal overpacks. This would require emplacement of electrodes and/or excitation currents within the Supercontainer. The impact of these materials on the functions of the Supercontainer components would need to be evaluated before this technique could be considered feasible. An alternative would be to use the corrosion sensors in a pilot facility or sacrificial cell. In addition, the relaying of the information from such monitoring, e.g. using the high-frequency methods described in Section 3.2.3 would require demonstration.

Research into Supercontainer Monitoring within the MoDeRn Project

The half-scale Supercontainer test incorporates approximately 150 sensors to monitor temperature, strain, deformation, displacement, relative humidity, total pressure, corrosion and micro-seismic activity. The test is planned to last approximately 18 months and includes two heating and cooling periods to study the thermo-mechanical properties of the concrete materials used in the Supercontainer.

Approximately half of the monitoring techniques use classical instrumentation such as resistance and vibrating wire strain gauges, thermocouples, linear displacement transducers, time-domain reflectometry humidity probes and diaphragm pressure sensors. The other half use state-of-the-art technologies, including:

- Fibre optic sensors to measure radial, axial and circumferential strain, and temperature (research into fibre optics within the MoDeRn Project is discussed in Section 3.2.5).
- DIC in combination with AE and UT to measure onset and evolution of micro cracks in the concrete buffer and cementitious filler.
- Four types of corrosion sensors are being used in the second half-scale test to monitor the corrosion activity of the carbon steel overpack. These include the use of weight-loss coupons cast in the concrete buffer, one technique based on the variation of the linear polarization resistance, one sensor based on the open circuit potential which applies low amplitude, multi-frequency alternating current signals between a reference nickel auxiliary electrode and a sample of carbon steel representing the metal overpack, and finally a technique that measures the instantaneous corrosion using the single sine electrochemical impedance spectroscopy (EIS) method.

Research Results

The Supercontainer tests continue to provide valuable information on all aspects of the performance and quality of the sensors in general, including improvements in installation, design, robustness and accessibility.

So far, the DIC monitoring in the second half-scale test has demonstrated its value in detecting surface shrinkage, onset of crack initiation, crack propagation and crack width, and displacement and strain fields at different levels across the height of the concrete test cylinder as a function of time.

The main conclusions pertaining to the experience gained with the use of AE in the second half-scale test include its capability to detect phenomena occurring in fresh and early-age concrete such as particle segregation, migration of gas and water during initial stages of curing and setting, and monitoring of the hydration process.

Cracks detected through the use of DIC in combination with AE and UT, have allowed cracks with a diameter of 13 microns to be detected, and the results indicate that DIC in combination with AE and UT can be used to track, in real time, the development, depth and evolution of micro cracks in concrete.

Results from three of the four types of corrosion sensors were not available at the time of writing. However, the sensor based on the single sine EIS method has been tested in laboratory experiments, and has allowed measurement of accumulated corrosion rates and detection of passivation of the surface of a steel sample. It is anticipated that this method will allow measurement of corrosion rates on the order of µm/yr.

Further Research Requirements and Potential Application

The most important technical issues regarding concrete monitoring technologies that still remain to be addressed before these techniques can be implemented in a geological repository are those related to accessibility, data transmission, power requirements and the potential impact of the monitoring equipment on the safety functions of the barriers being monitored. Future research is needed to address these issues.

3.3 Conclusions on Monitoring Technologies

There is a wide range of technologies available for repository monitoring. These include geophysical and remote sensing techniques that facilitate the acquisition of data on the general phenomena resulting from repository evolution. These phenomena include the surface manifestations of processes and events occurring within the repository, such as vertical displacement of the ground in response to first excavation (leading to subsidence) and then thermal expansion in response to the heat output from the waste (which leads to uplift).

In addition to technologies that can be used to model general phenomena, there are several innovative technologies that could be applied for direct monitoring of the near field, and these technologies include non-intrusive monitoring where signals are transmitted and/or acquired remotely from the near field, and *in situ* monitoring where measurements are taken in the near field and wireless data transmission systems are used to transfer the acquired data to receiver stations either within other (un-backfilled) parts of the repository or to the surface.

Such innovative EBS monitoring technologies have been the focus of RTD work within the MoDeRn Project, and this work has brought the technical readiness of a range of potential technologies closer to that required for deployment within repository projects:

- New algorithms for full waveform elastic inversion of seismic tomography data have been developed and practical methods for acquiring tomographic data have been developed through testing at Mont Terri and Grimsel. These developments enhance the ability to monitor a range of processes (e.g. saturation, and gas generation and migration) that affect the velocity structure of the near field. See MoDeRn (2013g) for further information.
- A new seismic hammer for application in microseismic monitoring has been developed. The hammer will enhance the ability to generate strong S wave signals, and thereby improve the feasibility of conducting shear wave monitoring of the near field. This will improve the potential to provide information on changes to the EDZ, e.g. the mechanical response to heating. (MoDeRn, 2013i).
- A high-frequency wireless node that allows measurement of several parameters (e.g. pore pressure, total pressure and water content), and transmission of the measured data over distances of a few metres has been designed, developed and tested. The node is expected to have a lifetime of 20-25 years. A patent application for the wireless node has been submitted as an outcome of this work. (MoDeRn, 2013h).
- A low-frequency data transmission system, capable of transmitting data through 225 m of an electrically highly-conductive geological medium, at frequencies up to 1.7 kHz has been designed, developed and tested at the HADES underground research

laboratory (URL), and the conditions under which low-frequency data transmission may be applied have been evaluated. This potentially provides a method for wireless transmission of monitoring data from a repository to the surface following repository closure. (MoDeRn, 2013j).

- Research into distributed monitoring using fibre optic sensors has been undertaken in the HADES and Bure URLs. Sensors have been successfully installed and tested at both URLs and have successfully measured displacement around experimental tunnels in response to tunnel excavation. (MoDeRn, 2013i and MoDeRn, 2013k).
- Digital Image Correlation (DIC) and acoustic emission (AE) monitoring have been successfully used to detect crack initiation and growth during a half-scale test of the Belgian Supercontainer. (MoDeRn, 2013i).
- Corrosion sensors that can measure *in situ* corrosion rates have been developed and tested in surface facilities. (MoDeRn, 2013i).

These developments have significantly increased confidence in the ability to monitor the evolution of the near field, following waste, buffer and backfill emplacement, through monitoring in adjacent tunnels, during the progressive closure of a repository, and even post-closure.

In addition, work in other industries is also increasing the feasibility of using a range of other technologies for repository monitoring. These include work on wireless data transmission systems, fibre optics, seismic interferometry, time-lapse 3D seismic surveying, AE/MS monitoring, geotechnical monitoring of underground mines, satellite-based imagery and satellite-based radar. Within the MoDeRn Project, links were established between researchers in geological disposal and those in other industries, and it is anticipated that these links will help the future development of monitoring technologies.

However, the technologies are still limited in their applicability. Although the work in MoDeRn has addressed some of the key concerns for repository monitoring, e.g. power supply and remote transmission of data, further developments are required to develop the more novel technologies from being feasible/novel to being standard techniques widely applied in repository environments. In addition, it remains for WMOs to define how these technologies will be employed within national programmes. Work on integrated repository monitoring systems is presented in the next section of this report. This work serves to illustrate further how the technologies discussed in this section of the report can be mapped to specific parameters relevant to the safety case.

4 Monitoring Programmes: Case Studies and Consideration of Failure Detection

4.1 Introduction

In Chapter 2, the MoDeRn Monitoring Workflow was presented as a structured approach for specifying, designing and conducting a monitoring programme. In Chapter 3, developments in some of the technologies that could be applied in repository monitoring were presented. In this chapter, this work is built on and used to develop example monitoring programmes that illustrate how the key challenges in implementing monitoring can be addressed in an integrated fashion.

The objective is to illustrate that an approach to monitoring key safety case events and processes, or key pre-closure management decisions, can be developed for specific contexts based on existing technologies or on technologies with a reasonable likelihood of development in time for deployment in repository programmes. The approaches presented are based on the MoDeRn Workflow as discussed in the Chapter 2.

Three examples were selected in order to develop monitoring programme case studies for the three principal types of host rocks considered for geological disposal: salt, clay and granitic rocks. Each one of these case studies has specific and different issues that challenge the implementation of monitoring programmes.

All of the case studies considered the specific national context, and do not represent generic monitoring programmes that could be applied in other national programmes without further tailoring and modification to reflect the national context:

- The *salt host rock case study* selected focused on the development of a post-emplacement and post-closure monitoring programme for disposal of HLW in the Gorleben salt dome in Germany (Bollingerfehr *et al.*, 2011). This case study is presented in Section 4.2. It is related to the monitoring objective *support the basis for the long-term safety case*, as identified in Figure 2.2. The salt rock case study includes consideration of how a monitoring programme can be used to detect near-field evolutions that are inconsistent with the assumptions in the safety case.
- The *clay host rock case study* selected focused on the monitoring of HLW in a disposal cell prior to closure of the repository. This case study was based on the reference disposal concept for HLW in France (ANDRA, 2005). It is presented in Section 4.3, and is related to the monitoring objective *support pre-closure management of the repository*, as identified in Figure 2.2. In addition to a theoretical discussion of the monitoring programme, testing and demonstration of the proposed programme has been conducted in the Bure URL as part of the MoDeRn Project. This integrated testing is also described in Section 4.3.
- The *granitic host rock case study* selected considers the monitoring of the reference concept for spent fuel in Finland, which is based on the KBS-3V concept (Posiva, 2012). The case study considers the monitoring of emplaced waste, buffer and backfill to support the licensing process. This case study is presented in Section 4.4. It is related to the monitoring objective *support the basis for the long-term safety case*, as identified in Figure 2.2.

One of the key challenges in developing a monitoring programme is to have confidence in the data acquired using the monitoring system. This requires that failures in the monitoring system can be detected and strategies implemented for distinguishing between data that can be used in support of decision making and data that should not be so used. This requires an approach to detecting monitoring system failure, where *monitoring system failure* is defined as *an instance when the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena occurring in the repository.* Section 4.4 provides a discussion of monitoring system failure detection.

The information provided in this report is a high-level summary of the case studies and other implementation issues considered within the MoDeRn Project. Specific elements of the designs are highlighted, with the objective of demonstrating how key monitoring challenges can be met through the use of a structured approach to design of a monitoring programme (i.e. by following the MoDeRn Monitoring Workflow). Further details of the monitoring programmes described in this section can be found in the MoDeRn Case Studies report (MoDeRn, 2013l).

4.2 German Case Study: Salt Host Rocks

4.2.1 Programme Context

Based on the existing repository concept for the Gorleben site, a repository layout was designed for the borehole disposal option that considers the disposal of spent fuel casks as well as HLW casks in 300-m-deep vertical boreholes drilled from underground access drifts with a diameter of 600 mm. The initial Gorleben working model allows for three emplacement fields for the disposal of spent fuel in the east of the repository, designated East 1, East 2 and East 3. An option to develop a further three emplacement fields for radioactive waste with negligible heat generation has been considered for the western part of the repository, and these are designated West 1, West 2 and West 3 (Figure 4.1).

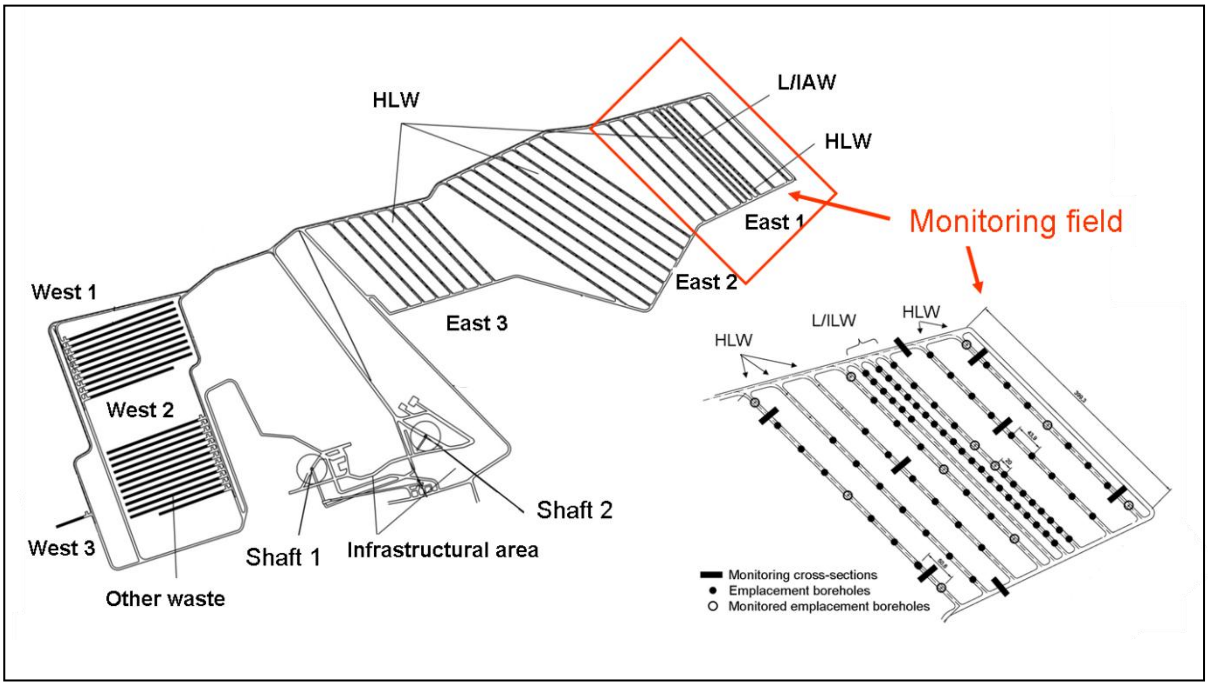

Figure 4.1: Potential layout of the Gorleben repository site, and the location of the representative monitoring field and sensor locations for the salt case study, (modified after Bollingerfehr *et al.*, 2011).

In addition to a thermal boundary condition (the maximum temperature of the rock must not exceed 200°C), a number of mining-related boundary conditions (e.g. minimum width of pillars, safety pillars in shafts, etc.) must be adhered to in the repository design. As a consequence of the thermal and operational boundary conditions, the containers are emplaced using a retreat method, i.e. disposal starts in the fields farthest from the shaft, and the corresponding drifts and boreholes are the first to be backfilled and sealed.

In 2010, the German Ministry for the Environment launched new safety requirements for the disposal of high-level heat-generating waste (BMU, 2010). With regard to monitoring, the following statement is included in the safety requirements:

> *"A monitoring and evidence preservation programme must be used during emplacement operations, decommissioning, and for a limited period following repository closure, in order to verify that the input data, assumptions and statements of the safety analyses and safety cases performed for the phases are valid. In particular, this measurement programme should record the impacts of the rock's thermo-mechanical reactions on the heat-generating waste, technical measures and the rock-mechanical behaviour."*

The requirements also define a need to monitor the baseline and long-term concentration of radioactivity in spring water, groundwater, soil, water bodies and the air in the region likely to be affected by the presence of the repository. Any significant deviations from the data, statements and assumptions in the cited safety cases should be evaluated with regard to their safety relevance. If necessary, counteractive measures should be carried out by the operator during emplacement or decommissioning in order to avoid any impairment to important safety functions. Where approval is needed for such counteractive measures, this should be obtained by applying to the competent authority. The competent authority shall also decide who will perform the measurement programme following repository closure, and when this measurement programme may be stopped.

4.2.2 Safety Assessment Concept

In Germany, a concept for the demonstration of safety, the *Safety Assessment Concept*, has been developed (Mönig *et al.*, 2012). The safety concept relies on siting to ensure confinement by the geological barrier, and demonstration of confinement of radionuclides by the waste and the engineered barriers, in particular the drift and shaft seals.

The safety concept is captured within a hierarchical structure of protection goals, safety assessment components and safety functions (Figure 4.2). This hierarchy allows a link to be established between the safety functions of the repository components and the protection goals.

4.2.3 Processes and Parameters

In order to derive a list of processes and parameters against which the monitoring programme can be developed, the MoDeRn workflow described in Chapter 2 was followed and each of the safety functions identified in Figure 4.2 was analysed in turn to identify a Preliminary Parameter List. The outcome of the analysis is presented in Table 4.1. In the salt rock case study, the analysis also considered the potential locations at which monitoring data could be collected for each parameter of interest (Figure 4.1).

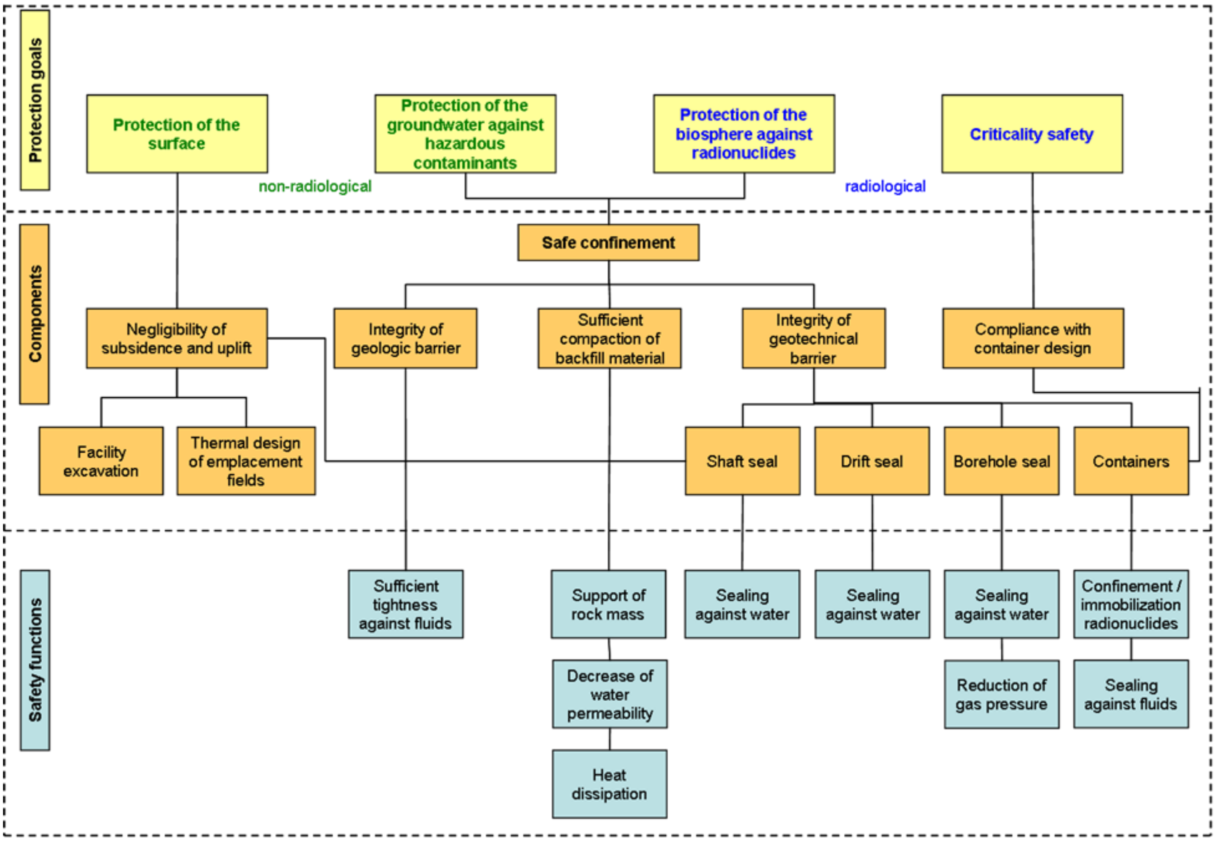

Figure 4.2: Hierarchy of protection goals, safety assessment components and safety functions for the German Safety Assessment Concept.

Table 4.1: List of processes and parameters for the salt case study.

Relevant Disposal Component	Safety Function of the Component	Relevant Processes	Preliminary Parameter List	Location of Measurement
Container	Confinement/ immobilisation of radionuclides Sealing against fluids	Pressure evolution at container Temperature evolution near container Corrosion on container surface	Radial stress at container Temperature near container Corrosion current on canister shell	At shell of measurement canister At shell of measurement canister At shell of measurement canister
Buffer or Borehole Backfill	Heat dissipation Decrease of water permeability	Borehole convergence	Backfill temperature Backfill humidity	Next to measurement canister Next to measurement canister
Borehole Liner	None	None	None	None

Relevant Disposal Component	Safety Function of the Component	Relevant Processes	Preliminary Parameter List	Location of Measurement
Drift Backfill	Decrease of water permeability Support of rock mass	Drift convergence	Rock displacement Cavity convergence Total pressure in the backfill Temperature in the backfill Humidity in the backfill Pore pressure in the backfill	On both sides of the drift plugs at three different locations on each side (all parameters)
Borehole Seal	Sealing against water Reduction of gas pressure	Borehole convergence Gas pressure build-up from inside Fluid pressure build-up from outside Temperature development	Rock displacement Borehole convergence Pore pressure at seal boundaries Total pressure at seal boundaries Temperature at seal boundaries Humidity at seal boundaries	On top and bottom of borehole plug (all parameters)
Drift Seal	Sealing against water	Drift convergence Fluid pressure build-up on one or both sides Infiltration of corrosive fluids	Rock displacement Drift convergence Total pressure Pore pressure Humidity pH-value of brine Electric conductivity of brine	On both faces of the drift plug including EDZ (all parameters)
Shaft Seal	Sealing against water	Rock convergence Fluid pressure build up on one or both sides Infiltration of corrosive fluids Subsidence of the entire sealing system	Shaft convergence Hydraulic pressure at seal top Pore pressure at seal bottom pH-value of water/brine Electric conductivity of water/brine Subsidence of plug/components	On top of the whole plug (all parameters)
Geological Barrier	Sufficient tightness against fluids	Rock stress evolution within host rock Temperature evolution within host rock	Rock stresses Rock temperature	In the vicinity of underground openings In the vicinity of canisters and underground openings
Overburden	No safety function	Uplift and subsidence of the earth's surface Change of groundwater level Change of groundwater temperature	Surface level Groundwater level Groundwater temperature Saltwater/freshwater boundary Activity	Earth's surface at the site All relevant aquifers at the site

4.2.4 Illustrative Monitoring Programme Design

Based on the Preliminary Parameter List in Table 4.1, a Monitoring Programme was developed. The monitoring programme design is based on monitoring of specific components of the EBS and also monitoring of the overall repository system, and is arranged in a way that is representative for the overall repository system.

Monitoring of specific components of the EBS is based on instrumentation of a single representative monitoring field (Figure 4.1). It is considered beneficial for the representative monitoring field to be the first to be filled with waste containers. This allows monitoring data to be gathered from this representative, sealed monitoring field while emplacement continues in the rest of the repository. The information collected in this manner could be used as a basis for forgoing monitoring in the rest of the repository, i.e. it provides sufficient confidence in the repeatability of performance making it unnecessary to monitor all emplacement areas.

The location and layout of the representative monitoring field is illustrated in Figure 4.1. Monitoring would be undertaken within deposition boreholes and within access tunnels. Monitoring locations would be distributed over the monitoring field. Measurements would be taken in the centre of the field to capture the greatest increase in temperature and other measurements would be taken towards the edge of the field to capture the greatest gradients in the thermo-mechanical response to waste emplacement.

In order to monitor the safe confinement of waste by the waste containers in the boreholes, the placement of a monitoring canister (sometimes referred to as a dummy canister) at the top of an emplacement borehole, directly below the borehole seal, is envisaged (Figure 4.3). A dummy canister would not contain waste. This monitoring canister contains the necessary hardware to collect and transmit monitoring data out of the borehole, and it monitors the conditions at the top of a borehole filled with containers containing HLW. Sensors to measure temperature, moisture, pore pressure, and total pressure would be placed on the outside of the monitoring canister.

The dimensions of the monitoring canister are chosen in a way that the gap between the monitoring canister and the borehole wall is only a few centimetres, and any fluid flow into or out of the borehole would be detected by the sensors on the outside of the canister. In this way, brine intrusion that may result in the migration of radionuclides from the waste containers/liner system to the sealing plug of the borehole can be detected.

The monitoring data would be transmitted via a wireless transmission system to the borehole cellar at the top of the borehole, used to store the power supply, data recording, and transmitting devices (Figure 4.3). In the current disposal concept, there are no special requirements on the backfilling of the borehole cellar, so this may be a suitable site for placing monitoring equipment. There would be a need, however, to demonstrate that degradation of the monitoring equipment in the long-term would not affect long-term safety.

In addition to borehole monitoring, monitoring of the geological barrier and of the overall repository closure system would be undertaken through testing of the performance of the backfill, drift and shaft seals. Backfill and drift seals monitoring are not discussed further here (see MoDeRn, 2013l for potential monitoring approaches).

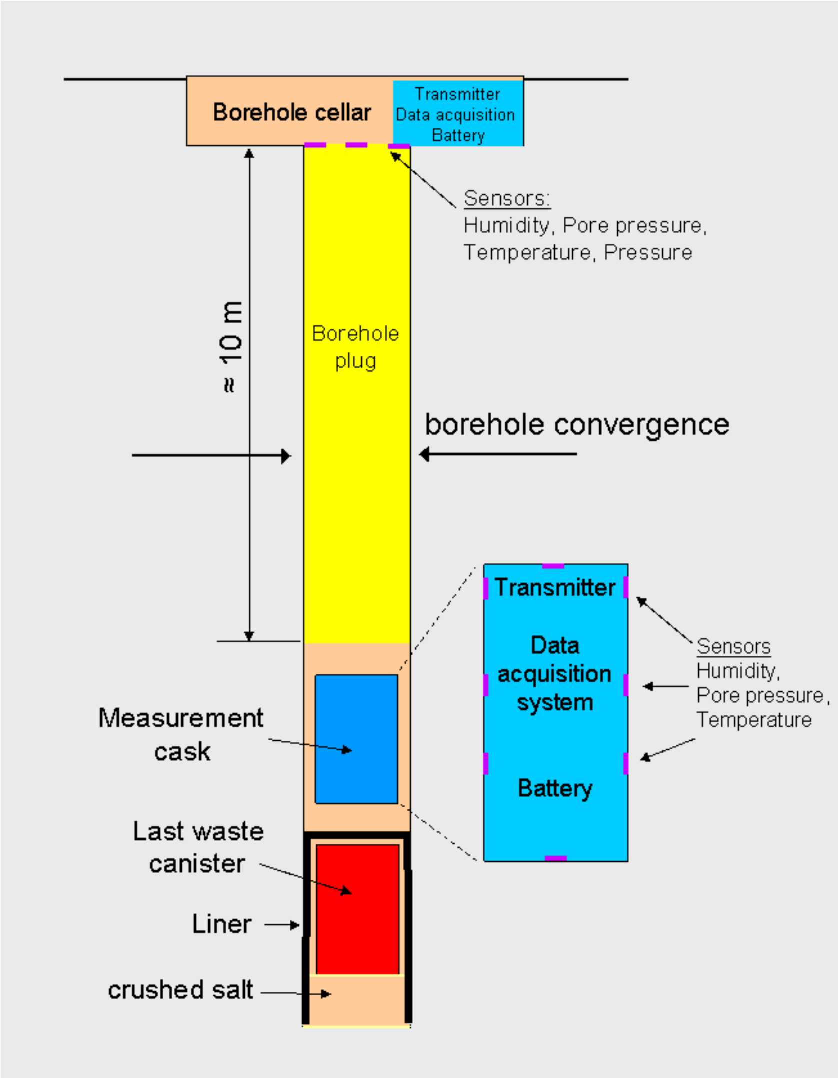

Figure 4.3: Location of a monitoring canister in the case of borehole emplacement.

The safety function of the shaft seal is to prevent or at least significantly slow down the inflow of water or brine from the overburden into the repository after its closure. Furthermore, in the event that radionuclides are mobilised during the post-closure phase, the function of the shaft seal is to retain these radionuclides in the repository. This ensures compliance with the conventional safety objective *protection of the groundwater against hazardous contaminants* as well as with the radiological protection goal *protection of the biosphere against radionuclides* (see Figure 4.2).

Key processes and parameters included within the monitoring programme envisaged for a shaft are listed in Table 4.1. Monitoring of the shaft envisages monitoring at several monitoring levels (Figure 4.4). Each level is equipped with total pressure and pore water pressure sensors as well as a data transmission unit consisting of a wireless transmitter and a long-life battery (Figure 4.5). The data transmission technology envisaged is based on the high-frequency wireless data transmission technologies described in Section 3.2.3.

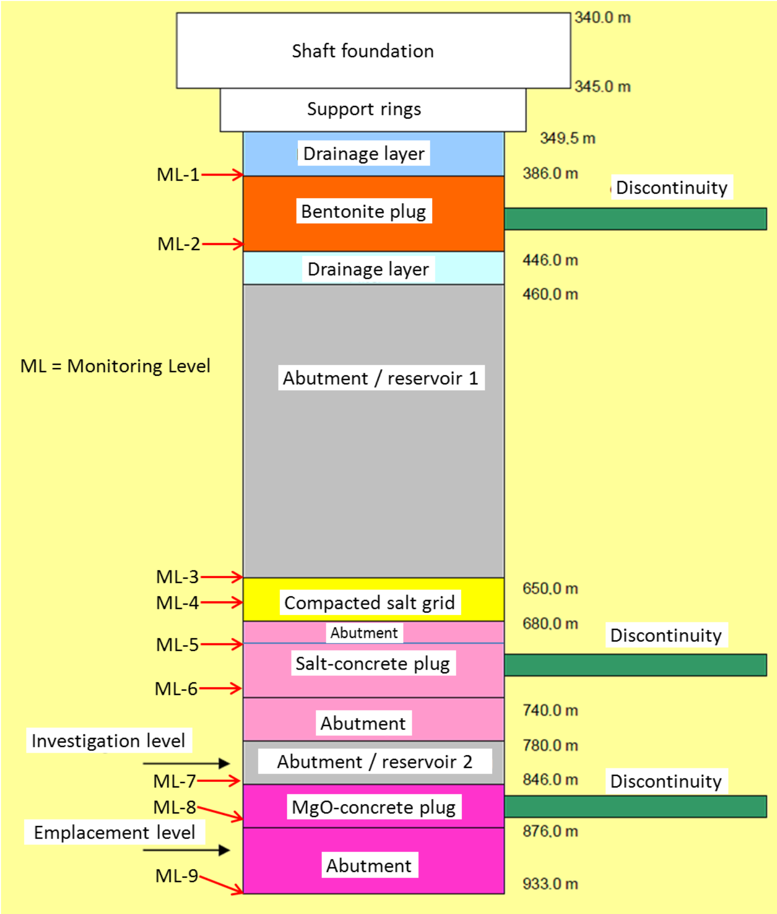

Figure 4.4: Preliminary shaft sealing concept illustrating the location of monitoring levels for measurement of total pressure and pore water pressure (modified after Müller-Hoeppe *et al.*, 2013).

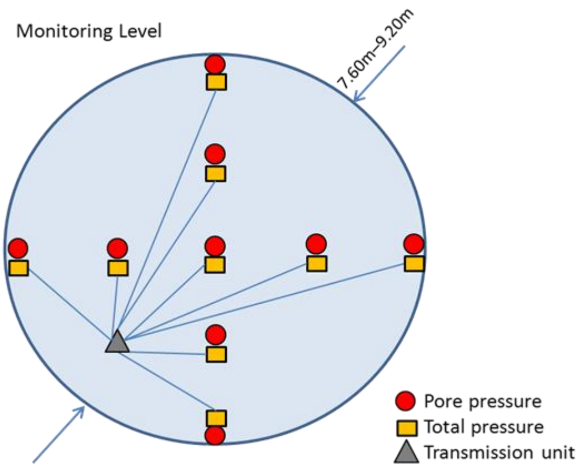

Figure 4.5: Location of total pressure and pore water pressure sensors, and transmission unit within a shaft monitoring level.

4.2.5 Monitoring to Check Compliance with the Safety Case

A key objective for a monitoring programme is to check that the system is performing within the bounds assumed in the safety case. Within the MoDeRn Project, an analysis of the German test case was undertaken to build confidence that it could be used to monitor processes that could contribute to altered evolution scenarios and thereby threaten the passively safe performance of the repository. Thirteen alternative evolution scenarios have been recognised within the German safety assessment (Buhmann, 2011; Rübel, 2011 and VSG, 2011). The ability for the monitoring system to detect the physical manifestation of each one of these scenarios was considered through a qualitative assessment. For twelve of the scenarios, monitoring could detect the physical manifestations of the scenario, i.e. the specified monitoring could detect the presence of brine as a result of the scenario occurring (in the safety case, brine is a prerequisite for radionuclide migration to occur). The other scenario involved the development of glacial channels; this scenario has a timeframe outside of monitoring and would be addressed through siting (e.g. through location of the repository at an appropriate depth). The results of the qualitative consideration of altered evolution scenarios are presented in MoDeRn (2013l).

In addition, a quantitative evaluation of the ability of the proposed shaft monitoring system to detect an alternative evolution scenario was undertaken. This concentrated on the requirement for the shaft seal to prevent or significantly slow down the inflow of water or brine from the overburden into the repository after closure.

For the reference scenario, performance assessment calculations were undertaken to determine the hydraulic load development (pore pressure evolution) on each side of the main barriers in the shaft seal. These areas correspond to the monitoring levels envisaged in Figure 4.4. The results are shown as solid lines in Figures 4.6 and 4.7.

The altered evolution scenario evaluated the pore pressure evolution assuming that the shaft seal had been incorrectly constructed, and that the properties of the seal had been affected as follows:

- The hydraulic conductivity of the bentonite plug is increased by half an order of magnitude.
- The hydraulic conductivity of the salt-concrete plug is increased by four orders of magnitude.
- The hydraulic conductivity of the MgO-concrete plug is increased by two orders of magnitude.

The pore pressure evolution for the altered evolution scenario is also illustrated in Figures 4.6 and 4.7 using dashed lines to illustrate the pore pressure at each monitoring level. Whilst for the reference scenario almost no pressure reaction will be detectable during the first 100 years, an increase in pore fluid pressure of 1-3 MPa would occur within 100 years after closure for the altered evolution scenario, and these increases are readily detected using the pore pressure monitoring system depicted in Figures 4.4 and 4.5.

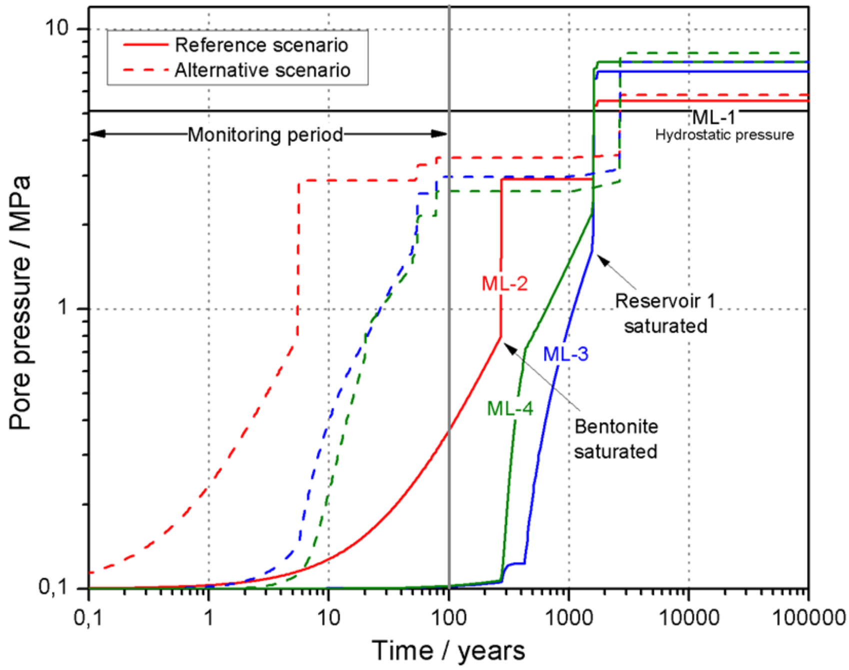

Figure 4.6: Results from the simulation of pore pressure evolution at monitoring levels 1 to 4, which correspond to the upper part of the shaft seal in the German case study (calculations performed by GRS).

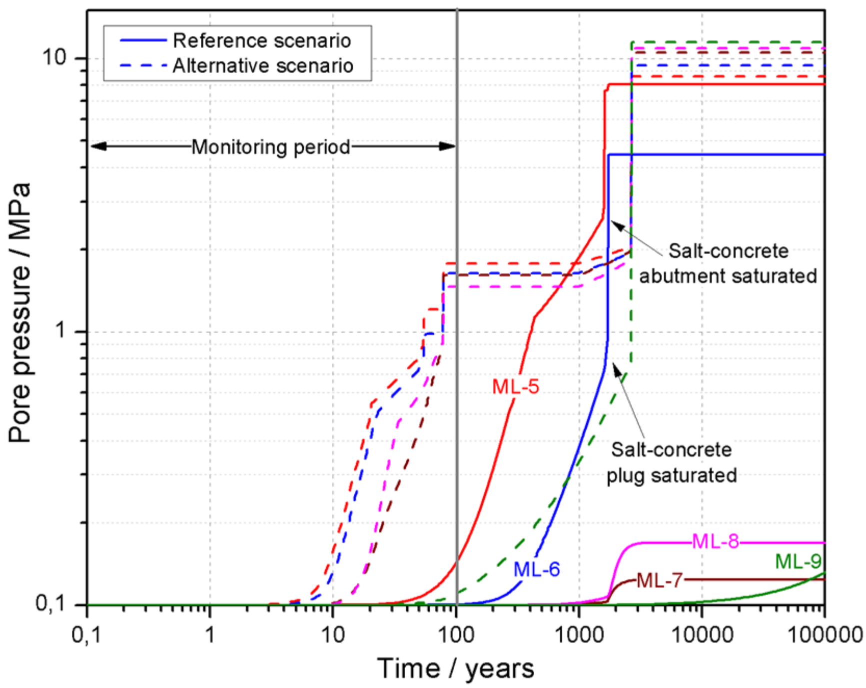

Figure 4.7: Results from the simulation of pore pressure evolution at monitoring levels 5 to 8, which correspond to the upper part of the shaft seal in the German case study (calculations performed by GRS).

4.3 French Case Study: Clay Host Rocks

4.3.1 Programme Context

In France, a final site has been identified for a repository for HLW, spent fuel and long-lived intermediate-level waste (LL-ILW) in Callovian-Oxfordian age indurated clay in north-eastern France, close to the site of the Bure URL. The choice of this host rock was justified in the 'Dossier 2005 Argile', which was an evaluation of the feasibility of implementing geological disposal (ANDRA, 2005). The reference approach for management of spent fuel in France is reprocessing, but some spent fuel may not be reprocessed and may require direct disposal.

The French case study focused on monitoring of the HLW disposal package, specifically the overpack of the disposal package, and, therefore, discussion in this section refers only to monitoring of parts of the repository designed for disposal of HLW. Further details of the case study can be found in MoDeRn (2013l).

HLW will be disposed of in small-diameter waste disposal cells (Figure 4.8). The inner diameters of the disposal cells will be approximately 70 cm. A steel cell liner provides mechanical stability, and allows the emplacement and potential retrieval of the waste disposal package. Its long-term resistance to corrosion – at a minimum during the 100-year operational phase – is ensured by its design and by placing the liner in a low-corrosion anoxic environment.

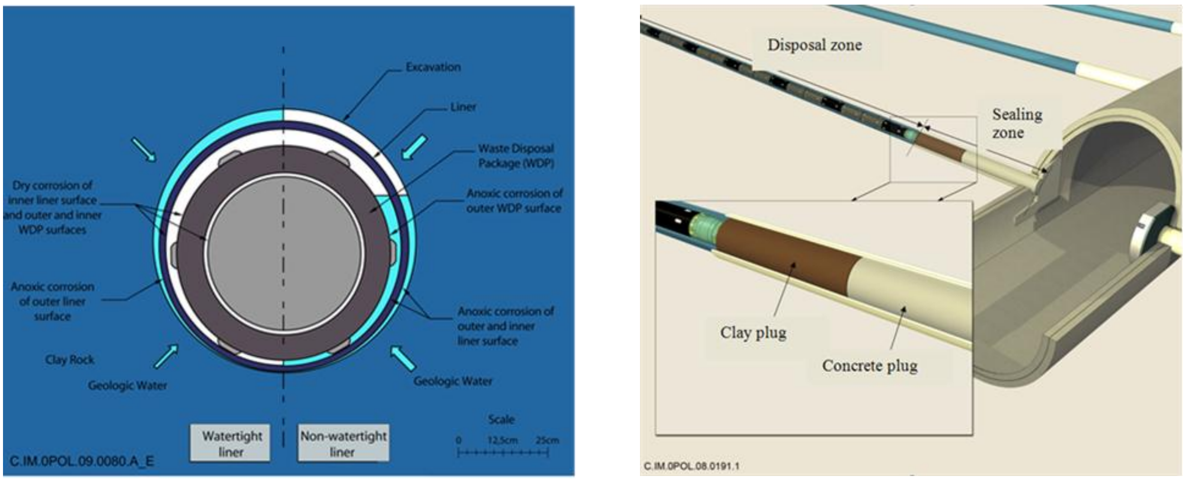

Figure 4.8: HLW disposal cell during the operational phase (left) and during the post-closure phase (right).

4.3.2 Safety Case and Retrievability

Long-term Safety Case

The overall safety objective recognised in the French programme is to protect man and the environment from radionuclides and other hazardous contaminants contained in the disposed waste. The depth of the repository protects it from long-term surface erosion and climate evolution. The long-term protection of man and the environment implies control and understanding of the physico-chemical degradation of the waste and waste forms, of the processes by which radioactive elements and toxic chemicals are confined as close as possible to their source, and by control and understanding of potential long-term transfer paths. While a transient potential of gaseous transfer is recognised and transfer in solid form is possible in the event of human intrusion, emphasis is placed in the safety case on transfer by water, either in dissolved or in colloidal form.

Therefore, one of the key functions of the multiple barrier system is to limit radionuclide migration to the biosphere by means of water. This can be further broken down to yield the following fundamental safety functions that have to be realised after repository closure (ANDRA, 2010):

- First Safety Function (SF1): Counter water circulation.
- Second Safety Function (SF2): Limit radionuclide release and immobilise radionuclides in the repository.
- Third Safety Function (SF3): Delay and reduce concentration of radionuclide migration outside of disposal cells.

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 a reversibility principle, including the ability to retrieve waste packages from disposal cells. Ease of retrieval relies, in part, on waste package integrity (retrieval operations of a damaged package might lead to substantial technical complications) as well as on the conditions in the disposal cell (e.g. quality of ground support and cell environmental conditions such as hydrostatic pressures). In addition, the surface dose rates of the HLW overpack should be limited to allow the package to be handled.

4.3.3 Processes and Parameters

The example monitoring design developed as part of the MoDeRn Project focused on the contribution of monitoring to the verification of the basis for the expected performance of the HLW overpack. This includes both the long-term safety case and pre-closure management in association with the retrievability function.

Within the MoDeRn Project, a qualitative analysis of the safety functions described above was undertaken and allowed the identification of a preliminary parameter list that addresses the recognised processes influencing the evolution of the HLW overpack (Table 4.2). The analysis undertaken distinguishes between the core of the engineered barrier, i.e. the actual overpack, and the surrounding components and the near field, both of which influence overpack performance. This list of preliminary processes and parameters needs to be further analysed as the programme develops and uncertainty is reduced, keeping in mind several considerations:

- Some of the processes and parameters may be correlated by available process models, and, therefore, monitoring a subset of them may allow others to be adequately inferred.
- The qualitative analysis did not take into account the acceptable uncertainty range for a given process or parameter, nor its relative importance to support the basis for the expected overall performance (i.e. the duration of overpack water tightness).

Table 4.2: Preliminary list of processes and parameters for the French case study.

Component	Process	Parameter	Potential Technique
Overpack material	Intrinsic material mechanical resistance	Stress (pressure, traction)	Verification on lab samples
		Strain	
	Intrinsic material corrosion properties	Corrosion under *in-situ* conditions	Indirect measurement (water and oxygen contents) with sampling lines, possibly verified by retrieving *in-situ* samples; many on-going developments for direct measurement
Overpack	Corrosion	Surface corrosion	Indirect measurement (water and oxygen contents) with sampling lines, possibly verified by retrieving sample canisters from sacrificial cells
		Weld seam corrosion	
		Runner contact corrosion	
In-cell environment	Heat dissipation Water exchange from near field	Temperature	Pt100 and optical fibre sensors inside sacrificial cell, and remote sensing from clay temperature monitoring
		Relative humidity	Instrumented plug
		Liquid water content	
	Gas exchange with access tunnel	Oxygen concentration	Instrumented plug, or application of the many on-going developments for direct measurement (at least in sacrificial cells)
	Anoxic corrosion	Oxygen concentration	
	Radiolysis		
	Radiation	Irradiation rate	Sensing in sacrificial cell with optical fibres on the metallic liner (under development)
Cell liner	Thermo-mechanical loading	Temperature	Pt100 and optical fibre sensors on the liner
		Strain	Vibrating wire sensors and fibre optic sensors on the liner
	Radial mechanical loading	Total pressure at contact surfaces	
		Load source position	
	Deformation	Radial deformation	
	Transient to hydraulic equilibrium	Relative humidity	Instrumented plug
		Hydraulic pressure	Developments for sensors in the sacrificial cell (flexible instrumented blades)
Near field	Heat dissipation	Temperature	Pt100 and fibre optic sensors in boreholes
	Transient to mechanical equilibrium	Radial deformation	Extensometers in boreholes
	Resaturation	Water content	Time-domain reflectometry and interstitial pressure sensors in boreholes
		Interstitial pressure	

- The preliminary listing of processes and parameters did not consider the technical feasibility of the associated monitoring.

Table 4.2 also identifies potential monitoring techniques that could be used to monitor the identified process. These techniques are based on the monitoring programme design discussed below.

4.3.4 Illustrative Monitoring Programme Design

In order to consider the feasibility of monitoring the processes and parameters identified in Table 4.2, an example programme for monitoring the HLW overpack has been developed within the MoDeRn Project. The example demonstrates how an integrated monitoring programme can be developed and highlights several on-going monitoring developments within the French programme.

The strategy envisaged for the monitoring programme is to undertake monitoring from several locations and to use different types of disposal cell. Monitoring of standard cells could be undertaken through instrumentation of the cell liner, instrumentation of the sealing plate and/or instrumentation of boreholes surrounding the disposal cells. Fully instrumented disposal cells are referred to as *witness structures* by ANDRA. In addition, *sacrificial cells* may be used to monitor parameters that cannot be monitored remotely. A sacrificial cell is one in which real waste is emplaced and monitored for a specific period, after which the waste is retrieved and disposed of separately, as discussed below. The sacrificial cells may have a reduced length, for example 25 m. The concept of sacrificial cells is considered by ANDRA to be similar to the pilot facility proposed in other countries, with the exception that sacrificial cells are planned to be in representative locations inside the main part of the repository. The distribution of the monitoring elements within the repository has also been considered as part of the monitoring programme example.

Liner Instrumentation

Monitoring of the liner would incorporate temperature and strain measurements, focused on checking of the expected temperature evolution assumed in the long-term safety case, and strain of the liner for purposes of reversibility. Much of the monitoring would be undertaken using distributed fibre optic sensors.

Instrumented Sealing Plates

To detect the presence of water in the cell, the possibility, in some cells, of incorporating sampling lines attached to metallic plates at the accessible end of the cell is being considered. The speed of corrosion will be assessed using indirect measurements, for example through monitoring of the gas content in the cell using miniature spectrometers. The progressive establishment of an anoxic atmosphere would be monitored using sampling lines from the plug and by measuring oxygen concentrations in the air.

Instrumented Boreholes Surrounding Disposal Cells

In order to support checking of the evolution of the repository near field in response to waste emplacement, monitoring of temperature, humidity, interstitial pressure, strain and gamma radiation is envisaged in boreholes surrounding the HLW disposal cells. The boreholes would be within a few metres of the cells. The inclusion of gamma radiation monitoring is proposed in anticipation of stakeholder expectations for such monitoring.

Monitoring in Sacrificial Cells

Collection of information on corrosion of the HLW disposal overpack is considered important within the framework of the ANDRA monitoring programme. Although indirect methods of monitoring corrosion are proposed using the instrumented sealing plates discussed above, it is also currently envisaged that material coupons will be placed in sacrificial cells. These cells would also include monitoring for a range of relevant processes, as illustrated in Figure 4.9.

It is expected that the transition towards low rates of corrosion will occur over several years to decades. Monitoring of sacrificial cells would therefore need to be undertaken for 15-30 years after waste emplacement.

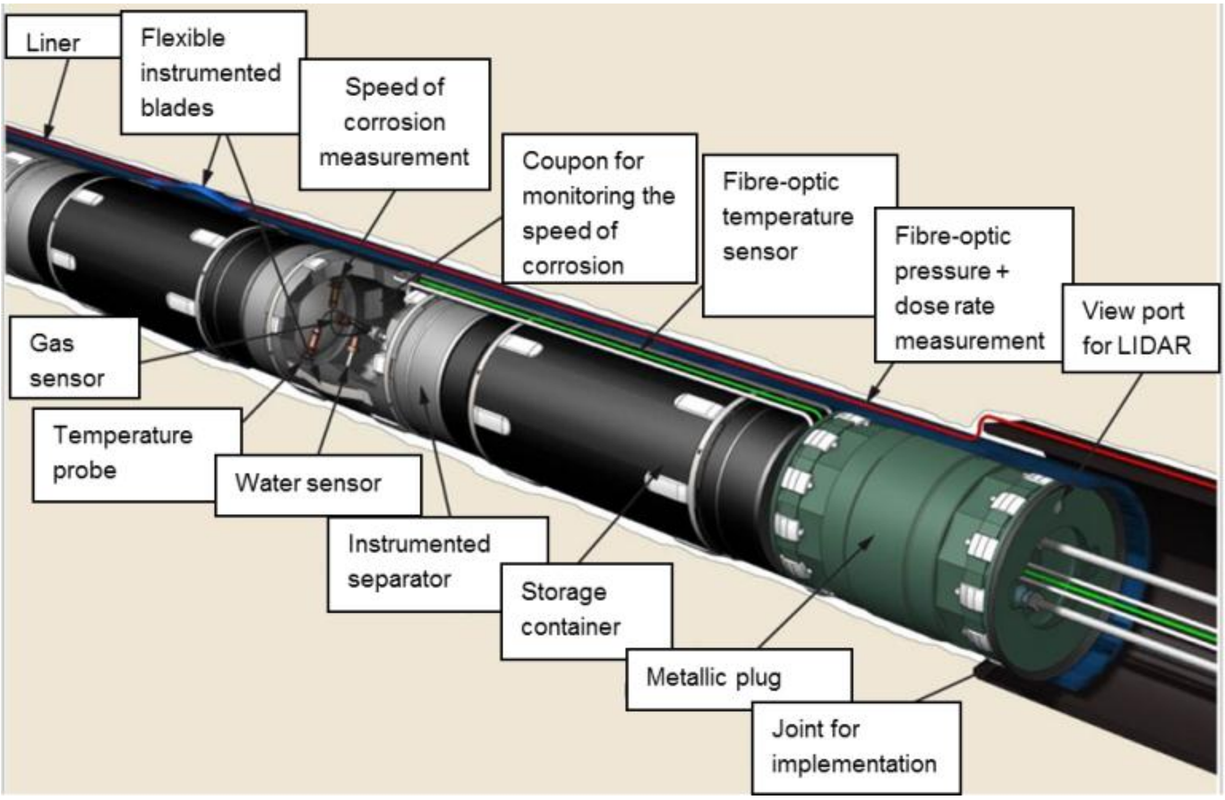

Figure 4.9: Illustrative scheme for monitoring in a sacrificial HLW disposal cell. LIDAR is a technology that measures distance by illuminating a target with a laser and analysing the reflected light.

Overall Design of Monitoring System

The overall design of the monitoring system would allow for a limited number of witness structures and sacrificial cells in each disposal module. Standard disposal cells would not be instrumented. A small number of *current structures* would also be included; these would contain more limited monitoring instrumentation than witness structures. The number of witness structures would be determined by the expected heterogeneity of the processes being modelled. It is envisaged that 2-3 sacrificial cells would be required.

An illustrative layout of the monitoring system has been developed within the MoDeRn Project, and this has focused on the distribution of monitoring systems that would be required for monitoring of the temperature evolution of the near field following waste emplacement. Witness structures would be implemented early during the development of the repository to maximise the duration over which monitoring can be undertaken.

The monitoring strategy anticipates the integration of an initial module constructed from witness cells distributed (i) in the core of the module and at its edge, (ii) along the length of the access tunnel (air intake and air return), and (iii) with respect to time (i.e. monitoring the first cells in which waste is emplaced rather than the last cells to be filled). With some witness cells able to monitor for a range of processes, a pooling of resources made it possible to restrict the number to eight witness cells (out of approximately 200 disposal cells in the case of the ANDRA (2009) architecture) within the initial waste disposal module (Figure 4.10). The number of witness cells will be amended over time as the monitoring programme is optimised.

The cell instrumentation would be supplemented by observation and monitoring in the tunnels. For example, an optical fibre providing distributed temperature measurements would contribute to the monitoring of tunnel ventilation. Concrete liner monitoring is also planned.

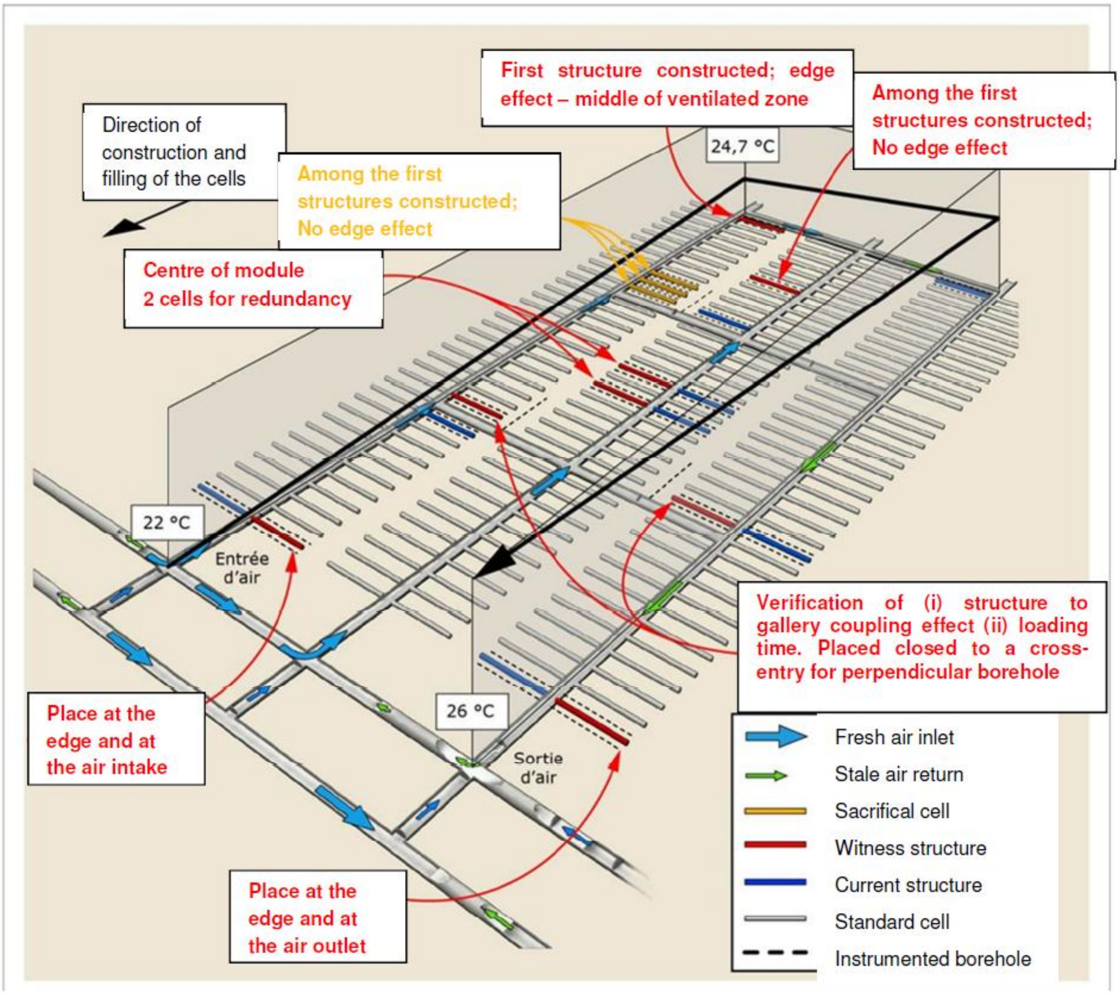

Figure 4.10: Example of the distribution of monitoring in a HLW module for the French case study.

4.3.5 Testing of Disposal Cell Monitoring Techniques within MoDeRn

The monitoring envisaged within the illustrative monitoring programme described above was evaluated in an integrated monitoring demonstration during the MoDeRn Project. This has focused on the ability to conduct monitoring of the cell liner and near-field rock around a specially excavated disposal cell constructed in the Bure URL, and also to test the emplacement of the monitoring system, i.e. to evaluate whether the cell liner monitoring system could withstand construction procedures and provide reliable monitoring results following construction. The cell used in the demonstration was 40-m long.

The demonstration had the following specific objectives:

- To evaluate the potential for emplacement of fibre optic sensors in parallel with liner installation; the fibre optic sensors would be used for monitoring the overall thermo-mechanical behaviour of the liner.
- To assess the hydromechanical impact of excavation of a cell, and to determine whether the impact could be monitored.
- To monitor near-field hydraulic pressure evolution through vibrating wire technology.
- To detect and monitor the mechanical behaviour of a 40-m-long casing in relation to the loading applied by the rock.

Monitoring of the cell liner involved instrumentation of four casing elements within the overall cell liner (Figure 4.11). Each of the four instrumented casing elements was equipped with the following sensors:

- Eighteen strain gauges on the internal surface and six on the external surface, so as to measure the local internal and external deformation of the casing element.
- Two displacement sensors in order to measure the convergence of the casing in the horizontal and vertical directions.
- One relative humidity and temperature sensor so as to measure these two values in the casing/rock annular space.
- Casing elements 3 and 17 were also equipped with three pressure sensors in order to measure the pressure of any possible water found in the annular space from three corner positions.
- The casing was equipped throughout its length with four optical fibres:
    - An external fibre to measure possible falls of break-outs after excavation.
    - Two internal fibres to measure the temperature profile throughout the length of the casing.
    - One internal fibre to measure the deformation profile throughout the length of the casing.

Only the stress gauges were placed on the casing elements before excavation of the cell. All the other sensors were installed manually either during (for the external optical fibre) or after excavation. The arrangement of sensors on each instrumented casing element is illustrated in Figure 4.12.

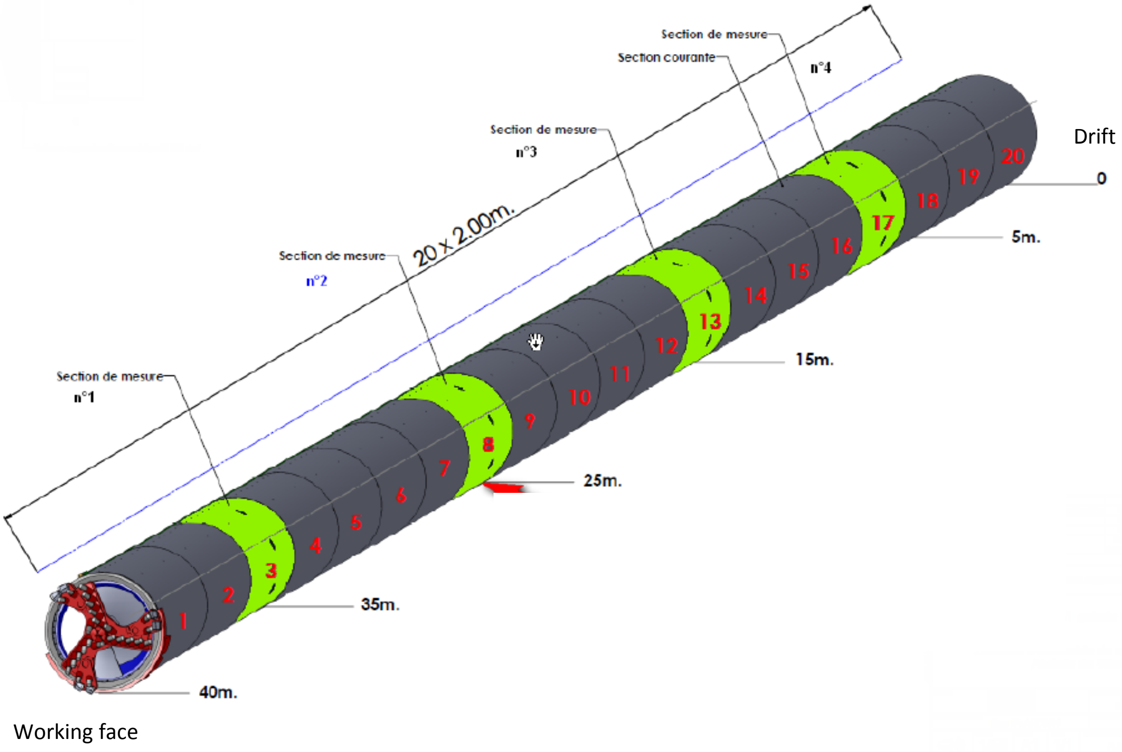

Figure 4.11: Location of the four instrumented casing elements in the cell liner monitoring demonstration.

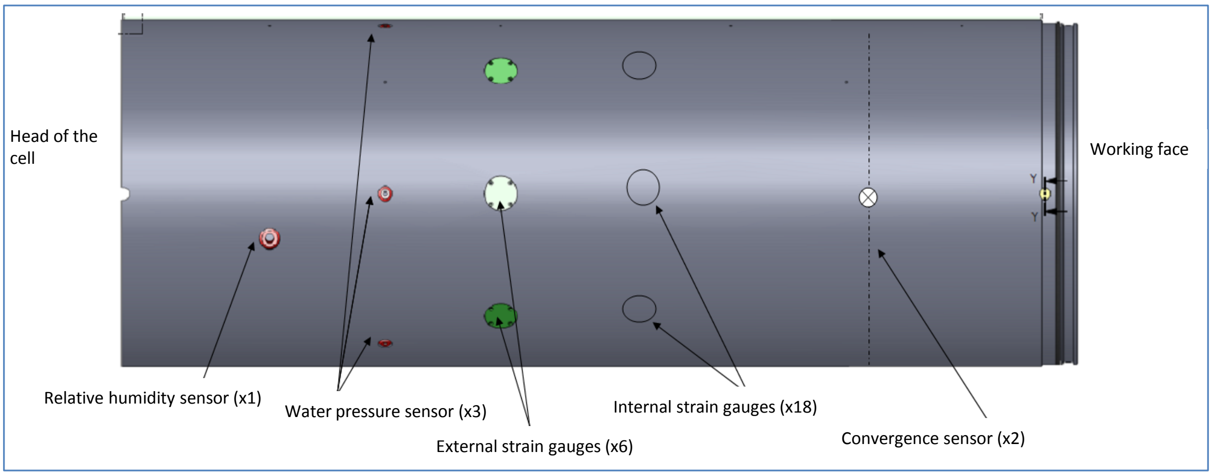

Figure 4.12: Location of the sensors on an instrumented casing element as implemented in the cell liner monitoring demonstration.

A series of other measurements were also made during the demonstration activity:

- Pore pressure, temperature and displacement were measured in a borehole, parallel to, and within a few metres of, the disposal cell.
- Deformation and temperature were monitored on the internal surface of the liner and deformation was monitored on the external surface of the liner so as to monitor its overall thermo-mechanical behaviour and to detect any possible rock spalling; these measurements were made with optical fibre sensors.
- The excavation rate and applied pressure were monitored to estimate the performance and the limits of the excavation method and to assist in the interpretation of the measurements of the displacement of the rock on the periphery of the cell.
- The geometrical characteristics of the cell were measured using a 3D laser scan.

Within the framework of the MoDeRn Project, the monitoring of the demonstrator was undertaken for 300 days following installation of the network. Saturation of the annular space around the cell liner has been successfully monitored with the three sections furthest from the access tunnel achieving a saturation of 98%. The section closest to the tunnel has not saturated owing to the influence of the tunnel temperature.

Creep of the rock around the liner has been monitored. This monitoring has identified that rock creep results in convergence in the horizontal direction and divergence in the vertical direction. The initial annular space of 40 mm between the rock and the casing in the horizontal direction closed in less than a month. The maximum values of strain on the internal surface of the liner were less than 300 µm/m.

The optical fibres were successfully installed with the exception of the external fibre intended to monitor for rock fall. This sensor is assessed to have been damaged owing to vibration during the installation process. No data has been acquired from this fibre.

Pressure monitoring in the borehole parallel to the disposal cell has been successful in monitoring pore pressure, including detection of an overpressure associated with the construction of a separate nearby cell.

Therefore, the disposal cell monitoring demonstrator has built confidence in the ability to monitor the thermo-mechanical evolution and retrievability function of a disposal cell. However, further developments in the monitoring technology are necessary, including development of approaches for monitoring the cell chemical evolution, development of installation methods for fibre optic cables, and testing of pressure sensors within the disposal cell; this was not feasible as full saturation was not achieved during the 300-day testing period available in the MoDeRn Project.

4.4 KBS-3V Case Study: Crystalline Host Rocks

4.4.1 Programme Context

A licence application was submitted for construction of a spent fuel repository to be built in Olkiluoto in Eurajoki, Finland, in December 2012. The repository design is based on the KBS-3V concept in which spent nuclear fuel is encapsulated in canisters made of cast iron and copper. The canister is emplaced in a vertical borehole in crystalline bedrock hundreds of metres below the surface and surrounded by a buffer of compacted bentonite.

4.4.2 Safety Case

According to the safety concept for the Olkiluoto repository, safe disposal is achieved first by long-term isolation and containment of the nuclear waste using multiple barriers until the waste no longer poses a risk, and second by ensuring that in the unlikely event of an early canister failure, safety is maintained by limiting and retarding the release and transport of radionuclides. Each component of the barrier system has one or several safety functions which describe its role in achieving the general goal of safe disposal. The barriers and their safety functions are:

- Canister: prolonged containment of the spent fuel.
- Buffer: primarily to provide favourable conditions for the canister to fulfil its safety function, and secondarily, to limit and retard the transport of radionuclides in the event of canister failure.
- Backfill: provide favourable conditions for the canisters and the buffer, limit and retard the transport of radionuclides, and contribute to the mechanical stability of the rock adjacent to the emplacement drifts.
- Host rock: physically isolate the spent fuel from the biosphere, impede (un)intentional human intrusion, provide favourable conditions for the previous barriers, and limit and retard the transport of possibly released radionuclides into the biosphere.

The geotechnical barriers (the canister, buffer and backfill) are associated with performance targets and the host rock contains target properties achieved through appropriate site selection. The performance targets and target properties are each linked to specific safety functions, and represent the parameters of relevance to this case study.

4.4.3 Processes and Parameters

Posiva (2012) has undertaken an iterative and structured approach to identify monitoring targets involving the identification of processes that can lead to performance targets and target properties being missed. A screening process considered the potential for each identified process to significantly affect performance of the repository and is used to judge whether or not the process should be included in the monitoring programme (Miller *et al*., 2002). Processes were screened out of the monitoring programme if they were of low significance to safety or if it was judged to be unfeasible to monitor the process. Processes that were considered as being unfeasible to monitor *in-situ* were addressed by additional research activities, including laboratory experiments. The illustrative EBS monitoring programme developed within the MoDeRn Project focused on a programme for monitoring the bentonite barrier performance, and the processes occurring within the bentonite barrier identified through the approach described above, and the associated monitoring targets (parameters) are listed in Table 4.3.

Table 4.3: Monitoring processes and targets for monitoring of the bentonite barrier in the KBS-3V concept as envisaged within the Finnish programme (Posiva 2012).

Process	Targets
Heat transfer	Temperature
Water uptake	Moisture in buffer
Swelling	Swelling pressure and pore pressure
Mass redistribution	Buffer displacement and uplift
	Canister displacement
Chemical changes of pore water	*In situ* pH (and other possible) measurements

4.4.4 Illustrative Monitoring Programme Design

In the KBS-3V concept, placing sensors within the bentonite buffer and bentonite backfill is judged to be not acceptable within the overall safety case. Therefore, the monitoring programme envisages development of a near-field monitoring system based on a disposal tunnel that does not contain real waste. Instead, the tunnel would be filled with dummy canisters. These would be heated, and would be made of the same materials, and have the same mass and dimensions as the waste canisters but would not contain any waste. The buffer and backfill would be emplaced as envisaged in the rest of the repository. At the end of the monitoring period, the canisters would be recovered to collect data on corrosion of the overpack, chemical changes in the bentonite and corrosion of steel auxiliary components.

Based on the processes and targets listed in Table 4.3, the monitoring system design contains sensors for monitoring temperature, total pressure, pore-water pressure and moisture content. This design is an example of how these specific parameters could be monitored based on available sensors and data transmission units, including recently developed systems. Table 4.3 also requires monitoring of buffer displacement and uplift, canister displacement and *in situ* pH; an approach for monitoring these parameters is still under development.

The envisaged monitoring scheme would include monitoring within and above the four deposition boreholes contained in the near-field monitoring system (Figure 4.13) and in two additional locations within the bentonite backfill (marked as F and H in Figure 4.13). In the deposition boreholes, sensors would be arranged at three levels, two just below and above the dummy canister, and one at the mid-height level of the canister. At each level, measurements would be made in four locations evenly distributed around the canister. In the proposed monitoring programme, all recorded data would be transmitted using a wireless data transmission system using electromagnetic waves.

Two types of transmitters are proposed for the system, both of which have been developed by the Radioactive Waste Management and Funding Centre (RWMC) of Japan[5]. The frequencies envisaged in this system are 1 kHz and 10 kHz, but the transmitter is a short-range type.

[5] RWMC was a partner in the MoDeRn Project.

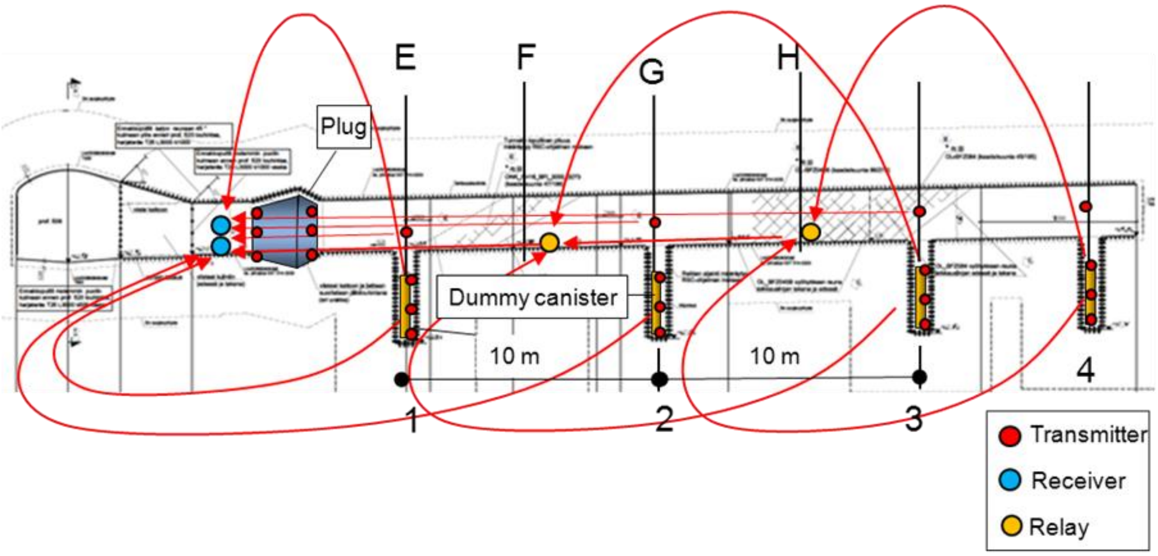

Figure 4.13: The principle scheme of a near-field monitoring system, illustrating the location of sensors, relay stations and receivers.

For the current designs of the transmitters and sensors, one sensor could be attached on the outside of the transmitter unit. This system could be installed in a deposition borehole, because of its small size and because it is water-tight up to a water pressure of 10 MPa. The transmission distance of this node is expected to be 25 m or more in saturated bentonite, and larger in unsaturated bentonite. The second, larger, node, which could have four sensors attached to the outside of the transmitter unit, could be used for an installation in the backfilled tunnel because sufficient space is available. Using these nodes, it is anticipated that the bentonite saturation process can be monitored by measuring swelling pressure, water content and relative humidity. Two different types of moisture sensors are proposed so that their measurement ranges overlap and in order to introduce a level of redundancy into the monitoring system.

Both of the nodes have one temperature sensor inside the transmitter unit for the necessary temperature correction. The life-time of each node is currently expected to be 10 years based on power being supplied by a lithium battery, a measurement frequency of once per day, and a data transmission frequency of once per week. The individual sensing units are small in length (240 mm) and diameter (60 mm). If emplaced in a longitudinal orientation in the buffer without placing them next to each other, its impact on buffer performance is assumed to be negligible, although this assumption will have to be tested within the safety case.

4.5 Detecting Failures in the Monitoring System

In order to support decision making during the stepwise implementation of geological disposal, there needs to be confidence in the monitoring data which might be used to support decision making. Accurate data acquisition requires a chain of sensors, cables, connectors, analogue-digital-converters, data-acquisition units, data-processing units, correction and calibration methods, and, in some cases data transmission units, all working to specification. Therefore, the quality of monitoring data does not only rely on the sensor itself, but also on the proper operation of each of the given components, and as it is the monitoring results and not the sensor readings that will be used for decision making, statements on data quality beyond the sensor level are required. These statements are part of method and procedure descriptions that have to be developed in order to quantify the performance of each applied system.

A failure in a monitoring system is defined as a specific circumstance that results in invalid monitoring data (data values that are influenced by factors other than those described by the method), i.e. the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena occurring in the repository.

Failure modes can be classified as follows:

- Technical failures:
    - Total or partial sensor failures.
    - Failures of signal transmission.
    - Failures of signal conversion.
- Methodological failures:
    - Failure of sensor installation and placement.
    - Distortion of sample environment.
    - Unidentified cross-sensitivity.
    - Failure of correction methods (drift, cross-sensitivities).
- Procedural failures:
    - Loss of redundancy (i.e. simultaneous failure of several sensors).
    - Failure of any error detection and error correction procedures.

4.5.1 Detecting Sensor Failure

Failure detection methods for sensors include:

- Redundancy: The basic principal of redundancy is that more than one sensor measures the same phenomena and signal deviation is used to detect defective functional blocks (Weiler, 2001). Redundancy can be introduced on several levels, including the use of several sensors at the same location, the use of several sensors at comparable locations, and redundancy in data transmission systems.
- Known Relations: Error detection by means of known relations is a method that is based on diversity. Diversity, or *distinct functional redundancy*, is a special form of redundancy where two different methods are used for measuring the same parameter.

An example of error detection integrated in a sensor element is a differential pressure sensor with redundant temperature measurement function (Schneider, 1996).

- Electrical Stimulation: The sensor element is directly stimulated by means of electrical impulses that – together with the measured variable – are processed by all subsequent components of the sensor system. In an accurately working sensor system, the electrical stimulation of the sensor element leads to a known sensor response that can be detected in the output signal. A basic application of electrical stimulation is the measurement of the insulation resistance of thermocouples by measuring the resistance (DC or low-frequency AC) along the conductors.
- Reliability Indicators: Failure detection by means of reliability indicators uses certain features of a circuit/system or sensor to indicate the occurrence of, or evolutions that might lead to, a failure. These features are continuously monitored to detect if they exceed or fall below certain specified ranges/values which are only physically possible if an error occurs. Examples of reliability indicators are steady-state current measurements in so-called Complementary Metal Oxide Semiconductors (CMOS), integrated circuits or temperature measurements using thermocouples inside data acquisition systems to check for any deviating conditions within the system.
- Local Sensor Validation: The detection of local errors in a sensor system can be undertaken by analysing the unfiltered signal of the system as certain signal characteristics in the unfiltered output signal of a sensor system, e.g. spikes, may suggest a failure (Amadi-Echendu, 1994). Yung (1992) proposed eight typical output signals that indicate a failure (Figure 4.14).

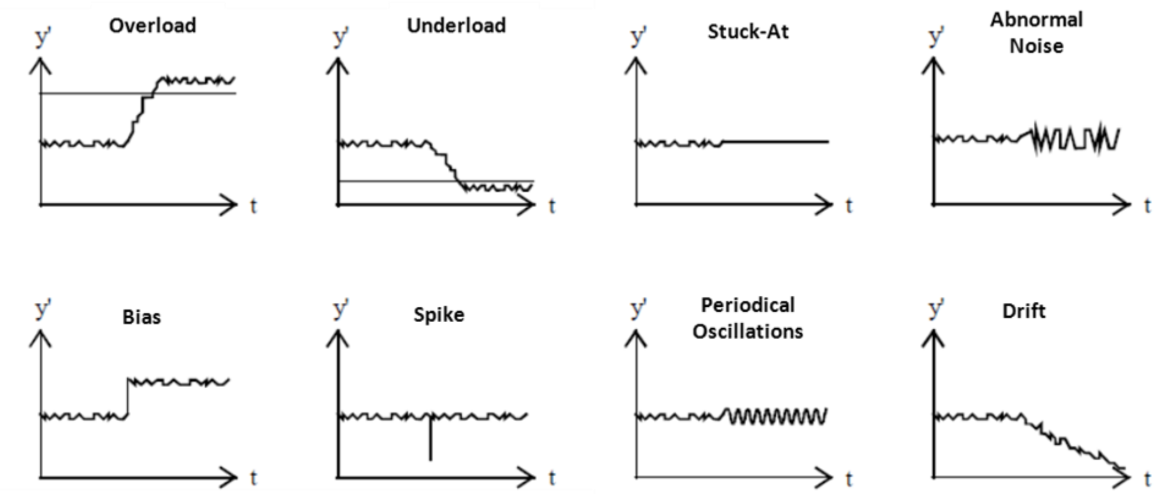

Figure 4.14: Examples of characteristic output signal in the case of a failure (Yung, 1992).

- Correlation: This method can be applied when sensors measure the same physical parameter and are placed in equivalent positions with respect to the measured object (e.g. measuring temperature at the same distance but in the opposite direction from a heat source in a medium with isotropic thermal conductivity). Then it is possible to evaluate whether the readings of one of those sensors are valid by directly correlating them with the readings obtained from the others. Indirect correlation can also be established between sensors measuring different parameters if they are embedded in media where these parameters are coupled.

In MoDeRn (2013l) an analysis is provided that identifies failure detection methods for different types of measurement, and which clearly identifies possibilities and limitations of failure detection methods with regard to long-term repository monitoring.

4.5.2 Detecting Data Transmission Failure

Failure of a monitoring method can also be the result of (incorrect) data transmission. Detecting data transmission failure is of particular relevance to the MoDeRn Project, given the consideration of wireless data transmission techniques in the project.

Three types of transmission failure mode are readily identified:

- General unit failure.
- Protocol errors (errors in the coding of software, which can be overcome through testing)
- Noise and/or interferences that alter the transmitted signal on its way from the transmitter to the receiver, e.g. channel interferences, signal distortion, or synchronization problems.

Assuming that data transmission in the case of repository monitoring is limited to binary digital data, data transmission errors are manifested by wrongly received bit values (i.e. *1* instead of *0* and vice versa). Transmission errors can be minimized by proper design, but not totally avoided owing to the random nature of noise and interferences. Quantification of the error probability is part of the performance description of a transmission method. Data transmission errors are quantified by the '*bit error rate*' (BER), and an example of the use of the BER to quantify data transmission performance has been applied in the MoDeRn Project as part of the development of low-frequency data transmission systems (see Section 3.2.4). The achievable BER is related to the signal strength. In repository monitoring, when supply of energy may be limited, the merits of a lower BER need to be balanced against the higher energy need.

Many error detection, elimination and correction schemes have been developed in order to detect, eliminate and correct errors in digital data streams, and, therefore, transmission errors do not necessarily result in incorrect data. All of these methods detect errors of the overall transmission chain, i.e. they do not depend on the specific localised cause of error. The simplest scheme is the use of a *parity bit* that is added to a group of bits and indicates if the number of ones in the group is even or odd. This allows the identification of single bit errors. More complex schemes exist that allows identification of the presence of multiple bit errors.

In cases where the error detection method has identified erroneous transmitted data, the accompanying data points can be eliminated. Elimination of incidental erroneous data might be a minor problem in many application cases, since monitoring data can consist of long timelines of slowly evolving processes, where incidentally missing data points are of no relevance. In the case of bidirectional transmission system, transmission errors can be notified to the transmitter station, allowing it to resend the missing data.

In addition to error detection methods, error correction methods can be used to restore the original data in the case of a transmission error. Error correction methods use comparable approaches to error detection methods, but are more complex because here, in order to restore the original data, the individual bit that causes the error has to be identified.

Error detection and error correction methods both make use of extra (redundant) data (checksum bits) that are added to the data stream, and therefore increase the amount of data to be transmitted. Simple error detection schemes like the parity bit involves a single additional bit for each group of data, while error correction schemes may increase the data stream significantly (e.g. 60% or more). As with the consideration for minimising the BER, the energy necessary to implement a certain error detection and/or correction method must be considered.

4.5.3 Detecting Overall System Failure

Additional options are available in order to avoid, detect and - if possible - correct monitoring system failures:

- By defining proper installation, testing and quality assurance procedures.
- By making use of overall system redundancy (in addition to sensor redundancy).
- By using cumulated information of different methods.

In industry, the operation of sensors and electronics in hazardous environments requires the use of intrinsically safe systems that are rated and approved for the specific environment. For the specific case of repository monitoring, especially for long-term monitoring of the EBS after emplacement of the waste, buffer and backfill, the method(s) of so-called *fail-safe sensors* as used in industry may be of value in developing reliable monitoring systems. These systems make use of error detection methods described above and apply these methods in a predefined, automated manner. Further details about fail-safe sensors and their working principles are described in MoDeRn (2013l).

Experience in failure detection has been developed in several URLs. For example, ANDRA uses the SAGD (Système d'Acquisition de Gestion de Données) data acquisition system in the Bure URL. The system provides a well-established example of an automated failure detection system that has been used for more than ten years.

4.5.4 Discussion of Detecting Failures in the Monitoring System

The overview of potential failure modes discussed above shows that, in numerous and widely varying safety-relevant areas, different methods to detect errors and failures have been developed, many of which are applicable to repository monitoring. These vary with respect to the degree of reliability that can be achieved, the technical efforts necessary and the special requirements of the particular application.

The relation between detection methods and failure modes gives a first idea of which failure modes may stay potentially undetected and which modes are less challenging (e.g. a simple sensor breakdown is easily identified by redundancy). It also shows what (combination of) measures/techniques are effective in addressing failure modes. By selection of principal techniques that are favourable with respect to failure detection, the ability to identify potential failures of the monitoring system can be improved. Understanding of the relation between failure detection and different techniques may also help to identify additional monitoring techniques or measures that can be applied in order to address as many failure modes as possible.

Robust methods and procedures that qualify all aspects of the performance of the applied monitoring systems are essential to allow the data to be used in decision making. Owing to the long timescales and the fact that sensors or other components of the monitoring equipment may be inaccessible, repository monitoring is challenging, and the possibility of failure detection will be an important aspect of the robust methods that need to be developed. When it comes to the detection of failures, several specific features of monitoring in waste disposal can be used:

- Evolution of parameters is usually slow, enabling efficient criteria to be defined for local failure detection systems.
- Redundancy can be applied easily and on different levels:
  - Redundant sensors in the same disposal component.
  - Sensors at different locations within, or distances from, a disposal component.
  - Repetitive monitoring of the same component in different parts of the disposal system.
  - Distinct functional redundancy.
- Correlations can be used because in most cases more than one parameter is measured, and some parameters have a constitutive relationship with each other.

4.6 Conclusions on Monitoring Programmes

Prior to the MoDeRn Project, limited development of EBS monitoring programmes had been undertaken for national repository programmes in Europe. As noted in the introduction to Chapter 2, prior to the MoDeRn Project, guidance on the development of monitoring programmes at the international level included only general requirements describing how monitoring can support the implementation of geological disposal in a broad sense (IAEA, 2001; EC, 2004).

Within the MoDeRn Project, monitoring case studies have been developed for the three main types of host rock considered suitable for the geological disposal of radioactive waste. The case studies have demonstrated that monitoring programme designs can be established based on a structured analysis of the FEPs and safety functions considered in the safety case and to address pre-closure information requirements prescribed in regulations (e.g. to demonstrate reversibility).

Several strategies for overcoming well-known challenges to repository monitoring have been identified and proposed in the case studies. These include:

- The use of different types of monitored disposal cells in the French case, including sacrificial cells that will be decommissioned and from which waste will be retrieved during the closure of the repository.
- Monitoring strategies which focus on the monitoring of wastes emplaced during the first stages of operation, which allows information to be gathered and used in decision making during the subsequent stages of operation.
- The monitoring of disposal tunnels that do not contain real waste (KBS-3V example). Both the German and the KBS-3V cases envisage the use of dummy canisters, i.e. canisters with the same material properties, mass, dimensions and heat output as canisters containing waste, but which can be instrumented to allow monitoring of the near field.

The case studies have shown how several of the technological developments made within the project and reported in Chapter 3 of this report can be directly employed within repository monitoring programmes.

The case studies have allowed some aspects of the MoDeRn Monitoring Workflow to be tested using existing safety case and other national context information. All of the case studies were developed using an approach that is consistent with the MoDeRn Monitoring Workflow, i.e. an approach that includes identification of the main objectives and reasons for monitoring, identification of sub-objectives, processes and parameters through an evaluation of the safety case and other drivers (e.g. requirements of stakeholders identified through specific engagement and involvement activities), and the development of monitoring system designs based on an understanding of the performance requirements and techniques available. However, some steps in the Workflow were not used in the case studies. The required performance of the monitoring system was not specified as information to allow the performance to be specified was not available. In addition, the use of monitoring programme results in decision making was not assessed as the programmes were not implemented.

An analysis of monitoring system failure detection has demonstrated that there is a range of methods available for ensuring confidence in the data acquired by monitoring systems, even when these systems have to operate remotely for long timescales. Failure identification procedures should always be a key part of a monitoring system, especially when thinking about the use of monitoring results for decision-making processes.

There is a need to further develop and test monitoring programme designs that utilise a range of monitoring technologies and are related to specific monitoring sub-objectives (integrated monitoring systems) to demonstrate that the considerations related to monitoring programmes presented in this section can be implemented in actual repositories.

5 Stakeholder Involvement in Monitoring Programmes

Experience in the development of national programmes for the geological disposal of radioactive waste to date has demonstrated that developing and implementing a programme for geological disposal attracts considerable public interest and attention. In some cases, agreements have been reached among the affected parties. In others, proposals that have been advanced have met strong opposition from members of the general or affected public and their political representatives. Indeed, sometimes the anticipated opposition may appear so strong that proposals are never advanced at all (IAEA, 2007).

At the 44th Session of the IAEA General Conference (IAEA, 2000), it was recognised that:

- Technological solutions to the safe management of radioactive waste exist, but public acceptance is needed.
- A structured participatory process is needed for decision making.
- Consensus of all parties is unlikely and therefore a formal, transparent decision-making process with public participation is essential.
- The decision-making process needs to be step-wise, with the ability to reverse decisions at a later stage.

International guidance documents on monitoring of geological repositories (e.g. EC, 2004; IAEA, 2001) suggest that monitoring can potentially contribute to public acceptance by building confidence in the behaviour of a facility and can play a role in structured participatory processes for decision making. However, in order for monitoring programmes to effectively contribute to building public and stakeholder confidence, they must be able to answer stakeholders' expectations within the limits of the technical requirements on implementation of geological disposal. To know and understand these expectations, WMOs should engage with different stakeholders, from an early stage of repository development, and be transparent about the limits of monitoring (including what could realistically be expected in terms of evolutions in monitoring techniques).

In the MoDeRn Project, research was undertaken on public stakeholder involvement in repository monitoring that was directed at a better understanding of views on the nature and role of monitoring in geological disposal, and the governance of repository development and staged closure. By improving this understanding, it was expected that information and guidance could be identified that would support the future development of national or repository-specific monitoring programmes.

Consideration of participatory processes in repository monitoring was conducted through a range of activities:

- Interviews were conducted with 18 specialists employed by European WMOs (MoDeRn, 2012).
- A workshop was held with stakeholders in which representatives of other organisations (mainly regulatory agencies, but also with a limited number of participants from advisory bodies and public stakeholder groups) discussed the research activities of the MoDeRn Project and provided insights into stakeholder views on repository monitoring (MoDeRn, 2011a).

- Workshops involving public representatives from nuclear facility host communities were held in Belgium, Sweden and the UK. The participants in these workshops had varying degrees of engagement with, and knowledge of, radioactive waste management projects (MoDeRn, 2013c).
- A visit to the Mont Terri URL and the Grimsel Test Site in Switzerland was undertaken with a subset of the public representatives that participated in the host community workshops.
- Discussions on the role of stakeholder involvement in repository monitoring programmes were also held during the international conference on monitoring in geological disposal of radioactive waste (MoDeRn, 2013a).

The work was led by a team of social scientists with experience of, and expertise in, participatory approaches in geological disposal of radioactive waste. A summary of the overall programme of work on stakeholder involvement in monitoring programmes is provided in MoDeRn (2013c).

The key messages from the research are presented in this section. These messages are discussed in terms of views expressed by the stakeholders consulted on five key questions associated with monitoring:

- Why conduct repository monitoring? This question is discussed in Section 5.1.
- What should be monitored, where in the repository should monitoring data be acquired and how should monitoring be undertaken? (Section 5.2).
- Who should monitor? (Section 5.3)
- Over what period should repository monitoring be undertaken? (Section 5.4).
- What is the overall role of monitoring in repository governance? (Section 5.5).

Overall conclusions from the research into stakeholder involvement in repository monitoring and guidance on participatory processes are presented in Section 5.5.

5.1 Views on Why Monitoring Should be Undertaken

As summarised in Section 1.2, technical reasons for monitoring include the provision of support to the post-closure safety case, demonstration of operational safety, and monitoring in support of EIA and safeguards. In addition, it is also expected by professionals in radioactive waste management that monitoring will 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 (EC, 2004). Monitoring is expected to support *public confidence* (IAEA, 2001; EC, 2004) and public *acceptability* (e.g. IAEA, 2011, p. 44).

The role of monitoring in providing assurance was explicitly mentioned by all of the technical specialists interviewed within the MoDeRn Project as one of the main drivers for monitoring. Distinctions were drawn in the way that this could be achieved for three different types of stakeholders:

- The implementer may see monitoring as a tool for assessing the performance of a repository and for contributing to quality assurance, i.e. supplying a means for the verification of both the repository system and the modelling behind it.
- Regulators may seek assurance that the repository monitoring programme has successfully incorporated specific societal expectations by being compliant with regulatory requirements, particularly in relation to requirements for operational safety and EIA.
- The public may make demands for transparency and oversight of repository development and staged closure including the provision of monitoring information.

The role of monitoring in supporting public confidence building was echoed in the workshop activities with local stakeholders in Belgium, Sweden and the UK. The Belgian group, for example, came to the conclusion that confidence building and *keeping guard* over the safety of the facility were the main reasons for monitoring. The UK group also identified stakeholder confidence in the safety of the repository as one of three reasons to monitor, the other two reasons being verification of compliance with prevailing regulations or standards, and *quality control* to support continuous refinement or improvement. Informing both the Belgian view on keeping guard and UK views on verification of continued safety is a notion of maintaining a watch over the repository.

Both local and national stakeholder representatives in Sweden discussed the importance of the timing and location of monitoring activities. The question of whether monitoring programmes carried out in URLs or pilot facilities during repository development can reduce the need for *in situ* monitoring of the actual repository was discussed. In both Sweden and Belgium, the argument was made by public participants that monitoring is needed *to know what happens in reality*. Confidence building through compliance monitoring and quality control thus seems to be a common reason for monitoring put forward by implementers, regulators and members of the public confronted with a geological repository programme.

A view commonly held by expert stakeholders is that the focus on assurance monitoring should be on *performance confirmation*. For example, this view was stated several times at the stakeholders workshop (MoDeRn, 2011a). Because expert stakeholders rely on the safety case as the principal method for demonstrating confidence in the long-term (post-closure) safety of the disposal system, they consider that checks on whether or not the system provides adequate safety come from the development of the repository design, from the site selection and site characterisation activities, and from the safety strategy used in development of the safety case (IAEA, 2012).

Furthermore, the participants at the stakeholders workshop noted that an underpinning philosophy applied by implementers was that obtaining a licence for constructing and operating a repository is proof of a high degree of confidence in the safe performance of a repository, and hence, as required in IAEA requirements on geological disposal (IAEA, 2011), there would not be reliance on monitoring as a basis for ensuring safety (MoDeRn, 2011a, p.18). If monitoring is dedicated to helping stake out a path to passively safe waste packages, facilities and sites, then it must be dedicated to progressively reducing the need to repeatedly 'check-up' on safety. It must be dedicated to verifying the needlessness of continuing to look.

In contrast, the community stakeholders in the Belgian, Swedish and UK workshops, as well as in the MoDeRn stakeholder workshop made clear they expect a more critical assessment of safety. Like the technical specialists, they do not see monitoring in itself as contributing to the safety of the repository. They do, however, expect it to assess or check that safety is ensured. For that reason, they do not only require operator and expert assurance of safety, but also the additional assurance of (independent) monitoring - and (independent) control of that monitoring - for any evidence of exposure to harmful releases. Such an attitude is confirmed by literature on (environmental) risk and trust in experts and expert systems (e.g. Giddens, 1991; Irwin, 2008; and Simmons and Wynne, 1993).

At several occasions during the workshops with public stakeholders it was commented that the use of the term 'performance confirmation' came across as arrogant, and that it was inappropriate to take as a starting point the assumption that no problems can occur in future. Monitoring was thus considered a necessary action to remain *on guard*, but was only seen as effective if accompanied by a proper response plan or a Plan B should anything unexpected be detected. One of the public stakeholders' main concerns is that designing monitoring programmes solely for performance confirmation is likely to lead to implementers prioritising the monitoring of different parameters to those that might be most appropriate for registering unlikely and unexpected events.

5.2 Views on What, Where and How to Monitor

Among technical specialists there appears to be a widely held perception that public and stakeholder expectations are likely to focus on environmental monitoring in order to protect against human health impacts. A review of literature on public and stakeholder engagement in monitoring within the nuclear sector and in other contexts seems to corroborate this perception (Bergmans *et al*., 2012). However, there is also evidence that some stakeholders do not draw a distinction or express a clear preference between monitoring of different parts of the repository system; they expect implementers to develop a plan including specification of what, where and how monitoring would be undertaken.

From the engagement exercises conducted within the MoDeRn Project, it appears that local citizens are less concerned about what parameters are included in the monitoring programme or the exact locations where monitoring is conducted. What they did insist upon, however, was that repository monitoring programmes were as comprehensive as possible, and should have a broad scope, including both near-field and far-field monitoring. Both the Belgian and UK groups acknowledged the potential tension between potentially intrusive near-field monitoring and the integrity of barriers and seals that are required for passive safety. It was also considered to be important, most notably by the Belgian group, to continue searching for alternative parameters or techniques for processes that would be difficult to monitor with current technology, and to consider laboratory simulations as alternatives to near-field monitoring (e.g. in a post-closure situation).

5.3 Views on Who Should Monitor

For the participants in the different workshops it appeared self-evident that the implementer would be responsible for setting up and conducting the monitoring programme. They did, however, insist on additional mechanisms for control. Control by the regulator is one possible mechanism, but other forms of independent control are also seen as important in contributing to building confidence. An example of independent control is the environmental monitoring of the Waste Isolation Pilot Plant (WIPP) in New Mexico, US, which is being conducted by an independent agency, the Carlsbad Environmental Monitoring and Research Centre (CEMRC). CEMRC is funded by the implementer (the Department of Energy) through a grant process to respects its independence (see MoDeRn (2013a) for a paper on the monitoring work of CEMRC).

Indeed, in several cases found in the literature, different forms of environmental monitoring were commissioned or conducted by local institutional stakeholders, particularly local governments, including some examples that integrate this with monitoring of the socio-economic environment (e.g. Conway et al., 2009). Dissatisfaction with or distrust of institutions has also led members of some communities to demand or even initiate participatory environmental monitoring, which involves local citizens in data collection (e.g. Vári and Ferencz, 2007; NEA, 2009). Both the literature review and the engagement activity conducted within the MoDeRn Project demonstrate the desire of members of the public and communities in many different contexts for active engagement with facility monitoring programmes.

5.4 Views on How Long to Monitor

For the technical experts, monitoring is primarily an activity dedicated to advancing and facilitating repository closure and confirming that the conditions outlined in the regulatory safety case have been achieved. Near-field monitoring following closure in particular was said by many of them to be unrealistic and even potentially counterproductive insofar as the techniques used could contribute to compromising barrier integrity. Nevertheless, many experts interviewed thought that there could be value in post-closure monitoring if it were needed to reassure other actors such as local communities, a position that is also expressed in international guidance (e.g. IAEA, 2011). It was furthermore recognised that although there is currently little evidence of statutory requirements for post-closure monitoring, it seemed possible that they would be introduced in some countries in the future in response to societal demands.

Evidence from the Belgian, Swedish and UK workshops confirmed that constructively engaged members of the public do have expectations and concerns regarding post-closure monitoring. What is less clear is the type of monitoring they would be expecting in the post-closure period, and where they might expect such monitoring to be based (i.e. monitoring of the near field, far field or the surface environment based on sensors located in the near field, far field or the surface environment). In the Swedish workshop, it was pointed out that even if post-closure monitoring is considered desirable, the technological innovation required to enable such monitoring is hardly likely to take place without the purposeful allocation of funds to related research and development. Community stakeholders were therefore concerned about post-closure safety but, unlike the technical experts, tended to see continued monitoring of some sort as being necessary not merely to confirm that the evolution of the repository system conforms to technical expectations, but to ensure that it continues to do so.

5.5 The Role of Monitoring in Repository Governance

For several decades now, one of the key principles informing the management and regulation of nuclear safety has been that of constant surveillance. This is first a political and moral principle which informs the practical design and development of nuclear activities; this principle is therefore an expression of what societies interpret nuclear safety to mean. Monitoring programmes focused on different types of nuclear activity are therefore ways of putting the moral principle of tireless vigilance into technical practice. This is particularly the case for nuclear installations such as power plants, fuel production plants, reprocessing plants, and storage facilities, as pointed out by nuclear scientist Alvin Weinberg, when he referred to the unusual degree of vigilance which had to be exercised over all programmes of nuclear power generation in order to guarantee safety (Weinberg, 1972). Geological repositories, incorporating the technical - and moral - principle of passive safety, can be understood as a way of trying to renegotiate the need for unremitting vigilance by delegating responsibility for safety to an engineered geological disposal system. The question then is how should the gradual transition from active human vigilance to passive safety without human intervention be organised? Weinberg (1972) believed that effective geological disposal reduced the need for vigilance to a minimum. However, the exploratory engagement with community stakeholders undertaken in the MoDeRn Project suggests that more is expected by many public stakeholders.

The principal of unremitting vigilance, as Weinberg (1972) reminds us, poses societal questions that cannot be answered from a technical-expert perspective alone (Weinberg 1972). Society will therefore have to decide what kind of human vigilance is needed and for how long it should continue. Nevertheless, for society to relinquish direct control of the wastes will require confidence in the repository system and trust in those responsible for designing, implementing, overseeing and regulating it. It may therefore be easier for national and local decision makers, and the communities that they represent, to commit to taking successive steps in repository siting, development, licensing, construction and operation if the contingent nature of their trust and commitment at each and every stage is acknowledged and the opportunity to influence plans is upheld.

In addition to providing confirmation of the assumptions, arguments, evidence and models upon which the safety case is based, therefore, there is another way in which monitoring can support public confidence. This is by the implementer accepting that monitoring could be undertaken to check that there are no uncertainties that have not been considered within the safety case, i.e. by using monitoring as a supporting argument in the safety case. Such a wider approach to addressing uncertainty is not without its risks, of course, in that it may appear to bring into question the premise of passive safety as the technological solution to the socio-technical problem of guaranteeing unflagging vigilance over long-lived radioactive waste. By introducing the notion of retrievability or reversibility into law, however, countries such as France are already moving towards an adapted socio-technical solution, one still directed towards achieving passive safety, but which recognises that this end point may be further away than initially planned, subject to a longer chain of socio-technical decision making, and that decisions made under the current socio-political framework may not be final. Such evolutions remind us that we inevitably pass the burden of decision making about final closure to subsequent generations. Acknowledging this requires that we think more specifically about the type of information, knowledge and skills that need to be passed on to future generations, and the role that monitoring might play in meeting the needs of future operators, regulators, decision makers and affected members of the public.

5.6 Conclusions on Stakeholder Involvement in Repository Monitoring

The national workshops and Swiss URL visits demonstrated that it is possible to discuss in a detailed manner monitoring issues with interested local stakeholders, even at an early stage in a repository programme. These activities furthermore revealed a mutual interest between participating technical experts and local stakeholders, leading to fruitful discussions considered beneficial and of interest by both parties.

The main conclusions from the work on stakeholder involvement in monitoring programmes are as follows:

- The opinion that monitoring should be a checking process rather than a confirmatory process was expressed by many stakeholders. Monitoring programmes are therefore likely to be viewed by some stakeholders as being more trustworthy if it is clearly communicated that they are designed from the perspective of challenging that repository behaviour is as expected, and if stakeholders are able to access clear information on how each aspect of repository performance is checked.
- Public stakeholders expressed a view that the checking of repository performance should be comprehensive and linked to an overall science programme. A continuation of research and development on repository monitoring techniques was expected. WMOs could ensure that this view is addressed by discussing with their stakeholders the role of monitoring during different phases of repository implementation, and by communicating the manner in which operational and long-term safety is assured.
- As anticipated, some public stakeholders do have expectations regarding post-closure monitoring, mainly in view of being able to prepare for (and respond to) unanticipated events or evolutions. Individual programmes will need to decide on ways to respond to this expectation. Additionally, communication of the understanding of remaining uncertainties, and a preparedness to allow options for monitoring to evolve and to respond to changes in the expected evolution of the repository (e.g. closure being postponed) could be beneficial to addressing stakeholders' expectations regarding long-term monitoring.
- Monitoring can be characterised as a socio-technical activity and could potentially contribute to building the confidence of public stakeholders in the safety of a particular repository project, though not by itself. Of course, many other factors will also play a role in building stakeholder confidence, such as the approach to decision making, and the level of public and stakeholder engagement. Monitoring can contribute to repository governance if it can address expectations from stakeholders, if it is expressed as a practical commitment to maintain a watch over the repository performance, and if there is transparency about the limits of monitoring, including what could realistically be expected in terms of evolution in monitoring techniques.

6 Conclusions

The MoDeRn Project was initiated by the MoDeRn partners to further develop the understanding of the role of monitoring in the staged implementation of geological disposal with the aim of providing examples, guidance and recommendations that may be useful, particularly to WMOs for their development of monitoring programmes, and the understanding of how these could be implemented and used as part of the overall disposal process. This has been achieved through the following activities:

- Developing the MoDeRn Monitoring Workflow, which provides a generic structured approach to the development and implementation of a monitoring programme, and the MoDeRn Reference Framework, which provides illustrations and examples of how monitoring can be undertaken for different contexts.
- Developing the understanding of, and undertaking RTD on, monitoring technologies, thereby extending the range of monitoring technologies available to WMOs, and evaluating the range of applications for which these technologies could be used.
- Describing a range of illustrative monitoring programmes that show how integrated repository monitoring programmes can be developed to address specific programme objectives.
- Evaluating the potential role of stakeholders within repository monitoring programmes, and considering how the views of stakeholders on repository monitoring may affect the development of a national repository monitoring programme.

6.1 Guidance on the Development and Implementation of Monitoring Programmes

The MoDeRn Monitoring Workflow provides a systematic top-down approach to developing monitoring objectives into processes and parameters to be monitored, designing a monitoring programme, and using the results of the monitoring programme to support decision making. The workflow should aid implementing organisations in developing monitoring programmes.

The MoDeRn Project has demonstrated that it is important to understand the motivations and associated goals that justify the decision to develop and implement a monitoring programme. A monitoring programme should provide information that will check performance against expectations, increase transparency for all stakeholders and inform decision making throughout the various stages of a repository implementation programme.

The MoDeRn Monitoring Workflow is not prescriptive and explicitly recognises that each programme will be influenced by a range of technical, social and policy boundary conditions. Therefore, rather than presenting a generic reference programme, the MoDeRn Project has developed the Workflow as an approach to address and integrate these national contexts into a specific monitoring programme. Indeed, the project clearly recognises the diversity of national contexts and, as a result, the diversity of monitoring solutions that are likely to be developed.

These national boundary conditions will dictate the specific details of the repository monitoring programme and the ways different stakeholders can and will be involved. Technical issues include the characteristics of the disposal inventory and the host rocks within which the repository is constructed, and the repository design and safety functions assigned to each component of the repository both during operations and following closure.

Stakeholder considerations will determine the nature of interactions between the WMO (or other organisation) responsible for the monitoring programme and other organisations, including regulators, advisory bodies, concerned communities and the general public. This will determine at which stages in the development and implementation of the programme advice or requirements are provided by stakeholders.

Policy boundary conditions could influence several aspects of the monitoring programme. This could include the strategy developed for the repository monitoring programme, such as the use of a pilot facility or sacrificial cells. Policy decisions could also influence decisions about post-closure monitoring or monitoring for retrievability, including how long such monitoring may be required and how it might be managed. Policy may also influence the extent to which the safety case must be supported by monitoring, and the extent to which the wider science programme can obviate the need for direct monitoring of the repository following waste emplacement.

6.2 Monitoring Technologies and Monitoring Programmes

The technical R&D work in the MoDeRn Project focused particularly on monitoring of the near field, as, from a technical point of view, monitoring of the EBS and the near-field rock remains the biggest technical challenge today, and one that is unique to geological disposal of long-lived radioactive waste.

The MoDeRn Project conducted a substantial amount of research into monitoring techniques, including the production of a report on the current state-of-the-art for monitoring technology, and has conducted several programmes of development and demonstration of state-of-the-art monitoring techniques in URLs and other research facilities. This research and development provides insight into the technical feasibility and limitations of monitoring of geological disposal and helps identify those areas of R&D that merit further investment.

The following developments in monitoring technologies have been undertaken during the MoDeRn Project:

- New algorithms for full waveform elastic inversion of seismic tomography data have been developed and practical methods for acquiring tomographic data have been developed through testing in Mont Terri and Grimsel.
- A new seismic hammer has been developed. The hammer will enhance the ability to generate strong S wave signals, and thereby improve the feasibility of conducting shear wave monitoring of the near field. This will improve the potential to provide information on changes to the EDZ, e.g. the mechanical response to heating.
- A high-frequency wireless node that allows measurement of several parameters (e.g. pore pressure, total pressure and water content), and transmission of the measured data over distances of a few metres has been designed, developed and tested. The node is expected to have a lifetime of 20-25 years. A patent application for the wireless node has been submitted as an outcome of this work.
- A low-frequency transmission system that allows transmission of data through 225 m of an electrically highly-conductive geological medium, at frequencies up to 1.7 kHz, has been designed, developed and tested at the HADES URL, and the conditions under which low-frequency data transmission may be applied have been evaluated. This potentially provides a method for transmitting monitoring data from a repository to the surface following repository closure.

- Research into distributed monitoring using fibre optic sensors has been undertaken in the HADES and Bure URLs. Sensors have been successfully installed and tested in both URLs and have successfully measured displacement around experimental tunnels in response to tunnel excavation.
- DIC and AE monitoring have been successfully used to detect crack initiation and growth during a half-scale test of the Belgian Supercontainer.
- Corrosion sensors that can measure *in situ* corrosion rates have been developed and tested in surface facilities.

These monitoring developments expand the range of near-field monitoring technologies that can readily be applied to monitoring the EBS and near-field rock, and a range of monitoring technologies are available that can address the majority of technical challenges presented by monitoring. However, further development is required (i) to improve the reliability of monitoring technologies and the implementation of failure identification procedures within a monitoring programme, (ii) to improve the possibility of providing long-term self-sufficient power supply especially to monitor EBS and near-field rock post closure, and (iii) to demonstrate how general monitoring approaches can be applied to monitor specific parameters and how monitoring technologies can be integrated within monitoring programmes. There is also a need to further define how monitoring data would support iterative development of the safety case as disposal programmes progress following granting of a licence to construct and operate a repository.

6.3 Conclusions on Repository Monitoring Programmes

Comprehensive examples of the type of monitoring programmes that could be undertaken in repositories hosted in evaporitic, clay and granitic host rocks have been developed. These illustrative programmes have been developed using the MoDeRn Monitoring Workflow and envisage the use of the technologies developed within the MoDeRn Project.

The illustrative monitoring programmes have demonstrated, on a theoretical basis, that near-field monitoring programme designs can be established based on a structured analysis of the FEPs considered in the safety case, and to address pre-closure information requirements prescribed in regulations (e.g. to demonstrate reversibility).

Several strategies for overcoming well-known challenges to repository monitoring have been identified and proposed in the illustrative monitoring programmes. These include the use of different types of monitored disposal cells, for example sacrificial cells that will be decommissioned and from which waste will be retrieved during closure of the repository; monitoring strategies that focus on the monitoring of wastes emplaced during the first stages of operation, which allows information to be gathered and used in decision making during the subsequent stages of operation; and the monitoring of disposal galleries that do not contain real waste. The use of dummy canisters, i.e. canisters with the same material properties, mass, dimensions and heat output as canisters containing waste, but which can be instrumented to avoid any potential impact on the passively safe disposal of waste, is proposed in two of the illustrative programmes.

The development of the illustrative monitoring programmes has allowed testing of the MoDeRn Monitoring Workflow using existing safety cases and other national context information. The illustrative programmes were developed using a process consistent with the MoDeRn Monitoring Workflow, i.e. a process that includes identification of the main objectives and reasons for monitoring, identification of sub-objectives, processes and parameters through an evaluation of the safety case and other drivers (e.g. assumptions on the requirements of stakeholders), and the development of a monitoring system design based on an understanding of the performance requirements and techniques available. Therefore, the MoDeRn Monitoring Workflow can be considered an appropriate structured approach for developing a monitoring programme.

6.4 Conclusions on Stakeholder Involvement in Repository Monitoring

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