Deliverable 17.1: Initial State-of-the-Art on Monitoring in Radioactive Waste Repositories in Support of the Long-Term Safety Case

Work Package MODATS

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Executive Summary

Building on repository monitoring research, development, and demonstration (RD&D) in previous European Commission projects and other international collaborative activities, the Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (MODATS) work package (WP) of the European Joint Programme on Radioactive Waste Management (EURAD) aims to:

- evaluate, develop and describe monitoring methods and technologies, and
- provide the means to measure, treat, analyse and manage monitoring data in a consistent manner.

This report provides an overview of the current state-of-the-art on monitoring in radioactive waste repositories in support of the long-term safety case, at the start of the MODATS WP. In particular, it presents the state-of-the-art on monitoring objectives, strategies, technologies and data. It is a reference document for EURAD actors, providing knowledge that will be updated at the end of the MODATS WP as new understanding becomes available.

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List of Acronyms

AE:	Acoustic Emission (monitoring)
AI:	Artificial Intelligence
DDM:	Data-driven model
DECOVALEX:	DEvelopment of COupled models and their VALidation against EXperiments
DIC:	Digital Image Correlation
DMS:	Data Management Systems
EBS:	Engineered Barrier System
EC:	European Commission
EDZ:	Excavation Disturbed Zone
ETN:	European Thematic Network
EURAD:	European Joint Programme on Radioactive Waste Management
FEIS:	Full-scale Emplacement (experiment) Information System
FEPs:	Features, Events and Processes
FP7:	Seventh European Community Framework Programme
GSL:	Galson Sciences Limited
HLW:	High-level Waste
IAEA:	International Atomic Energy Agency
IGD-TP:	Implementing Geological Disposal of Radioactive Waste Technology Platform
ILW-LL:	Long-Lived Intermediate-Level Waste
INBEB:	Interactions in Bentonite Engineered Barriers (Task D of DECOVALEX 2019)
L/ILW:	Low and Intermediate-level Waste
MoDeRn:	EU-FP7 project "Monitoring Developments for Safe Repository Operation and Staged Closure"
Modern2020:	Horizon2020 - project “Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal”
MS:	Micro seismic (monitoring)
NASA:	National Aeronautics and Space Administration
NDA:	Nuclear Decommissioning Authority

NEA:	OECD Nuclear Energy Agency
NIREX:	Nuclear Industry Radioactive Waste Executive, UK (today NWS)
NPP:	Nuclear Power Plant
OECD:	Organization for Economic Co-operation and Development
OFS:	Optical fibre sensor
PBM:	Physics-based models
R&D:	Research and development
RD&D:	Research, development and demonstration
RWMC:	Radioactive Waste Management Funding and Research Centre
RWMD:	Radioactive Waste Management Directorate
R&R:	Reversibility and Retrievability
SAGD:	Système d'Acquisition de Gestion de Données
SKB:	Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering Aktiebolag)
SOTA:	State-of-the-Art
SRA:	Strategic Research Agenda
SSG:	Specific Safety Guide
SSM:	Swedish Radiation Safety Authority
SSR:	Specific Safety Requirements
RWMC:	Radioactive Waste Management Research Organisation, Japan
URL:	Underground Research Laboratory
VTT:	Technical Research Centre of Finland Ltd
WIPP:	Waste Isolation Pilot Plant, USA
WMO:	Waste Management Organisation
WP:	Work Package

1. Introduction

Geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste (HLW), intermediate-level waste (ILW) and spent fuel considered as waste [1]. Implementation of radioactive waste disposal should address both technical and societal needs, and monitoring has the potential to contribute to both of these aspects [2].

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 considered to be a discipline within this wider context, and is related to monitoring the features, events and processes (FEPs) affecting the behaviour of a geological repository. However, the monitoring must not impact the safety of repository implementation.

Monitoring can form part of a repository safety strategy; it can contribute to public and stakeholder understanding of processes occurring in the repository, and hence, it can respond to public concerns and be used to build confidence in geological disposal. Monitoring could therefore play a role in enabling waste management organisations (WMOs) to work towards the safe and accepted implementation of geological disposal [3].

In the context of geological disposal of radioactive waste, repository monitoring is defined in this report as [4]:

> *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.*

This definition represents international consensus and is adapted from definitions from the International Atomic Energy Agency (IAEA) [2]. Other broad definitions of monitoring are also in use [e.g., in the IAEA Safety Glossary; 9].

1.1 MODATS

The Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (MODATS) work package (WP) of the European Joint Programme on Radioactive Waste Management (EURAD) aims to evaluate, develop and describe monitoring methods and technologies, and to provide the means to measure, treat, analyse and manage monitoring data in a consistent manner.

In particular, the MODATS WP is conducting research, development and demonstration (RD&D) into:

- repository monitoring data management and use of monitoring data to enhance system understanding, including development of digital twins,
- interactions with civil society and other stakeholders,
- development of repository monitoring technologies, and
- development of knowledge regarding repository monitoring.

At the end of the WP, a series of tools, methods and guidance documents on, and examples of how, monitoring data acquisition, management and treatment can be undertaken will be available for programmes to use in designing specific repository monitoring programmes. To facilitate meeting this ambition, the WP will work on real data sets from five recent full-scale underground research laboratory (URL) experiments, referred to as the MODATS Reference Experiments.

The RD&D in the MODATS WP focuses on monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. It builds on previous international collaborative RD&D activities, such as the European Thematic Network (ETN; 2001-2004) [5], the Geneva Workshop (2007) [6], the MoDeRn [4] and Modern2020 (2015-2019) [3] projects, and relevant publications from intergovernmental organisations (including the Nuclear Energy Agency (NEA) and the IAEA) and national waste management programmes. The ambition of the MODATS WP is to address detailed questions regarding monitoring data that have been identified, but not resolved in previous international collaborative activities.

This report provides an overview of RD&D in repository monitoring, spanning the last few decades. It draws on the conclusions from the previous international collaborative RD&D activities and relevant publications from the NEA and IAEA, as well as understanding from national waste management programmes.

1.2 Report Objectives and Scope

The primary objective of this State-of-the-Art (SOTA) report is to describe the current knowledge in repository monitoring, at the start of the MODATS WP.

The target audience of the report are assumed to have a good understanding of radioactive waste management; however, this report provides up-to-date knowledge and thereby is intended as a reference for EURAD actors. It can also be used to support engagement with a range of stakeholders. It will be updated at the end of the MODATS WP as new understanding becomes available.

1.3 Report Structure

Following this introduction, this SOTA report is structured as follows:

- Section 2 provides a high-level history of international collaborative RD&D activities in repository monitoring,
- Section 3 describes the SOTA on repository monitoring strategies and the role of repository monitoring in programmatic decision making and stakeholder engagement,
- Section 4 describes the SOTA on the technologies that could be used to monitor repositories,
- Section 5 discusses the current thinking on repository monitoring data management and use, and
- Section 6 provides a high-level summary of the main repository monitoring RD&D priorities, some of which will be addressed in the MODATS WP.

2. History of International Collaborative Activities

Key collaborative RD&D activities on repository monitoring over the last few decades are summarised in Figure 2-1. This section describes these activities, including their objectives and scope.

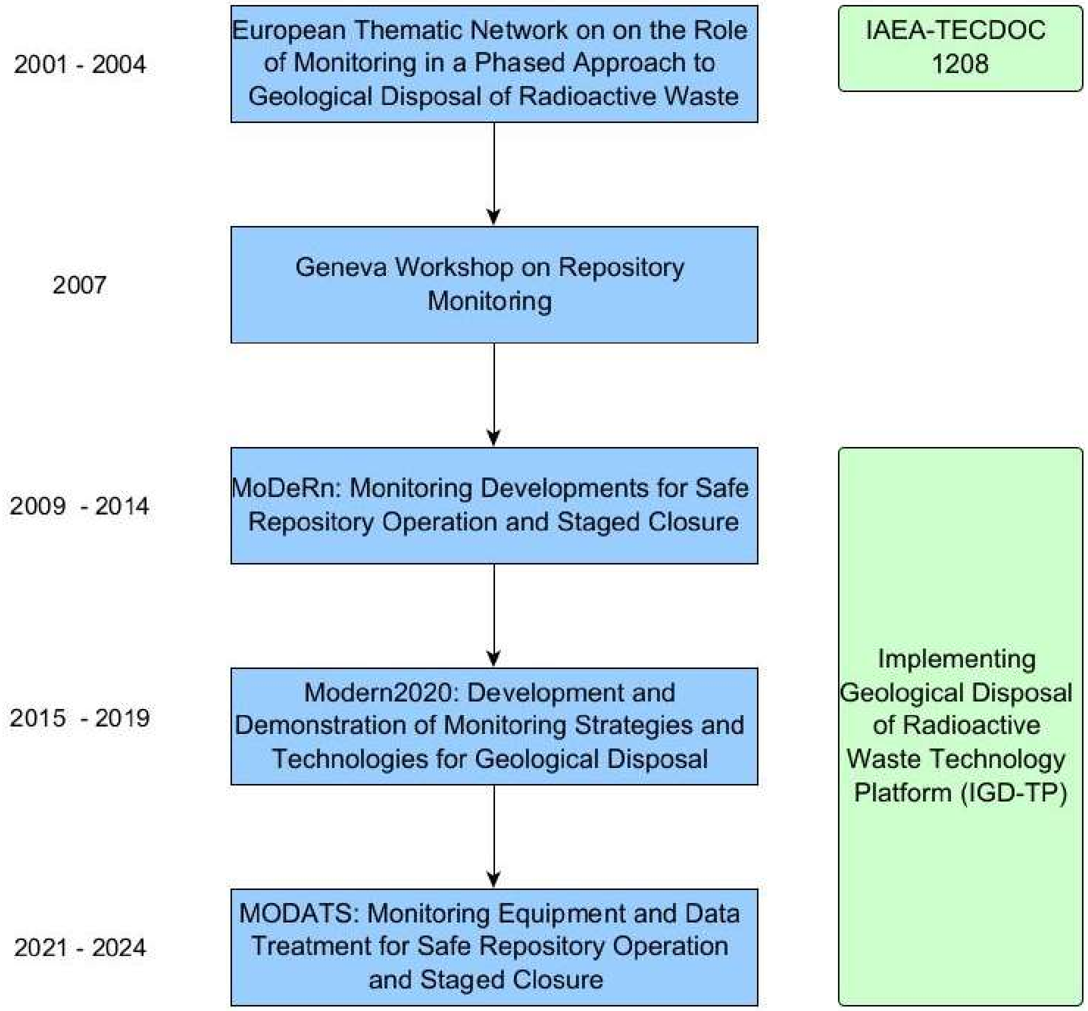

Figure 2-1 - Summary of international collaborative RD&D in repository monitoring. The Implementing Geological Disposal of Radioactive Waste Technology Platform contributes vision and strategy to radioactive waste management RD&D, including repository monitoring RD&D.

The IAEA-TECDOC 1208 [2], published in 2001, was a discussion document with purpose of identifying key issues that national radioactive waste management programmes might wish to consider in developing their own approaches to monitoring.

Building on the IAEA-TECDOC 1208 [2], the **European Thematic Network (ETN)** considered the role of repository monitoring in a phased approach to the geological disposal of radioactive waste [5]. The objectives of the ETN RD&D were:

- to improve both the understanding of the role of and the options for monitoring within a phased approach to deep geological disposal of radioactive waste, and
- to identify how monitoring can contribute to decision making, operational and post-closure safety and improve understanding of and confidence in repository performance.

The scope of the ETN RD&D included potential monitoring strategies and requirements during all phases of the implementation of a disposal system, including site investigation and characterisation, facility construction and operation, steps leading to closure of the facility and any post-closure monitoring that may be carried out [5].

In 2007, the Radioactive Waste Management Funding and Research Centre (RWMC) of Japan and the Radioactive Waste Management Directorate (RWMD) of the UK Nuclear Decommissioning Authority (NDA) organised an international workshop on repository monitoring in Geneva, Switzerland, known as the "**Geneva Workshop**" [6]. The objective of the Geneva Workshop was to define the strategic basis for the development of effective repository monitoring programmes, such that these would provide:

- a basis for consultation with stakeholders seeking greater confidence in the safe implementation of geological disposal,
- a process for progressive confidence building in the capability to monitor repository systems and
- identification of areas where deeper knowledge and/or improved techniques may be required, thereby suggesting future RD&D priorities.

The Geneva workshop proposed future RD&D topics for the development of repository monitoring programmes. These topics included the development of [6]:

- monitoring strategies and objectives to contribute to the decision-making process,
- an understanding of how monitoring may contribute to the long-term safety case for a repository,
- monitoring strategies to accompany repository design concepts,
- a shared vision on how to respond to unexpected and/or contradictory data, and
- data management strategies for monitoring data collected from a variety of sources and locations over extensive time frames.

It was also agreed at the Geneva Workshop that a collaborative approach to future RD&D would be beneficial to the development of repository monitoring programmes [6].

In response to the conclusions from the Geneva Workshop, the **MoDeRn Project** (Monitoring Developments for Safe Repository Operation and Closure), a collaborative European Commission research project, was launched in 2009 and ran until to 2013 [4]. MoDeRn considered how monitoring can contribute to the safety strategy and engineering design of repositories for long-lived radioactive waste, as well as contribute to public understanding, confidence and 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 repository monitoring programmes.

In the MoDeRn project, operational safety, environmental impact assessment and nuclear safeguards monitoring were considered to involve monitoring activities and technologies similar to those already in use in tunnels and mines, at other nuclear installations, and in association with environmental protection. It was therefore assumed that their implementation could be planned and further developed based on prior experience. On the contrary, engineered barrier system (EBS) monitoring was considered to be unique because it involves long timescales and the requirement that monitoring does not affect the passive safety of the disposal system. The main focus of the MoDeRn Project was, therefore, the monitoring of EBS performance.

In parallel with international collaboration on monitoring, the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) was launched in November 2009. Monitoring was recognised as a priority topic by the IGD-TP in its Strategic Research Agenda (SRA) in 2011 [7]. Key Topic 6 of the SRA pointed to the need for "practical monitoring strategies including techniques for implementation" and "monitoring of progress in relevant scientific and technological areas". In addition, Key Topic 7 of the IGD-TP SRA focussed on "governance and stakeholder involvement" with the objectives to "develop guidance for communicating to decision makers and stakeholders the results of research that underpin the development of safety cases and environmental assessments".

Following the completion of the MoDeRn Project, the need for future international collaborative research into monitoring was discussed at the 4th IGD-TP Exchange Forum. It was recognised that further work on repository monitoring was required, specifically relating to strategic aspects, technology development, practical implementation, and communication and stakeholder dialogue [3 and 8]. The **Modern2020 Project** (Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal) was launched in 2015 in response to this need.

The overall objective of the Modern2020 Project was to provide the means for developing and implementing an effective and efficient repository monitoring programme, which takes into account the requirements of specific repository programmes. Thirteen project objectives were defined relating to repository monitoring strategies, technologies, demonstration and practical implementation and stakeholder involvement [3 § 1.2.1].

The project focused on monitoring of the near field[a] (as per the definition of [9]) during repository operations, and, in particular, monitoring of the EBS to provide further confidence in the post-closure safety case. Similar to the MoDeRn project, these topics were selected because this is where the greatest challenges were considered to lie in terms of strategy, technology and public stakeholder engagement [3].

It was intended that the work carried out within Modern2020 project would provide the means for advanced radioactive waste disposal programmes to design monitoring systems suitable for deployment when repositories start operating in the next decade. The results of the project were also expected to support less-developed programmes and other stakeholders by illustrating how the national context can be taken into account in designing monitoring programmes [3].

The **MODATS WP** was launched in 2021 in recognition of the need to investigate repository monitoring data acquisition, treatment and management methods and the use of monitoring data to enhance system understanding, as well as to continue RD&D into repository monitoring technologies and interactions with civil society and other stakeholders (see sub-section 1.1). In particular, the work in MODATS is focussed on the means by which confidence can be established in monitoring data used to support development of further confidence in the post-closure safety case.

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

3. Objectives and Strategic Aspects of Repository Monitoring

This section provides a summary of guidance on, and objectives of, repository monitoring, and the strategies that could be used to achieve the objectives.

Non-programme-specific repository monitoring guidance and objectives are discussed in IAEA publications, as well as some general strategic aspects, which are also discussed in the NEA publications. These publications include:

- IAEA TECDOC Series:
  - Discussion document on Monitoring of Geological Repositories for High Level Radioactive Waste (TECDOC 1208 [2]), and
  - Planning and Design Considerations for Geological Repository Programmes of Radioactive Waste (TECDOC 1755 [10]).
- IAEA Safety Standards for Protecting People and the Environment Series:
  - Disposal of Radioactive Waste, Specific Safety Requirements (SSR) 5 [11],
  - Geological Disposal Facilities for Radioactive Waste, Specific Safety Guide (SSG) 14 [12], and
  - Monitoring and Surveillance of Radioactive Waste Disposal Facilities, SSG 31 [13].
- NEA project on Reversibility and Retrievability (R&R) for the Deep Disposal of High-level Radioactive Waste and Spent Fuel [14].

However, most the repository monitoring strategy state-of-the-art has been developed in international collaborative RD&D, specifically MoDeRn and Modern2020.

3.1.1 High-level Guidance and Recommendations on Repository Monitoring

The IAEA has published safety requirements that include a safety requirement related to repository monitoring programmes (Requirement 21: Monitoring programmes at a disposal facility) [11 and 12]:

> "*A programme of monitoring shall be carried out prior to, and during, the construction and operation of a disposal facility and after its closure, if this is part of the safety case. This programme shall be designed to collect and update information necessary for the purposes of protection and safety. Information shall be obtained to confirm the conditions necessary for the safety of workers and members of the public and protection of the environment during the period of operation of the facility. Monitoring shall also be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure*".

In relation to requirement 21, the IAEA recommends that monitoring should be [12]:

- defined prior to construction and in conjunction with development of the safety case,
- revised periodically to reflect new information gained during construction and operation,
- included as part of the safety case and should be refined with each revision of the safety case, and
- subject to audit and independent verification by the regulatory body or other recognized organisations.

3.1.2 Objectives of Repository Monitoring

According to SSG 31:

> "*Monitoring [and surveillance] programmes are important elements in providing assurance that a disposal facility for radioactive waste performs at the required level of safety during the operational and post-closure phases*" [13 § 1.4].
>
> "*In general, monitoring [and surveillance] programmes should be driven by, and should inform, the safety case. The results of the programmes should be used to strengthen the safety case and to build confidence in safety*" [13 § 2.13].

The ETN states that the safety case 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. Monitoring is, therefore, a means to assist in confirming that key assumptions regarding the safety-related features of the disposal system are valid.*" [5 § 3.2].

IAEA TECDOC 1208 [2] notes that the primary objective of monitoring is to provide information to assist in making decisions on how, when and if to implement various steps in the management of the repository system. In this context, the key purposes of monitoring of repository systems are [2 § 2]:

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

Relating to operational monitoring, the ETN states that:

"*…regulatory authorities are likely to define specific radiological and non-radiological conditions for the routine operation of the repository as part of the operation licence. Activities related to the development and operation of the repository and related facilities are not allowed to have unacceptable impacts for the operating personnel, the general population and the natural environment. Monitoring may include* *measurements of emissions, immissions, key features of the facility and of related physical, chemical and rock mechanical processes.*" [5 § 3.2].

The ETN recognised that there are different approaches to repository monitoring in waste management programmes, depending on the objectives, and specifically "*the extent to which monitoring is seen as confirming processes related to evolution of the repository and its long-term safety*" [5 § 7.3]. The factors that are typically considered in the objectives of the repository monitoring programme include [5 § 7.3]:

- waste type and EBS properties and expected performance, which affect the extent to which parameters related to long-term performance can be measured,
- implementation strategy, including plans for progression from one step to the next, including periods of observations in (open) underground structures,
- regulatory regime and requirements,
- degree of concept flexibility, and
- political and/ or public expectations.

3.1.3 Role of Repository Monitoring in Decision Making in Repository Programmes

The link between repository monitoring and decision making during the lifetime of the repository was established in IAEA TECDOC 1208 [2 § 2], as noted above.

Additionally, the IAEA-TECDOC 1755 states that:

> "*Monitoring is expected to play an important role in both development and execution of geological disposal programmes. In particular, monitoring would provide essential information for the satisfactory completion of the various phases of the disposal facility programme and, in doing so, will strengthen confidence in long-term safety, which is the key objective of radioactive waste disposal"*
>
> "*Delivering an effective monitoring programme through all stages of development will help to enhance public and key stakeholder confidence and will be an important support to the decision-making process*" [9 § 4.1.14].

In the NEA R&R project, the role of monitoring in decision making is discussed, specifically in relation to reversibility and retrievability. This report identifies different phases in repository programmes (pre-operational, operational and post-operational phases), as well as distinct periods within each of these phases (Figure 3-1) [14 § 3.3].

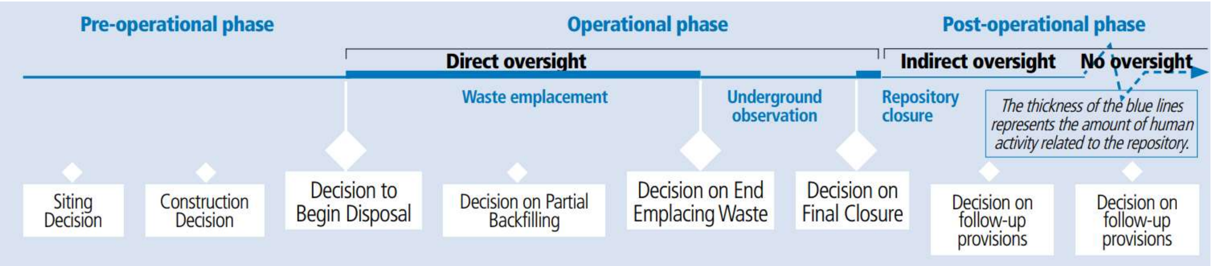

Figure 3-1 - Repository life phases and examples of major decisions [14].

A series of decision points can be identified at the transition between the different periods and phases, i.e., where a decision is taken on whether to advance to the next period and/ or phase within the programme. This stepwise programmatic approach is progressively informed by data, such as monitoring data, which confirms the basis for long-term safety and provides confidence to progress to the next phase and/or period. Importantly, monitoring will provide information to inform decisions; however, decisions will be made through the safety case, and not based on monitoring information alone.

3.1.4 Role of Repository Monitoring in Stakeholder Engagement

International guidance documents suggest that monitoring can potentially contribute to public acceptance by building confidence in the behaviour of the repository and can play a role in structured participatory processes for decision making [2, 4 § 5 and 5].

In particular, the ETN states [5]:

> "… *the public has a strong desire to be involved in the major steps of repository implementation, and … monitoring must, therefore, also include the observation of values and views of society at large regarding the disposal of radioactive waste. Such 'soft' (non-technical) information needs to be understood as an essential input to the decision-making process as regards the level of public acceptance*" [5 § 4.5.1].

Additionally, the IAEA TECDOC 1208 states [2]:

> *"Some... decisions* [that use monitoring data]*, particularly the decision to close a repository, have wider significance and may need to be taken by means of a consultative process involving various sectors of society"* [2 § 5].

RD&D has been conducted into the role of repository monitoring in stakeholder engagement in MoDeRn and Modern2020.

MoDeRn

In MoDeRn, RD&D was undertaken to develop a better understanding of the views of public stakeholders on the role of monitoring in geological disposal and stakeholder involvement in the development and implementation of monitoring programmes [4 § 1.2.1].

Participatory activities, such as workshops, visits to URLs, interviews and discussions, were organised in MoDeRn with different stakeholders, ranging from specialists in WMOs to public representatives [4].

The workshops and 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 also revealed a mutual interest between participating technical experts and local stakeholders, leading to fruitful discussions that were considered beneficial to both parties. The main views of the stakeholders on the role of monitoring, and the related conclusions, are as follows [4 § 5.6]:

- many stakeholders expressed the opinion that monitoring should be a checking process rather than a confirmatory process:
    - Monitoring programmes are therefore likely to be viewed by some stakeholders as being more trustworthy if it is clearly communicated that they are designed to check 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:
    - 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,
- public stakeholders have expectations regarding post-closure monitoring, mainly in view of being able to prepare for (and respond to) unanticipated events or evolutions:
    - 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, and

- 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.
    - 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.

Modern2020

In Modern2020, further RD&D focussed on the methods that could be used to involve local citizen stakeholders (e.g., people in potential repository host communities, and people in communities hosting a URL) in repository monitoring RD&D. The specific objectives of the stakeholder engagement RD&D in Modern2020 were to [3 § 5.2]:

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

Several engagement activities were conducted, involving local stakeholders from Belgium, Finland, France and Sweden in order to better understand the views and expectations held by local stakeholders regarding repository monitoring. Representatives from these communities were invited to several Modern2020 Project meetings to establish direct interaction between researchers from the technical work packages and the local stakeholders. Additional workshops (or "home engagement sessions") were set up in the home communities giving a broader group the opportunity to share and discuss their opinions about repository monitoring with social scientists and technical experts (with expertise in various specific subjects) in their own language. All sessions were arranged, documented and analysed by social scientists in Modern2020. The same local stakeholders were also offered the opportunity to share their experiences by taking part in an online survey, to which all Modern2020 partners were also invited to participate [3 § 5.3].

A Stakeholders' Guide to monitoring in geological disposal and public participation was developed collaboratively by social scientists, technical experts and local citizen stakeholders [3 § 5.6 and 15]. The Guide was envisaged as a way to communicate the state-of-the-art on geological disposal and repository monitoring to a non-scientific audience, and, through this, facilitate dialogue between scientists and public groups (for example, citizens, policy-makers and journalists) about technological and social concerns. Through the joint writing process, the nature of the Stakeholders' Guide evolved from being focused on the technical details of repository monitoring to giving a broader view on monitoring in the context of repository governance and the role of public participation. The production of the Stakeholders' Guide was itself a valuable exercise in stakeholder participation, which helped to clarify the different social perspectives, interests and concerns of citizen stakeholders and technical experts surrounding repository monitoring [3].

The main conclusions from the engagement with citizen stakeholders are as follows [3 § 5.8]:

- citizen stakeholders felt that their role in the project was not to influence the course of the technical research, but to understand what it was for and how it could affect the national waste management programmes,
- citizen stakeholder participants were not prepared to legitimise research outcomes, but wanted to ask critical questions in order to increase understanding and give feedback,
- citizen stakeholders indicated that they want to be engaged from an early stage in research processes and technology development; they indicated that they did not want to participate in the research itself, but they wanted to enhance their own understanding of the research and the process by which it proceeds, to broaden the thinking of the researchers, and to ensure that local stakeholders' views are taken into account,
- many local stakeholders involved in Modern2020 were already quite trusting towards their particular WMO and the work undertaken by them; being able to participate in this project, in close contact with an international group of researchers, further enhanced this trust; this was not because this group spoke to them in one voice, but precisely because being part of "science in action" unveiled differences between countries and repository programmes, and showed knowledge, as well as remaining knowledge gaps,
- focusing on reaching an international consensus on a standard monitoring strategy and the route by which this is obtained, risks concealing national differences, and political interests, which may become disguised as technical issues, and
- co-production of the Stakeholder Guide helped local citizen stakeholders increase their understanding of repository monitoring.

These conclusions led to the formulation of key recommendations to integrate citizen stakeholders' concerns in RD&D projects more generally [3 § 5.8].

As a result of this research into stakeholder engagement at an early stage in the RD&D process and on an international basis, the views of stakeholders in the context of the remit of Modern2020 are now better understood, as are the methods and advantages of engaging with stakeholders during, for example, the development of repository monitoring technologies [3 § 6].

3.1.5 Strategies for Repository Monitoring

IAEA TECDOC 1755 provides some high-level understanding of the strategic approach to repository monitoring linked to the objectives:

"*To deliver an effective programme of monitoring across the phases* [of a repository programme] *will require a specification of monitoring requirements to be developed in advance of each phase of development and incorporated within the quality management system to ensure effective management by identifying and/or developing appropriate techniques in time. Monitoring objectives may vary at different stages. The link with safeguards measurements should be organized when appropriate*" [10 § 4.1.14].

The Geneva Workshop in 2007 highlighted future development needs, specifically relating to monitoring strategies (see section 2). This led to international collaborative RD&D into monitoring strategies in MoDeRn and then Modern2020, which provided most of the state-of-the-art thinking on repository strategies and is summarised in this section.

MoDeRn

The MoDeRn project developed guidance on the design and implementation of repository monitoring programmes to support decision making, taking 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)

In particular, it 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. It 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 in the MoDeRn Monitoring Workflow, which is a structured approach to developing, implementing and operating a monitoring programme [4 § 2.1, Figure 2.1]. The MoDeRn Monitoring Workflow was subsequently updated in Modern2020 and superseded by the Modern2020 Monitoring Workflow; see next section *Modern2020*. The Modern2020 Monitoring Workflow is illustrated in Figure 3-6.

Three key stages in developing and managing a monitoring programme are identified in the workflow; these are [4 and 16 § 3]:

Stage 1 (Objectives, Processes and Parameters) involves the identification of monitoring programme objectives and sub-objectives, 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 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.

Stage 2 (Monitoring Programme Design) involves 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.

Stage 3 (Implementation and Governance) involves conducting the 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.

Within the MoDeRn project, three illustrative monitoring programme case studies were developed to test the MoDeRn Monitoring Workflow using existing safety cases and other national context information [4 and 17]. The test cases included repositories in the three main types of host rock considered suitable for the geological disposal of radioactive waste (salt, clay and crystalline) [4 § 4.1]:

The first test case was a post-emplacement and post-closure monitoring programme for disposal of high-level waste (HLW) in the Gorleben salt dome in Germany. The illustrative monitoring programme design in this test case was based on monitoring of specific components of the EBS and the overall repository system with instrumentation in a single representative monitoring field, the location and layout of which is shown in Figure 3-2 [4 § 4.2.4].

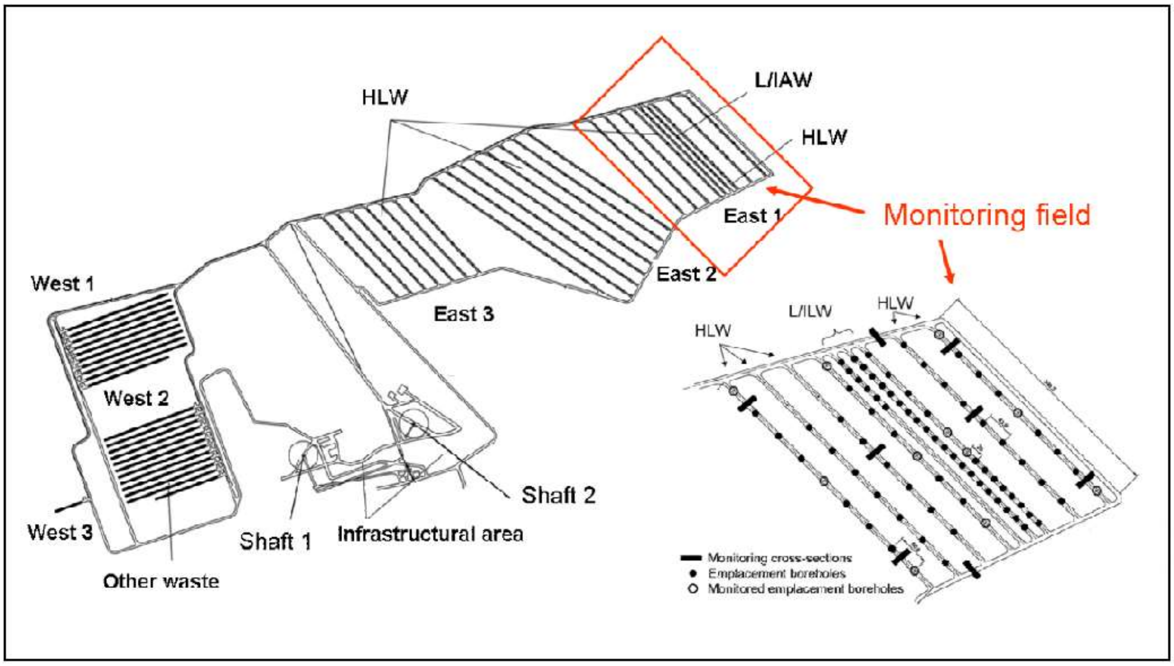

Figure 3-2 - Potential layout of the Gorleben repository site, and the test case illustration of the location of the representative monitoring field and sensor locations, modified after [18].

The second test case was a disposal cell operational period monitoring programme, based on a French reference disposal concept for HLW in clay host rocks. The monitoring strategy for this test case was to undertake monitoring in several locations in the repository by instrumenting selected disposal cells with different monitoring systems for varying purposes. For example, sacrificial disposal cells would contain real waste and would monitor parameters that could not be monitored remotely. These cells would monitor these parameters for a specific period, after which the waste would be retrieved and disposed of separately. Figure 3-3 provides an illustrative monitoring system design for a sacrificial cell [4 § 4.3.4].

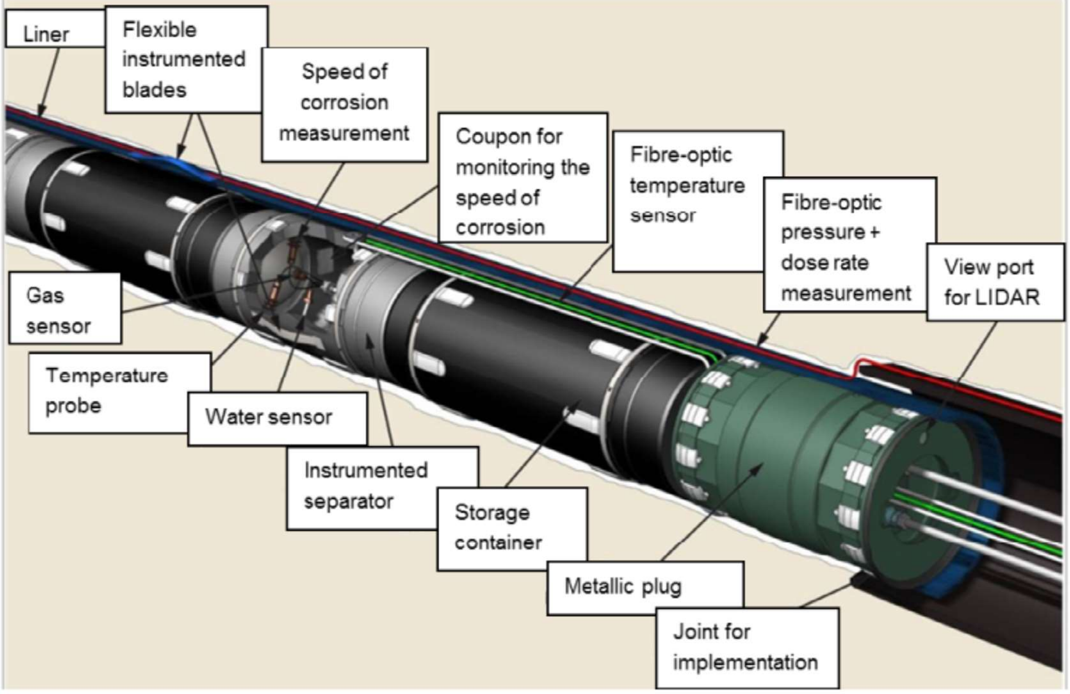

Figure 3-3 - Test case illustrative monitoring system in a sacrificial HLW disposal cell, based on a French reference disposal concept in clay host rocks [4].

The final test case was a monitoring programme of a Finnish reference concept for spent fuel in crystalline host rocks, based on the KBS-3V concept. 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 test case included a near-field monitoring system based on a disposal tunnel that does not contain real waste. Figure 3-4 illustrates the monitoring system within this test case; it includes wireless data transmission monitoring instrumentation within and above the four deposition boreholes and in two additional locations within a bentonite backfill (marked as F and H) [4 § 4.4.4].

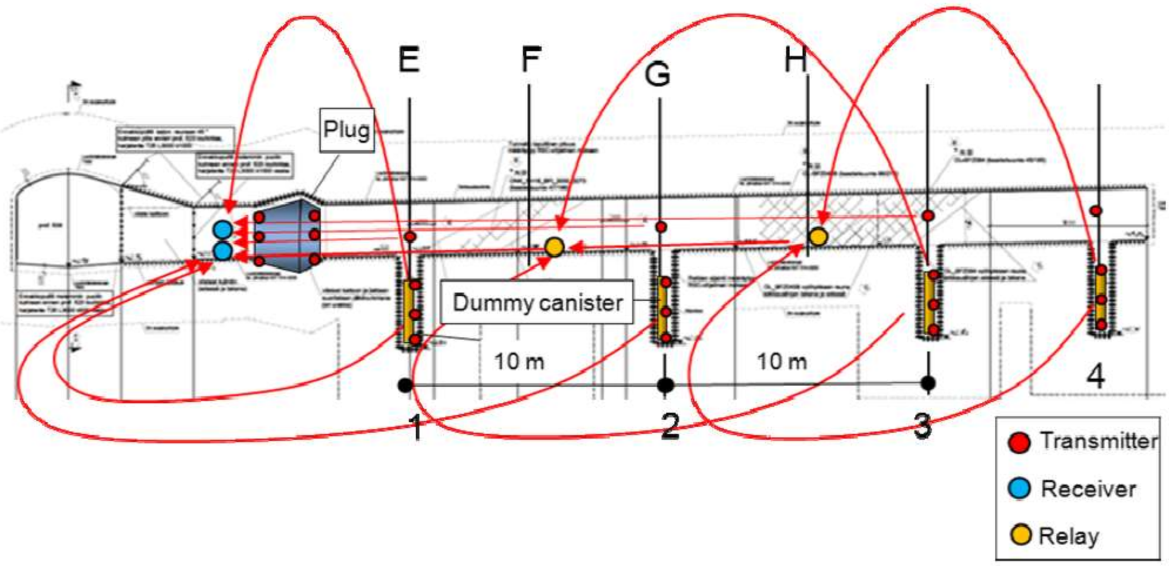

Figure 3-4 - Test case near-field monitoring system for the Finnish reference concept for spent fuel in crystalline host rocks (based on the KBS-3V concept), illustrating the location of sensors, relay stations and receivers [4].

These case studies considered the specific national contexts. Importantly, they do not represent generic monitoring programmes that could be applied in other national programmes.

The case studies 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 in the case of the French test case).

Several strategies for overcoming well-known challenges to repository monitoring were included in the illustrative monitoring programmes [4]:

- 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 representative disposal galleries, which, in the test cases considered 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, was proposed in two of the illustrative programmes. Other monitoring strategies considered in repository programmes (but not included in the MoDeRn project test cases) include representative galleries containing waste.

Modern2020

Following on from MoDeRn, it was recognised that RD&D was required to 1) further investigate how monitoring can support decision making in the safety case and 2) to develop screening approaches to define the parameters that should be monitored.

The following objective was defined in Modern2020 to address these RD&D needs [3]:

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

The Modern2020 Screening Methodology was developed in Modern2020 to fulfil this objective [3 and 19]. The methodology is designed as a component of the MoDeRn Monitoring Workflow. It is a generic process for developing and maintaining an appropriate and justified set of monitoring parameters in an implementable and logical monitoring programme [20 § 2.2].

The philosophy that underpins the Modern2020 Screening Methodology is to consider each potential monitoring process in turn at three interlinked levels:

- processes,
- parameters, and
- technologies.

First, the potential relevance of the process and value in monitoring it, with respect to the post-closure safety case, is evaluated. For processes considered to be both relevant and valuable, one or more parameters that could be used to monitor the process are identified. For each parameter, possible monitoring strategy and technology options are identified and the expected parameter evolution with respect to each option is determined. The technical feasibility of each strategy and technology option is then judged against the expected parameter evolution for each option in turn. Once technical feasibility has been assessed, the consideration of options are reviewed to determine whether there are sufficient feasible parameters to monitor each process identified earlier. If there are insufficient parameters to monitor the process, the earlier steps in the methodology would have to be revisited. Finally, the methodology includes cross-comparison of monitoring parameters to check completeness and appropriate redundancy, and to ensure that an integrated monitoring programme is developed [20 § 2.2].

The methodology is intended to be indicative and flexible rather than prescriptive, and can be regarded as a template that can be adapted by individual WMOs to suit particular needs. Flexibility includes, for example, the possibility to modify the starting points and approaches as appropriate for each waste management programme.

Seven test cases were undertaken to test the application of the Modern2020 Screening Methodology, each of which focussed on the identification of potential repository monitoring parameters through analysis of a recent safety case. These test cases were [20 and references therein]:

- Cigéo test case: The safety assessment for the planned repository for HLW and long-lived intermediate-level waste (ILW-LL) in the Callovo-Oxfordian Clay in France.
- ANSICHT test case: The safety assessment concept developed for a repository sited in clay in Germany.

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

The test cases provided a series of general conclusions, which are summarised in [20 § 6.1]. Additionally, Table 4.1 in [19] summarises the monitoring parameters selected in a location in the multi-barrier system in each of the test cases, together with the reason the parameter was selected and the strategy/ technology option that could be used. This table provides a comprehensive overview, for different national contexts, of some parameters that might be considered for monitoring, and why and how the parameters might be monitored. These parameters are summarised in Table 3-1 below. However, a key conclusion of the test case work is that there is no common set of parameters that should be monitored in every repository monitoring programme. Instead, the monitoring parameters will depend strongly on the specific drivers, constraints and objectives identified in the national and repository-specific context [20].

Table 3-1 - Summary of the monitoring parameters selected in a location in the multi-barrier system in each of the test cases, adapted from Table 4.1 in [19].

Parameter	Location in the Multi-Barrier System	Test Case that Selected the Parameter
Temperature	Disposal cell and surrounding near-field rock	Cigéo
	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT
	Near-field host rock	Opalinus Clay
	Canister, but measured in tunnels	TURVA 2012
Porewater pressure	Near-field rock	Cigéo
	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT
	Near-field host rock	Opalinus Clay
Fluid (gas) pressure	At the bentonite/host rock interface	Opalinus Clay
Permeability/ groundwater flow velocity	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT
	Tunnels and host rock around repository	TURVA 2012

Parameter	Location in the Multi-Barrier System	Test Case that Selected the Parameter
	Deposition tunnel plug	SR-Site
Confining pressure	Total pressure on cell sleeve	Cigéo
	Vertical pressure on deposition hole seal (concrete abutment)	ANSICHT
	Supercontainer – carbon steel overpack	OPERA
	Supercontainer – concrete buffer	OPERA
	Supercontainer – steel envelope	OPERA
Swelling pressure	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT
	Buffer	TURVA 2012
	Backfill	TURVA 2012
Diameter	Cell sleeve	Cigéo
Strain	Cell sleeve	Cigéo
Geometry	Canister	TURVA 2012
	Buffer	TURVA 2012
	Backfill	TURVA 2012
Displacement	Deposition hole seal (vertical displacement of concrete abutment)	ANSICHT
	Supercontainer – carbon steel overpack	OPERA
	Supercontainer – concrete buffer	OPERA
	Supercontainer – steel envelope	OPERA
	Tunnels and host rock around the repository	TURVA 2012
Hydrogen concentration	Cell atmosphere	Cigéo
	Supercontainer – carbon steel overpack	OPERA
	Supercontainer – steel envelope	OPERA
Oxygen concentration	Cell atmosphere	Cigéo
Relative humidity	Cell atmosphere	Cigéo
	Backfill	TURVA 2012
	Deposition hole seal (bentonite plug)	ANSICHT

Parameter	Location in the Multi-Barrier System	Test Case that Selected the Parameter
Water content/ saturation	Buffer	TURVA 2012
	Backfill	TURVA 2012
Porewater pH	Near-field rock	Cigéo
	Supercontainer – concrete buffer	OPERA
Porewater/ groundwater chemistry	Supercontainer – concrete buffer	OPERA
	Host rock around repository	TURVA 2012
		SR-Site
Redox potential	Supercontainer – carbon steel overpack	OPERA
	Supercontainer – concrete buffer	OPERA
	Supercontainer – steel envelope	OPERA
Thickness	Cell sleeve	Cigéo
	Overpack	Cigéo
Corrosion rate	Cell sleeve	Cigéo
	Overpack	Cigéo
	Canister	SR-Site
Mineralogy and chemistry	Buffer	TURVA 2012
	Backfill	TURVA 2012
Density (dry and bulk)	Buffer	TURVA 2012
	Backfill	TURVA 2012
Pore structure	Buffer	TURVA 2012
Piping and erosion	Backfill	TURVA 2012

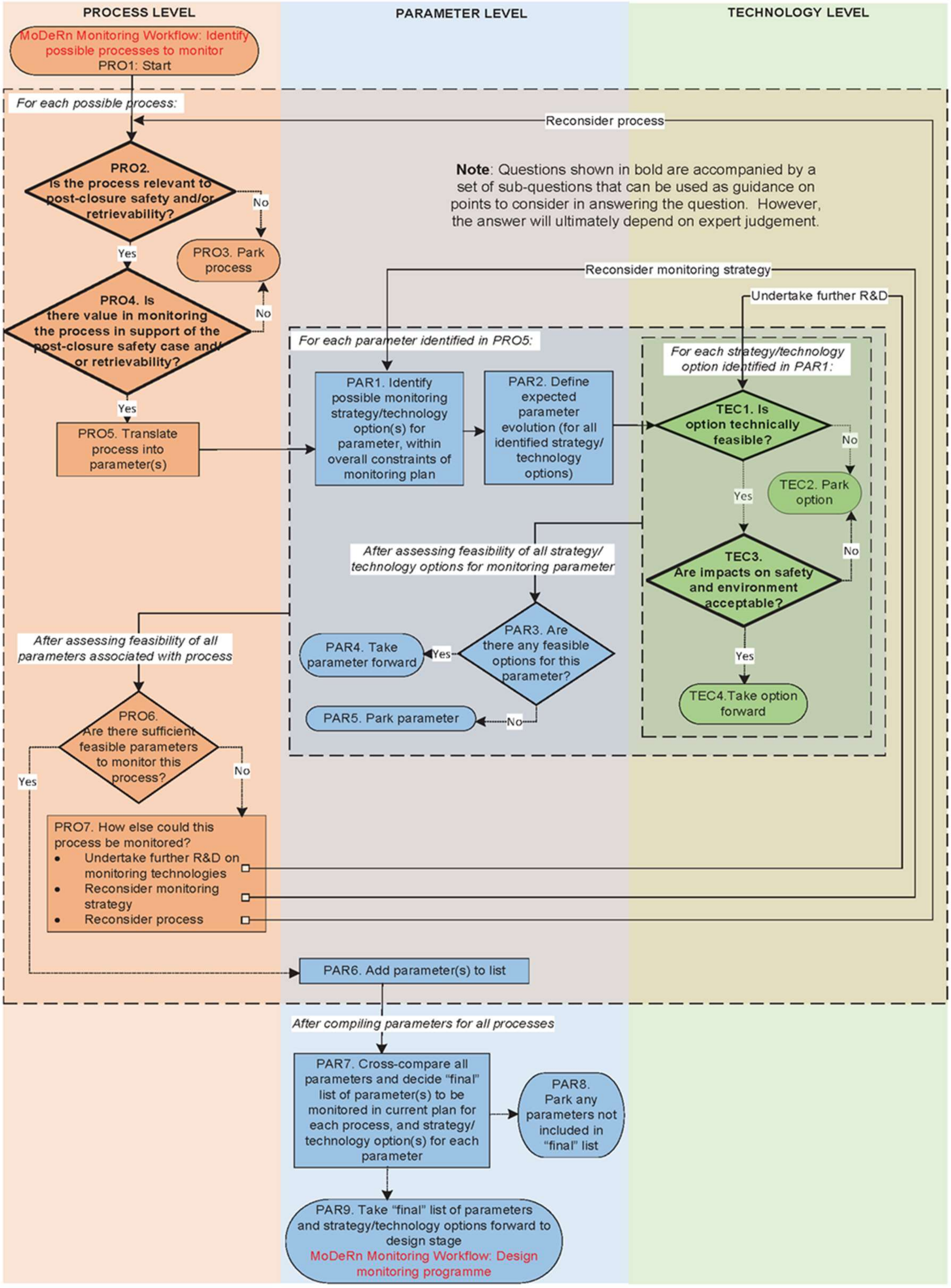

Figure 3-5 - The Modern2020 Screening Methodology [3].

The Modern2020 Project also provided recommendations and guidance on responding to monitoring results [36], which is summarised in the *Monitoring Data Use* sub-section of this report (see sub-section 5.2).

The MoDeRn Monitoring Workflow was subsequently updated in Modern2020 based on the Modern2020 Screening Methodology, but also considering the research on responding to monitoring results. The updated monitoring workflow, which is known as the Modern2020 Monitoring Workflow, is displayed in Figure 3-6.

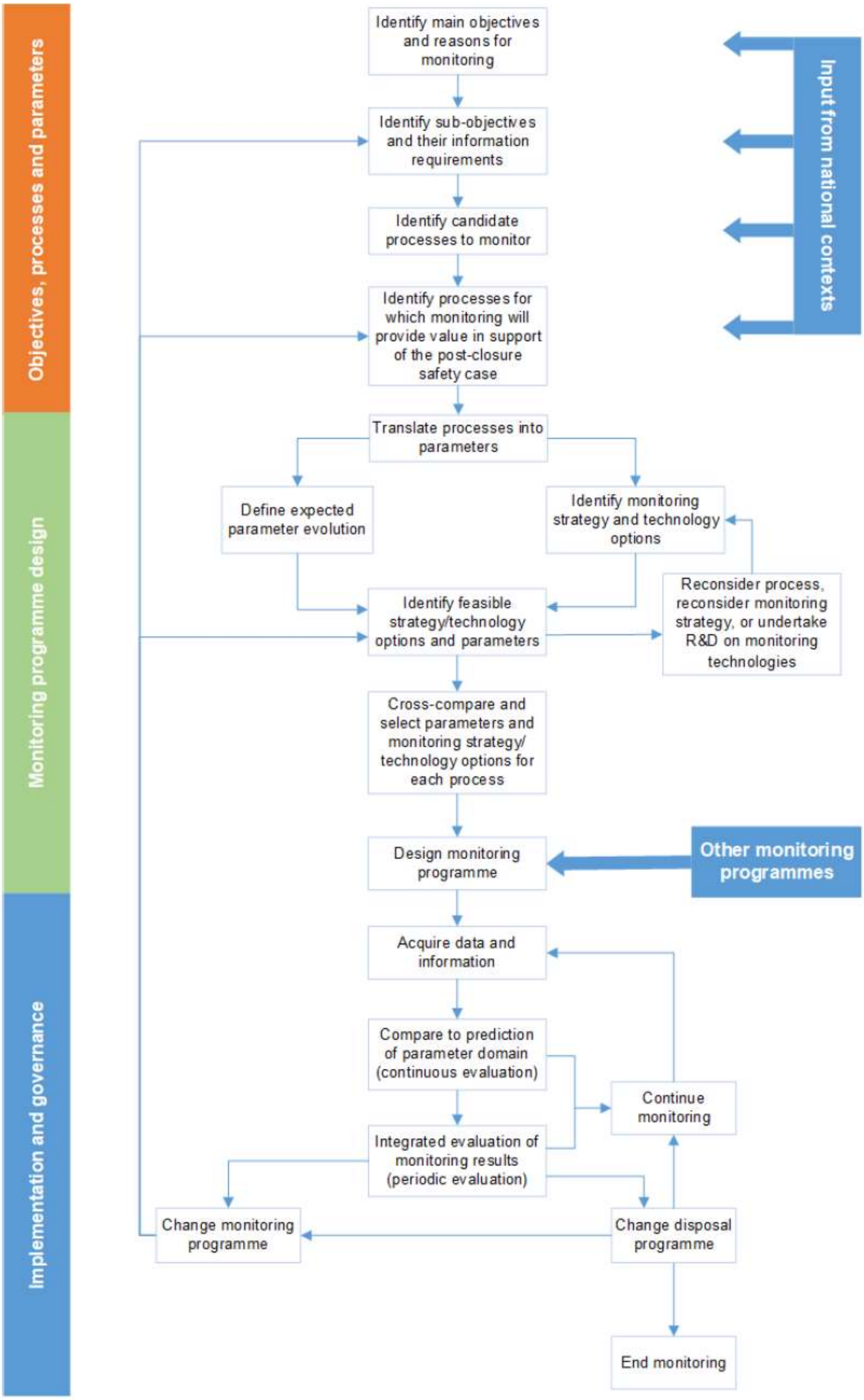

Figure 3-6 - The Modern2020 Monitoring Workflow [3], modified from the MoDeRn Monitoring Workflow.

Developments within Repository Programmes

In addition to the RD&D in international collaborative activities, WMOs have progressed their own monitoring strategies. WMOs are at different stages in implementing geological disposal, ranging from siting through to operations. Therefore, their monitoring programmes are also at different levels of maturity. Two examples of the monitoring strategies from different WMOs are provided here, based on readily available information.

The Waste Isolation Pilot Plant (WIPP) is an operating repository for transuranic waste constructed in bedded salt in New Mexico, USA. The licensing criteria for the WIPP Facility includes a requirement to develop a performance confirmation plan. Performance confirmation is a formal testing and monitoring programme focused on the essential elements of a licence basis, and is set up for the purpose of demonstrating that the bases of the safety case are substantiated. The WIPP monitoring programme is part of the performance confirmation plan. Development of the monitoring programme included a multi-stage process to identify a list of compliance monitoring parameters for monitoring during the operational phase as part of the performance confirmation plan. The process used the following criteria to assess potential monitoring parameters [3 § 2.1.2, 17 § Appendix B, and references therein]:

- addresses significant disposal system parameters defined by their: 1) effect on the system's ability to contain waste; or 2) effect on the ability to verify predictions about the performance of the disposal system,
- addresses an important disposal system concern,
- obtains meaningful data in a short period,
- will not violate disposal system integrity, and
- complements other existing environmental monitoring programmes.

Ten parameters met the criteria; these parameters relate to human activities in the surrounding area, hydrogeology, geotechnical performance, waste activity and overburden subsidence [20 § Appendix B]:

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

In 2022, the Swedish Government granted SKB a licence to build a final repository for spent nuclear fuel in Forsmark in Östhammar Municipality. SKB's approach to monitoring during the construction and operation of the Spent Fuel Repository at Forsmark is outlined at a high-level in [21 § 4.11.1].

Relating to the objectives of their monitoring programme, SKB state that "*monitoring will help to* [21 § 4.11.1]*:*

- *verify SKB's understanding of the evolution of the repository,*
- *support assumptions made in the post-closure safety assessment, and*
- *identify any previously unknown processes and events."*

SKB strategy for their monitoring programme is summarised as follows:

> "*The safety of the final repositories is based on passive barriers, and monitoring must not adversely affect these. The installation of monitoring equipment in a barrier may involve a risk for post-closure safety. This limits the choice of technology, location and time frames for conducting the monitoring. The risk for loss of signal or incorrect signals from sensors in the engineered barriers is also a reason why they will not be used. Incorrect signals could lead to unfounded decisions on measures associated with high costs and radiological risks.*"
>
> *There are other possibilities for monitoring that give relevant information on the evolution of the barriers at the repository site without jeopardising safety. One such possibility under consideration is the installation of long-term tests down in the rock in the Spent Fuel Repository at representative locations in the repository. The focus would be on the most important aspects of the engineered barriers, and experiments can be excavated and evaluated during the operating period and prior to closure in order to provide a basis for and confidence in the decision to close and seal the repository.*
>
> *Monitoring programmes for the Spent Fuel Repository will be prepared and submitted to SSM* [Swedish Radiation Safety Authority] *as a basis for the application to begin construction. Parameters and experiments that are suitable for monitoring will be identified and their relevance for post-closure safety will be explained. In addition, qualitative descriptions of anticipated development must be prepared. A rationale for the type of measures that may be adopted to handle any situations where results deviate from expectations will be presented. Monitoring to support the post-closure safety assessment is planned in the following areas:*
>
> - *hydrology,*
> - *groundwater chemistry,*
> - *mechanical and thermal behaviour of the rock,*
> - *cementitious materials, clay barriers and closure, and*
> - *copper corrosion."*

4. Technologies for Repository Monitoring

A repository monitoring system will be composed of the following main technological components (Figure 4-1):

- sensors that transform physical or chemical properties into analogue signals,
- data transmission media between different parts of the monitoring system, usually composed of cables, amplifiers, filters, signal converters (that transform sensor signals into digital data), hubs and other electronic devices including wireless data transmission units,
- data management systems (DMS) to register, preprocess/ process, store and display the digital data from the converters, and
- power supply systems to power all the equipment.

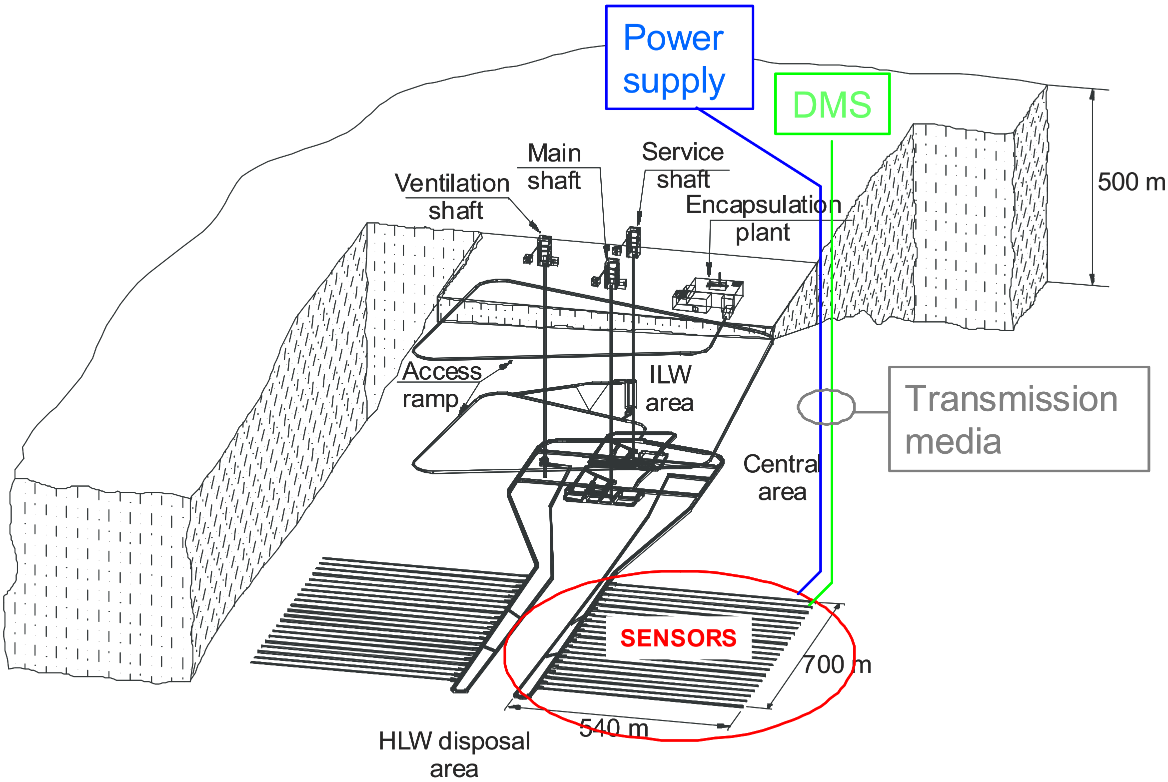

Figure 4-1 - Layout of a generic monitoring system [22].

Technologies exist for the majority of parameters that are likely to be of interest in repository monitoring (see Table 3-1). However, monitoring in the repository environment, especially the near field[a], involves challenges that are specific to repository programmes [4] and extending the toolbox of repository monitoring technologies is necessary to ensure that repository monitoring can be undertaken efficiently and effectively over the operational period.

The repository environment is likely to be more aggressive to some monitoring equipment than environments for which such equipment was originally designed. Monitoring of the repository near field must also respect the passive safety of the multi 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 [4].

Owing to the specific challenges of repository monitoring, much of the state-of-the-art relating to repository monitoring techniques has been developed in the international collaborative projects on repository monitoring, particularly MoDeRn and Modern2020.

4.1 MoDeRn

One of the aims of the MoDeRn project was to develop and demonstrate innovative monitoring technologies that enhance the ability to monitor repositories [4 § 1.2.1]. MoDeRn provided a description of monitoring system technical requirements [22] and undertook RD&D on innovative technologies that could be used for direct monitoring of the near field [4 § 3].

It also included a report that provides an overview of the SOTA on technologies relevant for use in repository monitoring, as of 2013 [23 § 1.6]. The SOTA report also summarises the advantages and disadvantages of available technologies for repository monitoring, proposes RD&D to address some of the disadvantages and concludes on feasibility and limitations for repository monitoring [23 § 1.6].

4.1.1 Requirements

The technical and/or operational requirements that may be imposed on monitoring systems may be attributed to several factors [22 § 2.3]:

- repository monitoring strategies and scopes,
- the safety functions that should not be impaired,
- the specific nature of the parameters that need to be measured,
- Operational requirements for the implementation of the measurement method (e.g., sensitivity, range of values, precision, long-term stability) and the cross-sensitivity to other environmental variables
- the detection of defective monitoring methods and identification of erroneous readings,
- the long-term (decades) durability of the monitoring hardware in the environmental conditions present in the repository,
- the reliability of the system, for example:
    - redundancy of critical system components (e.g., sensors, cables, data processing devices), which could limit the loss of information in case of the failure of system components
    - redundant sensors using complementary measuring technologies can also be used to verify the coherence of the measurements,
- the influence of measurement equipment on the measured parameter, and
- the obligatory positioning of a sensor (for instance to compare measurements with model calculations).

Factors that will have a significant influence on repository monitoring technology requirements are the specific disposal concept and the defined process of staged closure that is considered during the operational phase. For example, requirements could be less restrictive if the monitoring programme is applied to a pilot facility or a dedicated test disposal drift, than in case they are applied in the main part of the repository [22 § 2.3].

At the time of this work in the MoDeRn project (and as is the case now), most WMOs were in the early stages of their repository programmes; therefore, the available information on their specific monitoring programme technical requirements was limited. However, in relation to the long-term durability of the monitoring hardware against the conditions present in the repository (which can be unfavourable to the long-term operation of monitoring equipment), the expected environmental conditions in certain areas within the repository where monitoring may be undertaken were identified in different programmes. These conditions related to temperature, mechanical pressure, hydraulic pressure, water saturation, salinity, radiation from the waste and deformation (expressed as displacement) [22 § 3.5]. Parameter ranges of the expected environmental conditions for each of the different host rocks being considered for geological disposal are summarised in Annex I of [22]. These parameter ranges are indicative only.

Since the completion of this work, WMOs have continued to develop the understanding of the subsurface environment at their selected or potential repository sites, as well as their monitoring strategies (see sub-section 3.1.5). On the basis of this, their specific monitoring programme technical requirements are expected to have evolved.

4.1.2 RD&D on Innovative Technologies

The MoDeRn RD&D into innovative technologies that could be applied for direct monitoring of the near field, is summarised as follows:

- New algorithms for full waveform elastic inversion of seismic tomography data were developed and practical methods for acquiring tomographic data were developed through testing at the Mont Terri and Grimsel URLs.
    - These developments improved capabilities to monitor a range of processes (e.g., saturation, and gas generation and migration) that affect the velocity structure of the near field [24].
- A new seismic hammer for application in microseismic (MS) monitoring was developed. The hammer improved the ability to generate strong S-wave signals, and thereby enhanced the feasibility of conducting shear wave monitoring of the near field.
    - This RD&D improved the potential to provide information on changes to the excavation disturbed zone (EDZ), e.g., the mechanical response to heating [25].
- 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 was designed, developed and tested. The node is expected to have a lifetime of 20-25 years [26].
- 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 was designed, developed and tested at the HADES URL, and the conditions under which low-frequency data transmission may be applied were evaluated.
    - This technique potentially provides a method for wireless transmission of monitoring data from a repository to the surface following repository closure [27].
- Research into distributed monitoring using fibre optic sensors was undertaken in the HADES and Bure URLs. Sensors were successfully installed and tested at both URLs and successfully measured displacement around experimental tunnels in response to tunnel excavation [25 and 28].
- Digital Image Correlation (DIC) and acoustic emission (AE) monitoring were successfully used to detect crack initiation and growth during a half-scale test of the Belgian Supercontainer [25].

- Corrosion sensors that can measure in situ corrosion rates were developed and tested in surface facilities [25].

RD&D 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 [4 § 3.3].

4.2 Modern2020

The developments in MoDeRn increased confidence in the ability to monitor the evolution of the near field, following waste, buffer and backfill emplacement. However, the technologies are still limited in their applicability. Although the work in MoDeRn addressed some of the key concerns for repository monitoring, e.g., power supply and remote transmission of data, further developments are required to further develop the novel technologies so that can be widely applied in repository environments [4 § 3.3].

In recognition of the need for further technological developments following MoDeRn, WP 3 of Modern2020 focused on development of monitoring technologies to provide a toolbox of solutions that can be utilised whilst respecting the passive safety of the repository [3]. The specific objectives of WP 3 were to [29 § 1.3]:

- improve wireless monitoring technology, including the combination of high-frequency and low-frequency systems.
- research alternative power supplies,
- develop new sensors based on optical fibre, low-intrusive techniques including sensors to monitor water content and water chemistry, pH and irradiation,
- refine and further improve the most promising geophysical methods for non-intrusive monitoring, and
- establish a common methodology for qualifying the components of the monitoring system.

The following sections summarise the key conclusions from the RD&D in work package 3.

4.2.1 Wireless Data Transmission

Significant advances were made in understanding, designing and demonstrating solutions allowing wireless data transmission through components of the EBS and geological barrier. Different technological solutions covering transmission distances between 0.5 m and 275 m were developed and tested under realistic conditions.

Versatile solutions for short-range wireless data transmission were developed based on medium-frequency and low-frequency systems. For data transmission over long ranges, the wireless transmission of data through 275 m of rock using a single-stage very-low-frequency system was demonstrated, and a method using multi-stage relay devices was also developed. Technical integration of short-range wireless solutions with sensors or long-range wireless solutions was also devised and shown to be feasible for a range of settings. Sufficient understanding was gained to allow their deployment after additional engineering and site-specific testing, which requires limited additional efforts to bring them into practical industrial use [3, 29 § 3.1 and 30].

4.2.2 Long-Term Power Supply

The lifetime of batteries is currently insufficient for repository monitoring without their replacement. Therefore, alternative solutions for providing power were investigated, with the main driver being the ambition to use wireless data transmission systems in some monitoring programmes. Alternative solutions include *in situ* power generation (use of thermoelectric generators, i.e., generation of electric power from the transfer of heat away from waste packages, or using radioisotope sources), and wireless transmission of energy through EBS components or the host rock to wireless sensor units. Energy-sourcing technologies were concluded to be a relevant and a feasible means of powering repository monitoring systems. Interim energy storage solutions are required in combination with the studied alternative power solutions and their performance is critical with respect to their application in repository monitoring.

A review of the options concluded that there were technical approaches which are sufficient for the purposes of repository monitoring. Continued research to further develop and verify the energy sourcing technologies and integrate them into a realistic monitoring system is still required [3, 29 § 3.2 and 31].

4.2.3 Optical Fibre Sensors (OFS)

Several new sensors and measurement systems based on OFS technology were developed. Sensors were developed for monitoring water content, water chemistry, pH and irradiation. Optoelectric sensing chains were developed to provide distributed measurements of strain and temperature. A distributed OFS solution for measuring thermal conductivity, density and water content in the EBS was developed using heatable fibre optic cables. Advancement was also made on the development of fibre-optic pressure cells for boreholes. Further work is mainly required to ensure these technologies can withstand repository conditions [3, 29 § 3.3.6 and 32].

4.2.4 New Sensors

Other new sensors were developed for monitoring water chemistry using ion-selective electrodes, relative humidity using the dew point method, and temperature, pressure and relative humidity in a single integrated sensor. These sensors require testing in conditions similar to those expected in a repository. In addition, preliminary research into monitoring displacement using short-range non-contact methods has been undertaken [3, 29 § 3.3 and 32].

4.2.5 Geophysical Techniques

A range of geophysical techniques were improved for specific repository environments. Seismic full waveform inversion algorithms were improved by extending the inversion algorithms to include a model of density and, thereby, to account for anisotropy in the seismic velocity of the rock, and an automatic anomaly detection algorithm was developed. Differential tomography algorithms were established which allow consistent and precise identification of differential changes of physical parameters. Electrical resistivity and induced polarisation tomography algorithms were tested and shown to be a suitable method of monitoring changes in temperature and moisture content. Further research in these areas is required to validate the methods and algorithms [3, 29 § 3.4 and 33].

4.2.6 Monitoring System Qualification Methodology

A multi-stage qualification methodology was developed that is applicable to all components of a repository monitoring system. The methodology includes four steps: selection of components; laboratory tests; mock-up tests (this step is optional); and on-site tests. The methodology needs to be applied systematically in order to ascertain its validity and to make improvements, if required [3, 29 § 3.5 and 34].

4.3 Future RD&D Needs

The technological RD&D in the Modern2020 Project made substantial advances in developing new, or adapting existing, technologies such that their readiness for use in a repository monitoring context has been raised. Fundamental research into new methods of measurement of relevance to repository monitoring needs was also conducted with success. However, further research is required to fully bring these technologies into practical use in an industrial setting.

Modern2020 concluded that specifications for monitoring sensors need to be developed based on strategic planning for monitoring programmes and on preliminary design of monitoring systems. Additionally, methods of assessing the impact of monitoring sensors on post-closure performance need to be developed and applied to demonstrate that monitoring of the EBS and near-field can be undertaken without significantly affecting post-closure safety [3].

5. Repository Monitoring Data

WMOs are expected to acquire significant quantities of data during their repository monitoring programmes, including data relating to multiple parameters, using different technologies and in a range of different locations. The data are also expected to be acquired at different frequencies and over different timescales, depending on the monitoring programme phase. Billions of data points are, therefore, likely to be acquired.

These data will be used to address different objectives, which will be dependent on the monitoring strategy of the WMO and information needs of its stakeholders. They could be used to check the behaviour of the system during the construction and operational phases of the repository or to fulfil regulatory requirements. As noted in Section 3.1.3, monitoring data will be used to inform decision making in a stepwise programme of repository construction, operation and closure and to build further confidence in the safety case [2 § 2]. Monitoring data are, therefore, a *"valuable source of information that should be rationally managed and safely stored …"* [2 § 4.3]. This section discusses the SOTA relating to monitoring data management and use.

5.1 Monitoring Data Management

Monitoring data management is generally defined here as the processes and procedures that ensure the acquired monitoring data can be used to fulfil the objectives of monitoring programmes. Monitoring data management involves the organisation of the data into databases with appropriate formats and structures, along with relevant metadata. According to the IAEA:

- "*Databases should be sorted by category in order to be readily usable for interpretation and tracking of any trends*" [2 § 4.4].
- *"Monitoring data will be very useful for future comparison with closure and possible post-closure monitoring. Therefore, records should be updated and maintained in such a form that they can be used in the long term. These records may also include detailed information such as the rationale for the design of the monitoring programme, the location and the frequency of measurements, the sampling and analytical procedures and data*" [2 § 4.4].

The methods and mechanisms for storing data used at a nuclear facility must meet varying levels of requirements depending primarily upon their link to safety functions and baselines. Completed, approved documents of safety systems, procedures, or other safety-adjacent calculations must be reviewed, approved, and archived according to regulatory requirements or guidance and implemented through mandatory guidelines.

Measurement data are prone to errors owing to, e.g., sensor fouling, calibration drifts, data transfer problems, and configuration errors in data acquisition. Data errors have to be detected and handled. Validation of monitoring data is one of important aspect of monitoring data management; it includes quality assurance and quality control processes and procedures to ensure monitoring data integrity throughout the repository lifecycle. According to the IAEA "*quality assurance and quality control procedures are intended to provide a framework within which work is planned, performed, reviewed and recorded to give an adequate level of confidence that the work is fit for purpose. In the context of a repository monitoring programme, it is expected that the application of quality assurance will require that…data are documented in such a way that their origin is transparent and traceable, that their significance is clear, and that data uncertainty is defined…"* [2 § 4.2].

Much of the current, relevant understanding of repository monitoring data management is gained from monitoring programmes in URLs, particularly multi-decade experiments, such as the FE experiment [35], where, similar to repository monitoring, there is a need to ensure data integrity over long periods of time.

Multi-decade URL experiments implement bespoke databases that are accessible through the internet in near real time or real time. For example, the FE experiment has included development and use of the FE Information System (FEIS), which combines a database and graphical user interface to allow the data acquired in the experiment to be accessed and compared. These databases incorporate raw data (i.e., electrical signals), along with processed data (i.e., electrical signals converted to the parameter of interest) and a wide range of metadata to provide visualisation and analysis functionality. Monitoring data can be plotted as time-series (monitoring data versus time) and profile graphs (measurement versus sensor distance from an axis) in the FEIS [35 § Appendix 3].

Research conducted in the MoDeRn Project summarised possible failure modes in monitoring systems, where failure is defined as a specific circumstance that results in invalid monitoring data and invalid data are defined as values that are influenced by factors other than those described by the method [17 § 7.2.1]. Failure modes could be technical (e.g., sensor failures, transmission failures), methodological (e.g., failure of sensor installation or placement) or procedural (e.g., loss of redundancy) [17 § 7.2]. In general, invalid data could fall outside the predicted range of values, in which case, they may be easy to identify or alternatively, they could sit within the predicted range and be difficult to differentiate from valid data [17 § 7.2].

This MoDeRn research also summarised possible methods to detect sensor, transmission and system failures, which include sensor redundancy, sensor diversity and parameter correlations. A comparative analysis of the failure modes and failure detection methods was undertaken to identify the failure modes that could be identified by the different failure detection methods and the failure modes that are likely to be undetected [17 § 7.2 and 7.3].

Alarm systems are incorporated into some URL experiment monitoring databases using failure detection methods to automatically alert users about potentially invalid data when it is transferred into the database, e.g., in the Système d'Acquisition de Gestion de Données (SAGD) used in the Andra URL at Bure [17 § 7.5.1]. Baseline monitoring and scoping calculation data have been used to establish the expected parameter ranges and algorithms are used to compare the monitoring data with the expected parameter ranges to identify errors and outliers. Algorithms are also used to identify gaps in the imported data.

Methods need to be further developed to efficiently and effectively manage repository monitoring data, so that it is easily accessible when required and that data providers and users have suitable confidence in the reliability of the monitoring data. In particular, methods are needed to collate, validate and store repository monitoring data to ensure its accuracy and allow its effective and efficient use in the long term (see section 6). Effective data management will allow the data to be used to fulfil the objectives of the monitoring programme.

5.2 Monitoring Data Use

Monitoring data will be used to inform decision making in a stepwise programme and to build further confidence in the safety case [2 § 2]. The IAEA states that:

> "*the results of monitoring are expected to be submitted to national safety authorities in the form of periodic reports documenting the performance of the repository, to meet regulatory requirements and to reveal any discrepancies with anticipated behaviour. Operators may need to establish a programme of repeat analyses and corrective actions to fulfil regulatory requirements"* [2 § 4.4].

With respect to monitoring data use in the decision making, the ETN states that:

> "*a procedure has to be developed that specifies how monitoring results should be interpreted and used. In general, monitoring will be carried out to define the range and normal variability of parameters of interest, to provide data to develop and validate models of system behaviour and to assure that conditions remain within the expected and acceptable bounds"* [5 § 3.5].

The ETN also discusses the responses to unexpected monitoring results and corrective actions [5 § 3.5]:

> "*A monitoring strategy should be supplemented by the possibility of corrective actions in the situation where unexpected and unacceptable system behaviour occurs. The requirement is not*

for a plan to deal with every possible eventuality – it is not possible to foresee every possible occurrence. Some provision is needed, however, for responding to unexpected events. The need for a response might be interpreted as a requirement for any anomalous result to be thoroughly investigated and for problems to be identified and dealt with. Pre-defined "response plans" for a range of conditions and trigger levels may or may not be available at an early stage of the development of a programme for deep geological disposal. Corrective actions may therefore be developed as required and may comprise technical measures as well as administrative measures, even going as far as retrieval of the waste." [5 § 3.5].

Research was undertaken in the Modern2020 Project to develop recommendations and guidance on responding to monitoring results, specifically to classify results from monitoring data and to explore the possible approaches to evaluate these results [36 § 3]. This research showed that it is necessary to evaluate both individual monitoring results (i.e., monitoring of the same parameter, potentially in multiple locations and/ or with multiple types of sensors) and integrated monitoring results (i.e. the full range of monitoring data). It also showed that the evaluation of individual results needs to be undertaken on a continuous basis during repository operations, whereas integrated evaluation would be undertaken periodically (e.g., 5-10 yearly, or when prompted by specific monitoring results).

This RD&D has been summarised into a generic process to respond to monitoring results [36 § 4.1] (Figure 5-1).

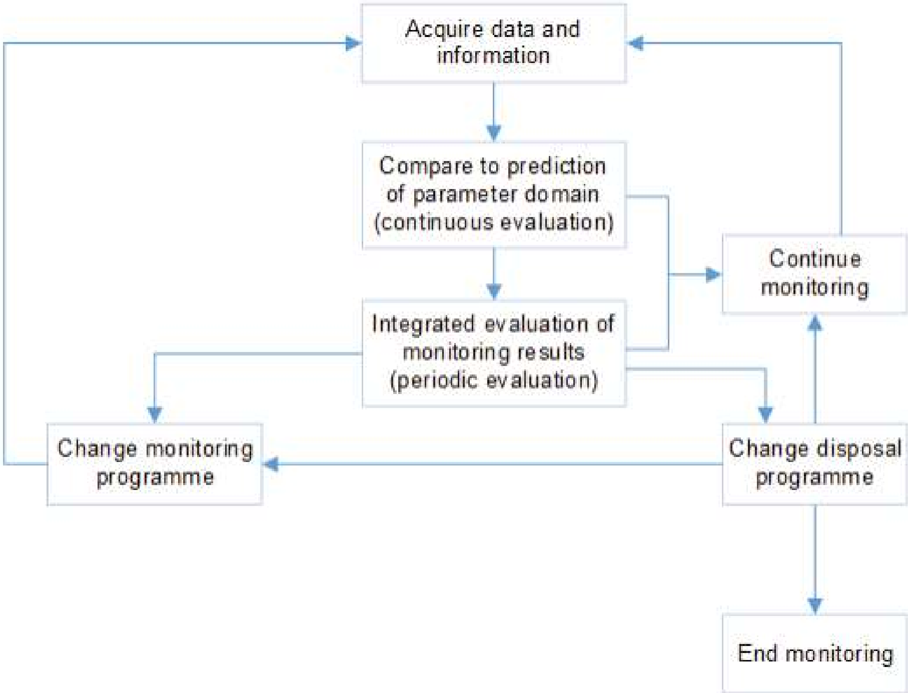

Figure 5-1 - Workflow for responding to monitoring results [36].

The main steps in the process are:

- acquire data and information,
  - raw monitoring data will be assured and transferred into interpretations and information, which will include adjustments and calibrations of the data for the *in situ* environmental conditions,
  - the outcome will be parameter values and time dependent results that can be compared to predictions in the next steps,
- compare results to prediction of parameter domain (continuous evaluation),

    - a "base case" for the predicted parameter values (spatially and temporally) for specific components of the near field will be derived prior to monitoring on the basis of existing knowledge and with the input of modelling and experimental data,
    - the outcome of the comparison would be a classification of the data as 1) consistent with the domain of predicted parameter values, 2) inconsistent with domain of predicted parameter values, but insignificant to safety or 3) inconsistent with the domain of predicted parameter values and potentially significant, the latter two of which could act as a trigger for a periodic evaluation,
- integrated evaluation of monitoring results (periodic evaluation),
    - an integrated evaluation of monitoring results could be triggered at a planned interval, in response to results inconsistent with the predicted parameter values and/ or as a result of an external decision,
    - it is expected that an integrated evaluation will involve the input of data and an update of the post-closure safety case,
    - the updates could include modifications to parameter values in underpinning models or in the safety assessment calculations, inclusion of new processes in underpinning models (e.g., coupled models; see sub-section 5.2.1) or in the safety assessment calculations, and/ or inclusion of a new scenario or new sensitivity calculation within the safety assessment,
    - however, given that a robust safety case is required for licensing, it is not expected that such actions will be undertaken,
    - any updates to the safety case will not only rely on monitoring data, but will also incorporate new information from the wider RD&D programme, from collaborative research undertaken by the waste management community, and from the wider scientific community,
- continue monitoring in the same way, if the monitoring data remain within the predicted parameter values,
- change the monitoring programme,
    - the outcome of a periodic evaluation might be a decision to continue the monitoring programme albeit with a modification of the way monitoring data are collected or processed, or by performing additional monitoring activities,
- change the disposal programme,
    - given the detailed RD&D, comprehensive safety case and regulatory scrutiny required to grant a licence for disposal of radioactive waste in a geological repository, it is expected that monitoring will provide further confidence in the safety case,
    - it is possible, however unlikely, that the implementer could mandate new repository-based actions, if the nature of information available at that time date is significant enough, and
- end the monitoring programme.

- if enough information is available for the implementer to be sufficiently confident in its understanding of the evolution of the specific EBS component that is the subject of monitoring to identify that no further information is needed, monitoring can cease, if agreed by the regulators and if allowed by the national regulatory framework.

5.2.1 Use of Monitoring Data in Coupled Models

As noted in sub-section 3.1.2, repository monitoring data are expected to be used "*to strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects… to provide information to assist in making decisions*" [2 § 2].

The evaluation of the impacts of the coupled effects of mechanical deformation, fluid and gas flow through the repository and thermal loading from the decaying waste is an important aspect of the safety assessment of a repository. The understanding of these impacts is gained through RD&D, including the integration of coupled models capable of simulating coupled thermo-hydromechanical-chemical (THMC) processes and monitoring data [37].

Most WMOs are in the early stages of their repository programmes, and therefore, the experience of using repository monitoring data in coupled models for purpose of supporting decisions is limited. However, there is considerable experience of the use of URL experiment monitoring data in coupled models.

DEvelopment of COupled models and their VALidation against Experiments (DECOVALEX) is a long-term international research collaboration for advancing the understanding and modelling of coupled THMC processes in geological systems [38], which provides a wealth of knowledge and experience on this subject. Summaries of recent research in DECOVALEX are presented in [37, 38 and 39].

For example, in DECOVALEX-2019, which was the seventh phase of the collaboration, Task D (Interactions in Bentonite Engineered Barriers; INBEB) involved the interpretation and modelling of the performance of an initially inhomogeneous bentonite barrier, based on experimental data from two full-scale long-term URL experiments. The two experiments were the isothermal Engineered Barrier (EB) experiment, which ran for over ten years at the Mont Terri URL, and the non-isothermal FEBEX heater test, which was in operation for more than 18 years at the Grimsel Test Site (Figure 5-2).

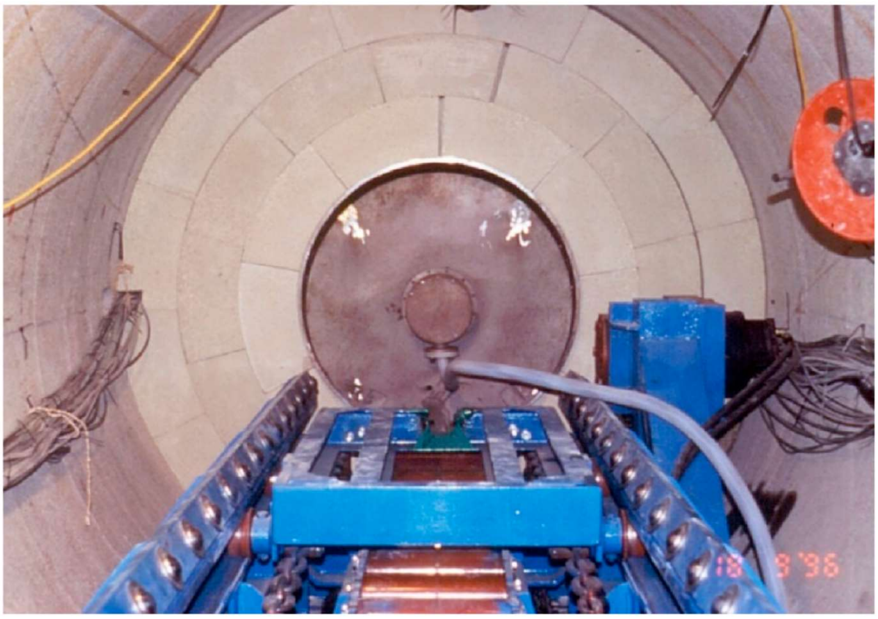

Figure 5-2 - Cross section of the FEBEX experiment during installation showing the heater surrounded by compacted bentonite blocks [40].

INBEB assessed the evolution from a newly installed unsaturated engineered system to a fully functioning barrier, by comparing HM and THM model predictions to the experimental data, which included THM process monitoring data and post-experiment dismantling and characterisation data. Special attention was paid to the evolution of barrier heterogeneity under transient conditions and on the final state reached upon saturation [37]. Further details of the modelling approaches are presented in [40].

In general, it was concluded in INBEB that the models were able to represent adequately the trends in the observed THM behaviour in the experiments [37]. Some comparisons of model predictions and monitoring data from the FEBEX experiments are presented in *Figure 5-3*.

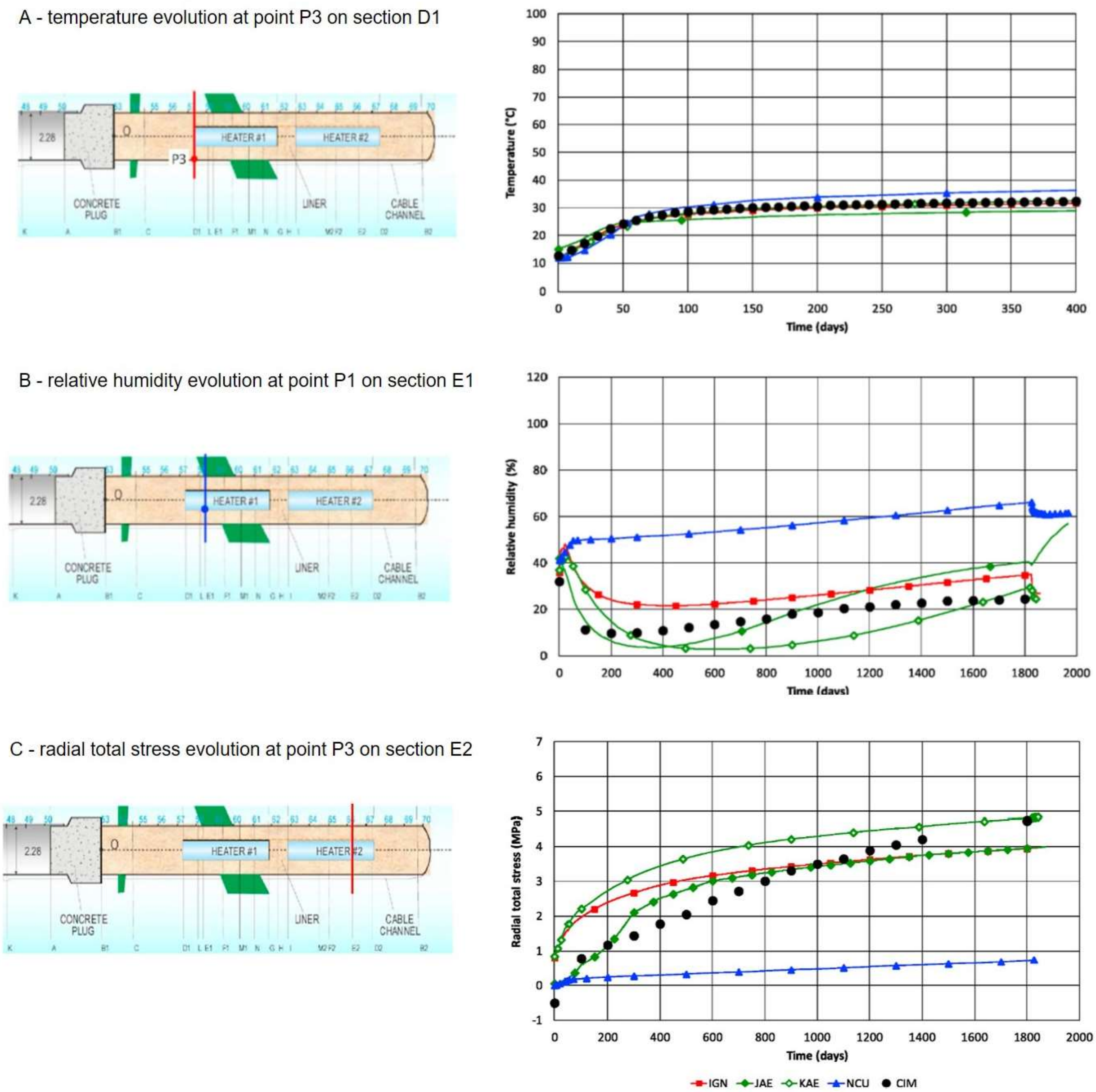

Figure 5-3 - Example comparisons of monitoring data (black dots) and 4 different modelling predictions (red, green and blue curves) for A) temperature, B) relative humidity and C) radial total stress in selected locations the FEBEX experiment, based on work in the INBEB ask in DECOVALEX 2019, modified from [40].

This example from DECOVALEX 2019 is representative of RD&D uses of monitoring data in coupled models. In repository monitoring programmes, monitoring data are expected to be used to inform and check coupled models of the system behaviour during the construction and operational phases of the repository, and thereby build further confidence in the safety cases. However, the processes and tools by which repository monitoring data will be used in coupled models to build further confidence in the safety cases need to be developed further. It is possible that digital representations of the disposal system could be built for these purposes, i.e. digital twins (see section 6).

6. Current Repository Monitoring RD&D Priorities

This section summarises current repository monitoring RD&D priorities, and in doing so describes the key RD&D activities in the current MODATS WP.

6.1 Monitoring Data

One of the key objectives of repository monitoring, as stated in sub-section 3.1.2 is "*to provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence, for as long as society requires, that the repository is having no undesirable impacts on human health and the environment*" [2 § 2].

Engagement with civil society was a significant part of previous EC monitoring projects, which included local stakeholder participation. These projects developed a thorough understanding of the views of public stakeholders at a European level and concluded that monitoring could potentially contribute to building the confidence of public stakeholders in the safety of a particular repository project, though not by itself.

Ensuring confidence in relation to monitoring data and the decisions it informs is an important aspect of repository monitoring; however, there is no accepted definition of monitoring data confidence, recognising that confidence is likely to have different meanings for different stakeholders. A high-level question that remains unanswered at the current time is: what monitoring data management and analysis processes are required to 1) demonstrate confidence in monitoring results and 2) support and build further confidence in the post-closure safety case?

The MODATS WP aims to address this priority topic of confidence in monitoring data by undertaking RD&D into data management and analysis in a task dedicated to data (Task 2, Data Treatment for Increased Confidence in Repository Monitoring[b]). This RD&D will be supported by data and understanding from five reference experiments, which are ALC1605 (Bure URL), FE experiment (Mont Terri URL), POPLU (ONKALO), PRACLAY (HADES URL), Prototype Repository II (Äspö Hard Rock Laboratory).

6.1.1 Repository Monitoring Data Management

Repository monitoring will be conducted over long periods, potentially stretching into decades. Furthermore, not all the acquired monitoring data will be valid owing to possible failures, e.g., sensor fouling, calibration drifts, data transfer problems, and configuration errors in data acquisition. Invalid data could fall outside the predicted range of values, in which case, it may be easy to identify. Alternatively, they could sit within the predicted range and be difficult to differentiate from valid data [17 § 7.2].

The long timescale, as well as the potentially large quantities of data that could be collected, and the potential for invalid data present challenges for managing repository monitoring data. Methods need to be developed to efficiently and effectively manage monitoring data to ensure its accuracy and allow its effective and efficient use in the long term.

Management of monitoring data requires methods for storing large quantities of data, future-proofing data management systems, and development of principles, methods, tools and routines for treating the data. RD&D in the MODATS WP will aim to develop data management methods that will allow monitoring data and metadata to be effectively managed, for use as required throughout the repository programme. Monitoring data from the reference experiments will be used to develop these methodologies.

[b] The MODATS WP also involves three other tasks: Task 1 relates to the WP project management, Task 3 addresses innovative repository monitoring technologies (see sub-section 6.2) and Task 4 deals with WP communication.

6.1.2 Repository Monitoring Data Analysis

In waste management programme, where considerable amounts of data will be generated, it is necessary to have appropriate methods and technologies to reliably analyse monitoring data to support programmatic decision making and the related objectives.

In general, few detailed methods exist that address how monitoring data will strengthen system understanding and therefore build further confidence in the safety case. Basic data analysis in the form of signal processing and trend-definition are routinely applied in the URL experiments (see sub-section 5.2). However, such basic techniques may not be appropriate for repository monitoring datasets. In particular, repository monitoring presents challenges related to the analysis of multi-modal data, i.e. data that are measured by different sensors, resulting in a range of independent parameters, at different locations and at varying spatial and temporal sampling scales. These data need to be analysed in a systematic and comprehensive way that considers the specifics of sensors and their spatial relationships and allows for the identification of anomalies related to sensor ageing and malfunction, outside influences, and deviations of the repository system from expected behaviour.

In the MODATS WP, RD&D will be undertaken with the objective of developing data-driven methodologies to analyse monitoring data, using the reference experiment datasets. This RD&D will aim to address the challenges relating to the analysis of multi-modal repository monitoring data and attempt to provide some understanding of how monitoring data could strengthen system understanding and therefore build further confidence in the safety case.

6.1.3 Digital Twins and Repository Monitoring

A digital twin is a virtual copy of physical locations, plant processes, business processes and/ or assets. The concept of digital twins was introduced by the National Aeronautics and Space Administration (NASA) during the Apollo missions. NASA define a digital twin as "*an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin*" [41].

Digital twins have most frequently been used to support the production and maintenance of structures, especially engineered structures such as aircraft, bridges, and machinery. However, in recent years, they have been emerging uses in other industries. A SOTA survey published in December 2021 provides an extensive account of the applications of digital twins in the nuclear industry [42]. In particular, the nuclear industry has applied digital twin technologies to the current light-water reactor fleet, the design of advanced reactors and the predictive maintenance of nuclear plants (e.g., the VERCORS project [43]).

The coupling of digital twins with data science applications such as artificial intelligence (AI) provides significant opportunities for the expansion of the use of digital twins, including in the geological disposal of radioactive waste. These opportunities could include a replica of a disposal system that progressively becoming more detailed and more closely representative of the real-world system, as more data is collected and information derived from the acquired data. Such a digital twin requires feedback from monitoring data to the underpinning models contained within it.

However, geological disposal presents unique challenges to the development of digital twins owing to the mix of engineered and natural structures, the presence of spatial and temporal heterogeneities, and the extent to which detailed information can be collected without disturbing the passive safety of the system. There is a need also to develop the methodologies and software tools through which digital twins can be developed and evolve during the operational phase in response to collection of repository monitoring data.

In the MODATS WP, RD&D will be undertaken to explore digital twin applications for repository monitoring, using the datasets from the reference experiments. This RD&D will also attempt to provide some understanding of how monitoring data could strengthen system understanding.

6.1.4 Stakeholder Engagement

The question of how monitoring data are used to address the evolution of the safety case, depending on the point of view (operator, decision maker, public) has not been tackled previously, nor has the question of how differences in perception can lead to potential different decisions.

In the MODATS WP, engagement workshops between EURAD experts and civil society will be undertaken to develop an integrated vision of how monitoring devices and corresponding data will contribute to develop a shared understanding of the repository system along with the decision-making process from the early phase of authorisation, to subsequent implementation phases, closure and post-closure.

6.2 Technologies for Repository Monitoring

The ability to monitor the disposal system and the extent to which such monitoring can provide detailed understanding of the disposal system evolution can be improved through development of innovative technologies. Therefore, it is necessary to keep up with the technological developments, to apply and adapt emerging technologies to repository monitoring and to develop innovative technologies that are suitable for the specific requirements of repository monitoring. Additionally, to monitor with confidence, there is a requirement to develop the understanding of the interactions between monitoring technologies and the medium in which they are emplaced. The MODATS WP aims to address these RD&D priorities in a task dedicated to technology (Task 3, Novel and Optimised Monitoring Technology for Repository Monitoring).

6.2.1 Innovative Technologies for Repository Monitoring

Innovative technologies with potential applications in repository monitoring systems include geophysical methods and fibre optic systems. Geophysical methods can be performed in a non-destructive fashion, and therefore, the integrity of the multi-barrier disposal system can remain unaffected. Importantly, repeated geophysical measurements allow spatial and temporal changes to be monitored over larger volumes. However, geophysical methods also suffer from some deficiencies. Firstly, they are often ambiguous, that is, several subsurface models explain the data equally well. Depending on the method employed, they can offer only limited spatial and/ or temporal resolution. Finally, geophysical methods yield physical material properties, such as elastic parameters, density, or electrical conductivities, and it is not straightforward to translate these material properties to parameters of interest (i.e., temperature, pressure, etc.).

Optical fibre sensors can allow distributed measurements, providing data over their entire extent. Furthermore, the small diameter of optical fibres reduces the invasiveness of measurements and the sensing units do not contain electronics that can be impacted by the potentially harsh repository conditions during the operating period. While some of these techniques have already been explored successfully for repository monitoring in MoDeRn and Modern2020, fibre optic sensing sees a fast-paced development and a continuous stream of innovation. In the MODATS WP, further RD&D will be undertaken focussing on:

- developing geophysical methods, specifically addressing the known deficiencies and
- developing, testing and qualifying new sensing technologies, including optical fibre technologies.

6.2.2 Interactions between the Monitoring Technologies and the Multi-Barrier System

Emplacing monitoring technologies in the multi-barrier system will result in interactions between the technology and the medium in which it is embedded. For example, placement of a sensor within a bentonite buffer could cause geometrical anomalies that lead to a lowering of bentonite density. RD&D will be conducted in the MODATS WP to understand the influence that monitoring technologies may have on the multi-barrier system.

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