Deliverable 17.2: Final 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

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

Significant international collaborative work on the reasons for, and principles of, repository monitoring has been on-going for decades. It has been undertaken under the auspices of the International Atomic Energy Authority (IAEA), the Nuclear Energy Agency (NEA) and the European Commission (EC). It has included consideration of monitoring strategies and the role of monitoring in decision making; research, development and demonstration (RD&D) on new and novel technologies specifically suited to repository monitoring; *in situ* testing and demonstration of sensors and monitoring systems in repository-like conditions; and engagement with civil society.

This RD&D has shown that repository monitoring data will be used to address different objectives, which will be dependent on the monitoring strategy of the WMO. Objectives include checking the behaviour of the system during the construction and operational phases of the repository or to fulfil regulatory requirements. Repository monitoring will be used to inform decision making and build further confidence in the safety case.

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) ran between 2021 and 2024 and conducted RD&D into: monitoring data acquisition, treatment and management; use of monitoring data to enhance system understanding, including development of digital twins; interactions with civil society and other stakeholders; development of monitoring technologies; and development of knowledge regarding repository monitoring. The focus of MODATS was monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case.

MODATS focussed on confidence in monitoring data. There are particular challenges associated with monitoring data acquired during repository operations, including challenges associated with its management (including processing and storage), modelling and visualisation. These are most frequently associated with the long timescales envisaged for monitoring programmes and the need to maintain the passive safety of the disposal system. Therefore, MODATS undertook RD&D to develop methods through which monitoring data can be processed, stored, modelled and visualised. This included preliminary work on the development of digital twins.

New and emerging monitoring methods could change the ways in which repositories can be monitored. In order to provide a toolbox of repository monitoring technologies, it is necessary to keep up with the technological development, specifically to apply and adapt emerging technologies to repository monitoring and to develop new technologies that are suitable for the specific requirements of repository monitoring. In recognition of technological advancements at the time, MODATS explored new and emerging technologies that could be implemented in repository monitoring programmes.

This report is one a series of deliverables from the MODATS WP. It is the final state-of-the-art (SOTA) report at the end of MODATS, which supersedes an initial SOTA report developed during MODATS (Deliverable 17.1). The initial SOTA provided an overview of RD&D in repository monitoring, spanning the last few decades and including the latest knowledge on monitoring objectives, strategies, technologies and data. Building on the initial SOTA, this report provides an update on the current repository monitoring knowledge, based on the progress made in MODATS mainly relating to monitoring data management and use and technological RD&D.

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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; [12]

1.1 MODATS and Report Objectives and Scope

As of 2024, 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) was the most recent international collaborative RD&D activity focussed on repository monitoring. The overall objective of the MODATS WP was to consolidate the implementation strategy for monitoring systems by developing methods through which confidence can be demonstrated in the data acquired and benefits derived for repository implementation.

This report is one a series of deliverables from the MODATS WP. It is final state-of-the-art (SOTA) report describing the current knowledge in repository monitoring, considering the advances in knowledge and understanding in the MODATS WP. It supersedes an initial SOTA written earlier in the WP [5]. In particular, this report provides an overview of RD&D in repository monitoring, spanning the last few decades. It draws on the conclusions from the international collaborative RD&D activities and relevant publications from the NEA and IAEA, as well as understanding from national waste management programmes. It summaries key advances in repository monitoring understanding in 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.

1.2 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 summarises 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 describes the current thinking on repository monitoring data management and use,
- Section 6 describes the MODATS opinions on digital twins, including the potential uses of the monitoring data in repository digital twins, and
- Section 7 summarises some of the gaps in repository monitoring knowledge, and in doing so highlights potential future repository monitoring RD&D.

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.

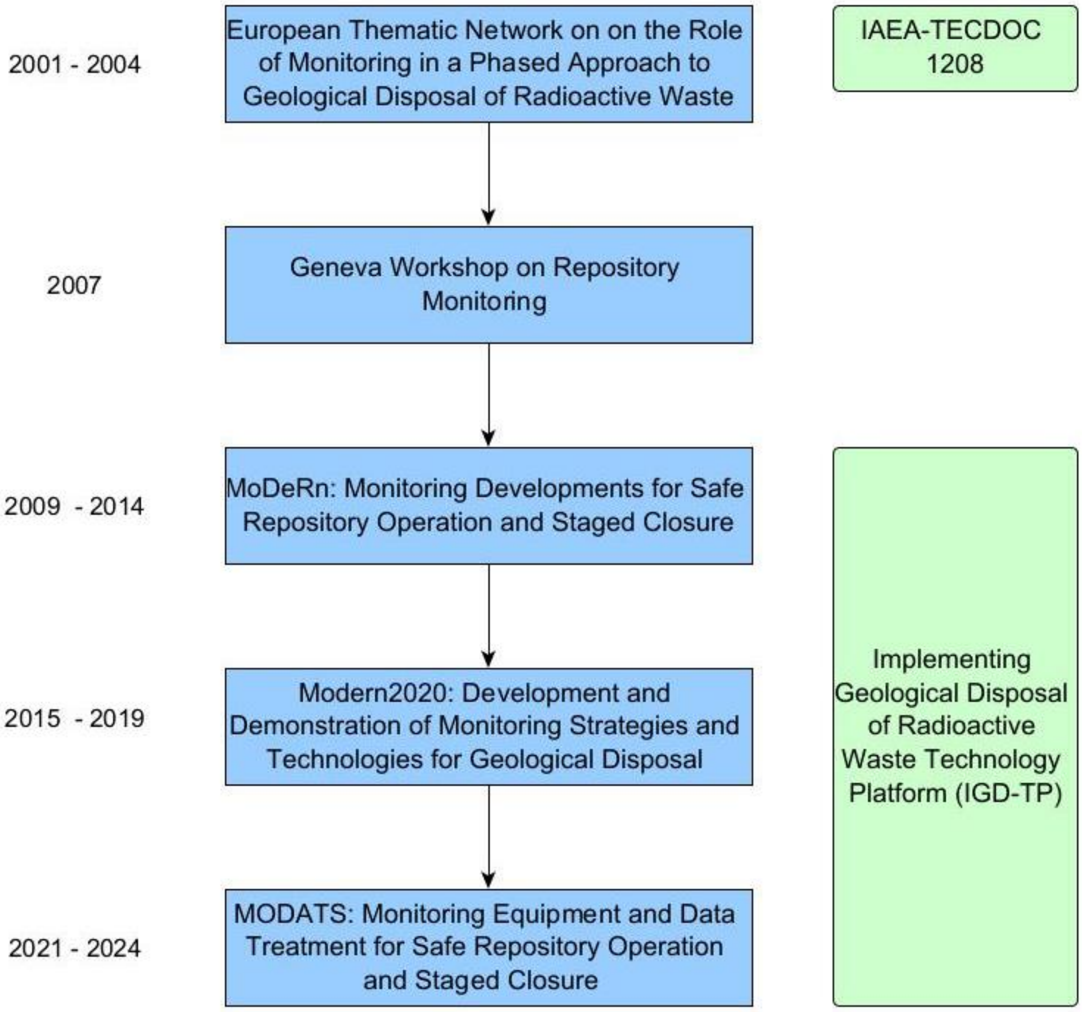


Figure 2-1 - Summary of international collaborative RD&D in repository monitoring.. The Implementing Geological Disposal of Radioactive Waste Technology Platform contributes vision and strategy to radioactive waste management RD&D, including repository monitoring RD&D.

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 [8]. 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 [8].

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**" [9]. 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 [9]:

- 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 [9].

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 [10]. 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 [2]. 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 focussed on monitoring of the near field[a] (as per the definition of [3]) during repository operations, and, in particular, monitoring of the EBS to provide further confidence in the long-term safety case. Like the MoDeRn project, these topics were selected because this is where the greatest challenges were considered to lie in terms of strategy, technology and 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].

At the end of Modern2020, it was recognised that there a need to continue RD&D to consolidate the implementation strategy for monitoring systems by developing methods through which confidence can be demonstrated in the data acquired and benefits derived for repository implementation.

The **MODATS WP** of EURAD ran between 2021 and 2024 with the aims of evaluating, developing and describe monitoring methods and technologies, and providing the means to measure, treat, analyse and manage monitoring data in a consistent manner. The RD&D in the MODATS WP focussed on monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. It built on previous international collaborative RD&D activities, with the specific objectives of:

- investigating management and use of monitoring data to enhance system understanding, including development of digital twins,
- continuing RD&D into repository monitoring technologies and
- continuing RD&D relating to interactions with civil society and other stakeholders.

One of the first activities conducted in MODATS was a detailed survey of monitoring in underground research laboratory (URL) experiments [6]. The objective of the survey was to identify learning for repository monitoring. In particular, the survey identified lessons relating to monitoring system design and monitoring data acquisition, management and analysis. It identified unpublished learning from individual experts based on their expertise and experience.

Following this, real datasets from five recent full-scale URL experiments, referred to as the MODATS Reference Experiments (ALC1605 in Bure URL, Full-Scale Emplacement (FE) in Mont Terri URL, Posiva Plug (POPLU) in ONKALO, Prototype Repository in Äspö Hard Rock Laboratory and Preliminary Demonstration Test for Clay Disposal (PRACLAY) in HADES URL), were used to develop a series of

[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.

tools, methods and guidance documents on, and examples of how, monitoring data acquisition, management and treatment can be undertaken in repositories [7]. These resources were intended for programmes to use in designing specific repository monitoring programmes.

MODATS also explored new and emerging technologies that could be implemented in repository monitoring programmes (e.g. geophysical methods and optical pH sensors) and investigated the capabilities of optical fibre sensors for the purposes of ensuring they can be used as required in repository monitoring programmes (e.g. for temperature and strain sensing).

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 [13]).
- IAEA Safety Standards for Protecting People and the Environment Series:
  - Disposal of Radioactive Waste, Specific Safety Requirements (SSR) 5 [14],
  - Geological Disposal Facilities for Radioactive Waste, Specific Safety Guide (SSG) 14 [15], and
  - Monitoring and Surveillance of Radioactive Waste Disposal Facilities, SSG 31 [16].
- NEA project on Reversibility and Retrievability (R&R) for the Deep Disposal of High-level Radioactive Waste and Spent Fuel [17].

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) [14] and [15]:

> "*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 [15]

- 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*" [16] § 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*" [[16] § 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*." [[8] § 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*." [[8] § 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*" [[8] § 7.3]. The factors that are typically considered in the objectives of the repository monitoring programme include [[8] § 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*" [[12] § 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) [[17] § 3.3].

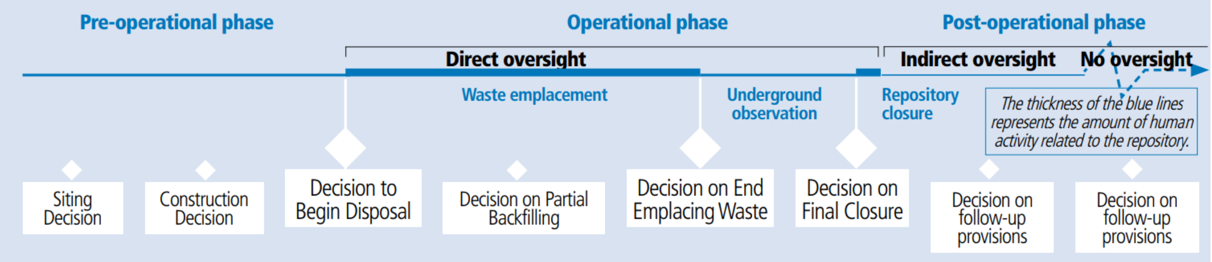


Figure 3-1 - Repository life phases and examples of major decisions [17].

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 [8].

Monitoring during the operational period could show that the repository is behaving as expected, and therefore might increase stakeholders' confidence in the long-term safety case. The ETN states [8]:

> "*… 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*" [[8] § 4.5.1].

Monitoring programmes may also play a role in decision-making processes involving the public, or their representatives, with the aim of attaining broader societal support for disposal. 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, Modern2020 and MODATS.

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 [18]. 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, policymakers 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 [18]

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].

MODATS

It is necessary to use effective methods to engage civil society stakeholders in monitoring discussions. However, establishing a dialogue between experts and civil society can prove challenging because of the complexities surrounding repositories, monitoring systems, safety cases, and their technical intricacies, alongside the unique nature of these facilities compared to other industrial installations.

Stakeholder engagement activities were undertaken in MODATS to continue to facilitate mutual understanding and shared perspectives among WMOs, REs and TSOs and civil society members on key challenges and topics related to monitoring. Two stakeholder engagement workshops were undertaken in MODATS. Each workshop was based on the three-plus-one dialogue approach, i.e. workshops involving the three colleges in EURAD (WMOs, TSOs and REs), plus representatives of civil society. Two categories of civil society participants were included: experts in civil society engagement and representatives of civil society (encompassing European and national associations, and local stakeholders). The workshops were organised to gather opinions, questions, and expectations for the purposes of enhancing socio-technical dialogues, with the main aim of advancing methodologies to facilitate effective discussions between different stakeholders.

The Pathway Evaluation Process (PEP) was originally developed within the Sustainable Network for Independent Technical Expertise on Radioactive Waste Management (SITEX) project as a means for engagement on broad issues in radioactive waste management. In MODATS, this methodology was modified and tested in the workshops as an approach to facilitate effective discussions between different stakeholders.

The PEP methodology is based on a "serious game[b]". It is designed is to facilitate conversations between different stakeholders to support their understanding of complex issues involved in the management of radioactive waste in the short, medium and long term. It is also a tool for stakeholders to better understand each other's views and opinions. The PEP objective is to identify and discuss issues that are important to the various stakeholders (including civil society), in the context of the different radioactive waste management "pathways" over a timescale of several generations.

The PEP is composed of boards (representing different types of strategies or "pathways" to manage the waste until a "safe terminus": a safe situation that does not require human intervention) and cards. For the application of the PEP in MODATS a new board was developed, which illustrates one possible lifecycle for monitoring within a repository programme (Figure 3-2). There are two sets of cards: the events cards describing events or/and uncertainties that could challenge the pathways and the evaluation criteria cards that are questions enabling to orient the discussions (Figure 3-3).

The PEP methodology invites the participants to frame the discussion by building their own practical cases (using one event card and two criteria cards). The discussion around a practical case is structured in two rounds of discussions. After the first round, the participant that suggested the practical case synthesised what they heard from the others. A second round of discussion is organised to give the opportunity to all of the participants to add additional comments and react to what they heard from the others. During the two rounds of discussions, every participant is invited to speak, one after the other, without being interrupted. The facilitator ensures an equal speaking time for each participant.

As it is deemed to be a demanding activity (participants have to listen carefully to what the others say and wait for their turn to express their views and to respond to the other viewpoints), it is recommended that the PEP is used in small groups of 4-6 participants and facilitated by someone familiar with the methodology.

In MODATS, the PEP methodology enabled discussions amongst different stakeholders on an equivalent footing. The monitoring PEP (developed specifically for MODATS) was considered a promising tool that could be used in future research involving different stakeholders. It was noted that members of the civil society can bring a different way of thinking that would be useful to consider in a comprehensive approach and they can take ownership of all issues surrounding this particular topic. By including civil society in face-to-face discussions trust can be built, and it may lead to technical experts improving the way that they explain their concepts.

[b] A "serious game" is a game designed for a primary purpose other than pure entertainment. Serious games are a subgenre of serious storytelling, where storytelling is applied "outside the context of entertainment, where the narration progresses as a sequence of patterns impressive in quality ... and is part of a thoughtful progress". See, https://en.wikipedia.org/wiki/Serious_game

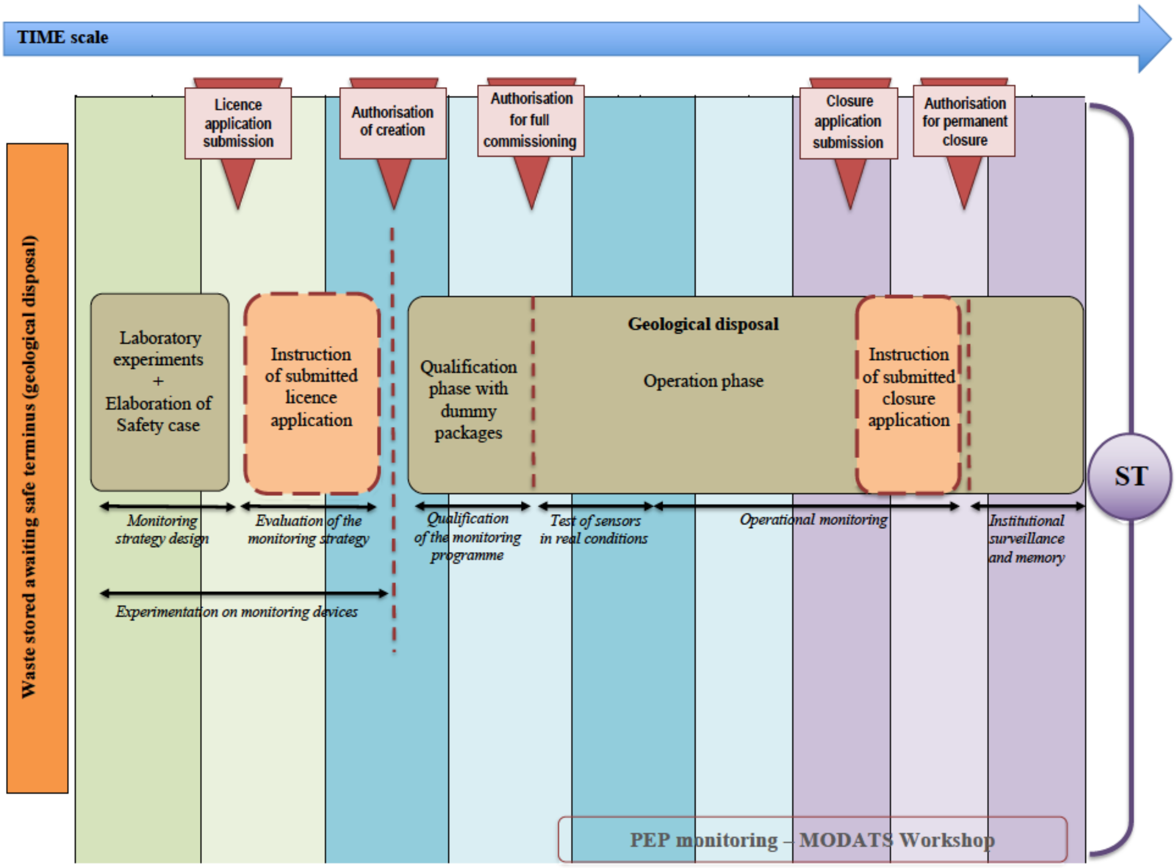


Figure 3-2 - The monitoring PEP Board – the pathway on monitoring tested during the MODATS stakeholder engagement workshops.

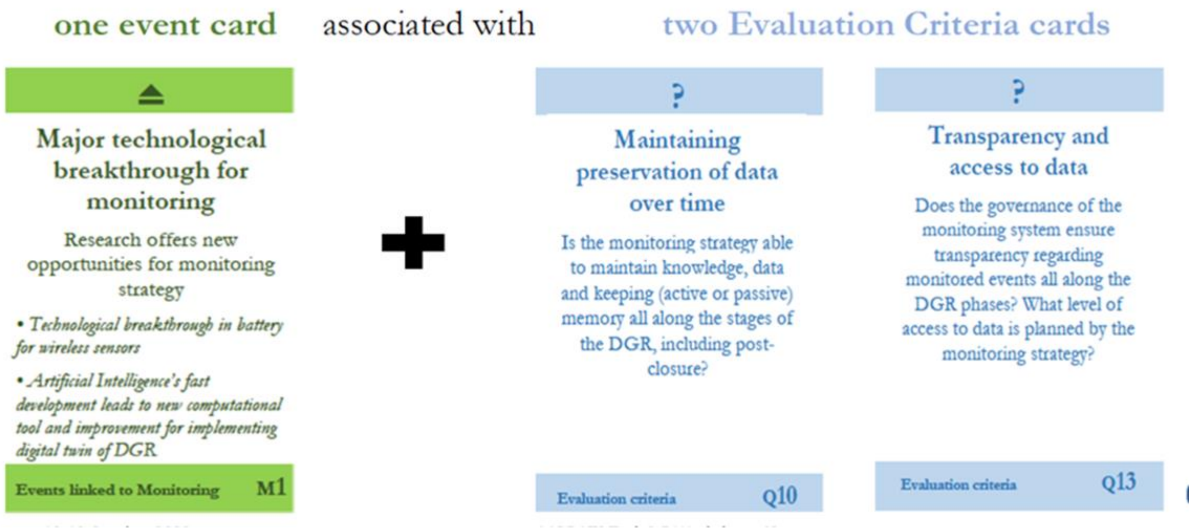


Figure 3-3 - Example of event (green cards) and evaluation criteria (blue cards) cards used for the PEP game developed in MODATS.

The stakeholder workshops provided a diverse range of views on:

- Repository concepts involved, including the meaning of monitoring.
- Data and models.

- Concerns held by civil society regarding the ability and the way to efficiently store and reuse monitoring data over the long term, and the more general issue of intergenerational transmission of the knowledge about the system.
- The impact of change over the long period of repository operation.
- The impact of uncertainty, and the importance of having confidence in the knowledge and understanding of the system.
- The question of transparency and pluralism in the repository decision-making process.

The views and opinions collated within the MODATS workshops are consistent with other engagement activities on monitoring, and extended understanding to topics specifically linked to monitoring data. This knowledge and understanding of civil society expectations can be used to help plan monitoring activities in specific repository programmes.

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*" [[13] § 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 3-8.

Three key stages in developing and managing a monitoring programme are identified in the workflow; these are [[4] and [19] § 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 [20]. 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 3-4 [[4] § 4.2.4].

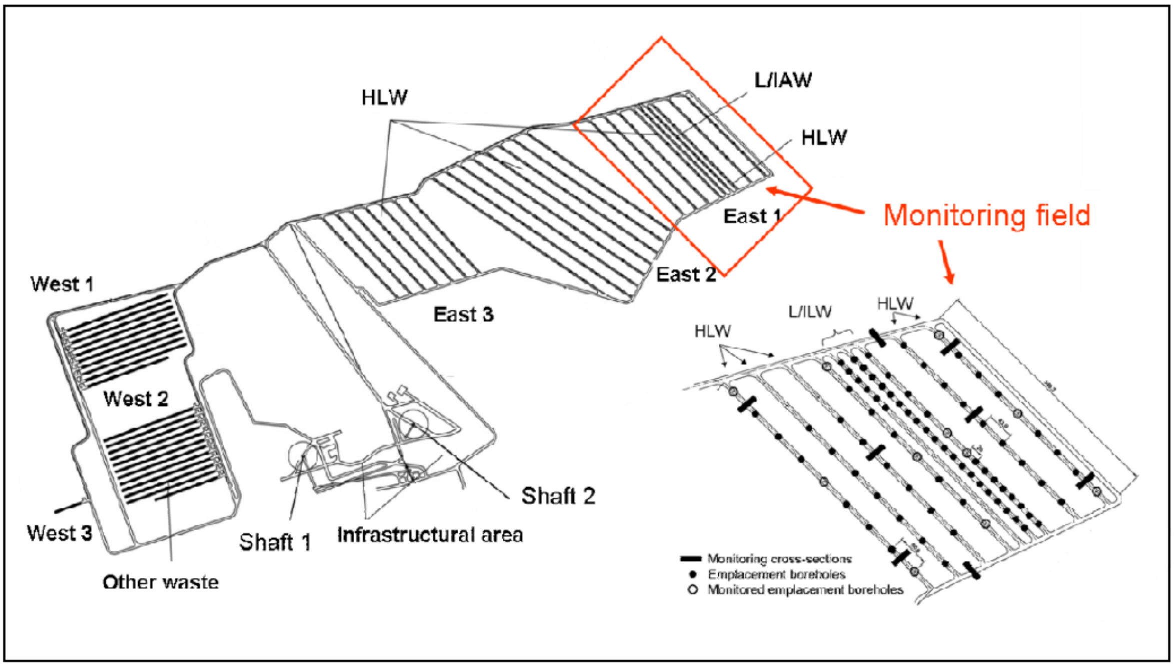


*Figure 3-4 - Potential layout of the Gorleben repository site, and the test case illustration of the location of the representative monitoring field and sensor locations, modified after [21].*The second test case was a disposal cell operational period monitoring programme, based on a French reference 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 3-5 provides an illustrative monitoring system design for a sacrificial cell [[4] § 4.3.4].

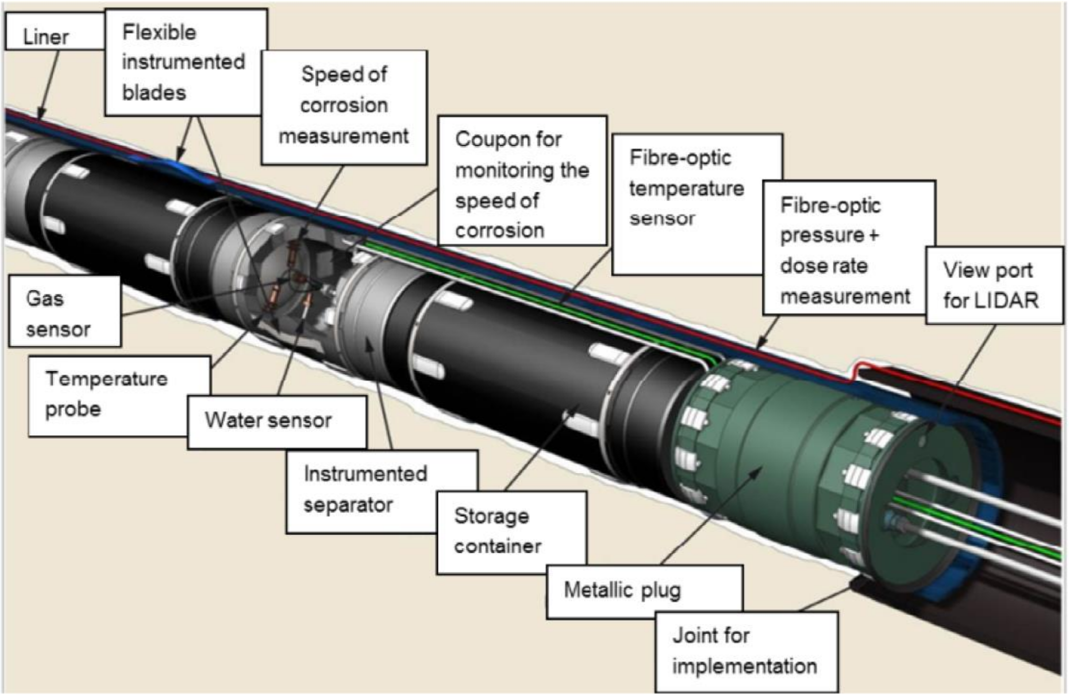


Figure 3-5 - Test case illustrative monitoring system in a sacrificial HLW disposal cell, based on a French reference disposal concept in clay host rocks .The final test case was a monitoring programme of a Finnish reference concept for spent fuel in crystalline host rocks, based on the KBS-3V concept. 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 3-6 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].

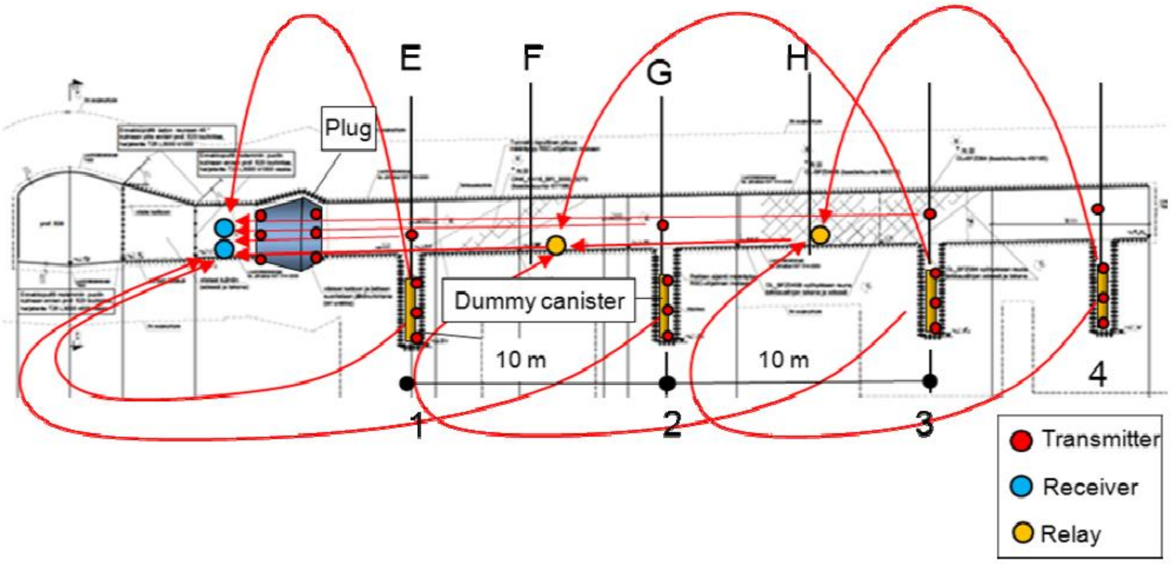


Figure 3-6 - Test case near-field monitoring system for the Finnish reference concept for spent fuel in crystalline host rocks (based on the KBS-3V concept), illustrating the location of sensors, relay stations and receivers [4].

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 waste canisters, 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 [22]. 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 [[23]§ 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 is 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 [[23] § 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 [[23] § 6.1]. Additionally, Table 4.1 in [22] 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 [22].

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
	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

Parameter	Location in the Multi-Barrier System	Test Case that Selected the Parameter
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
Water content/ saturation	Deposition hole seal (bentonite plug)	ANSICHT
	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

Parameter	Location in the Multi-Barrier System	Test Case that Selected the Parameter
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

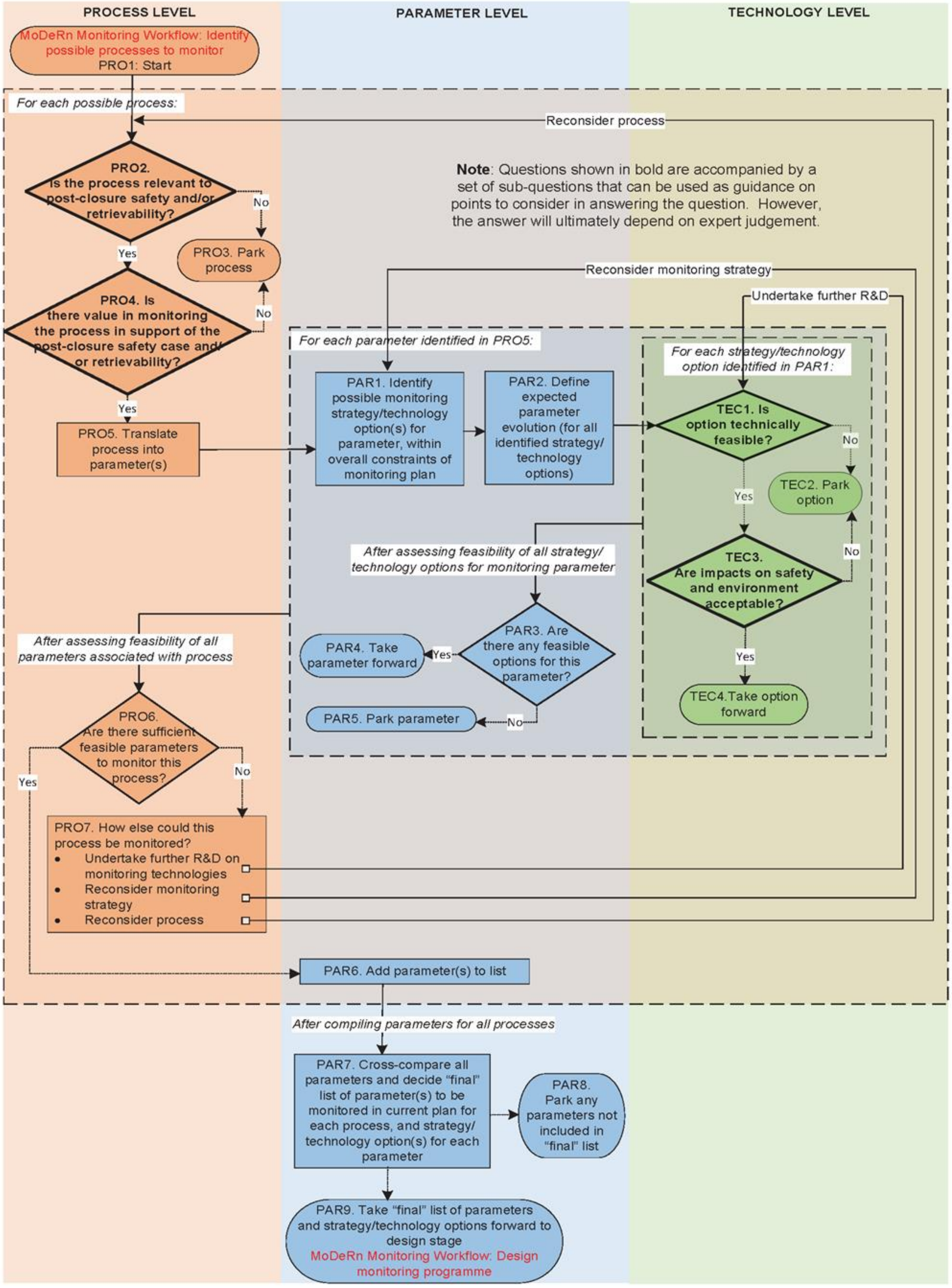


Figure 3-7 - The Modern2020 Screening Methodology [3].

The Modern2020 Project also provided recommendations and guidance on responding to monitoring results [43], which is summarised in the *Monitoring Data Use* sub-section of this report (see sub-section **Erreur ! Source du renvoi introuvable.**).

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 3-8.

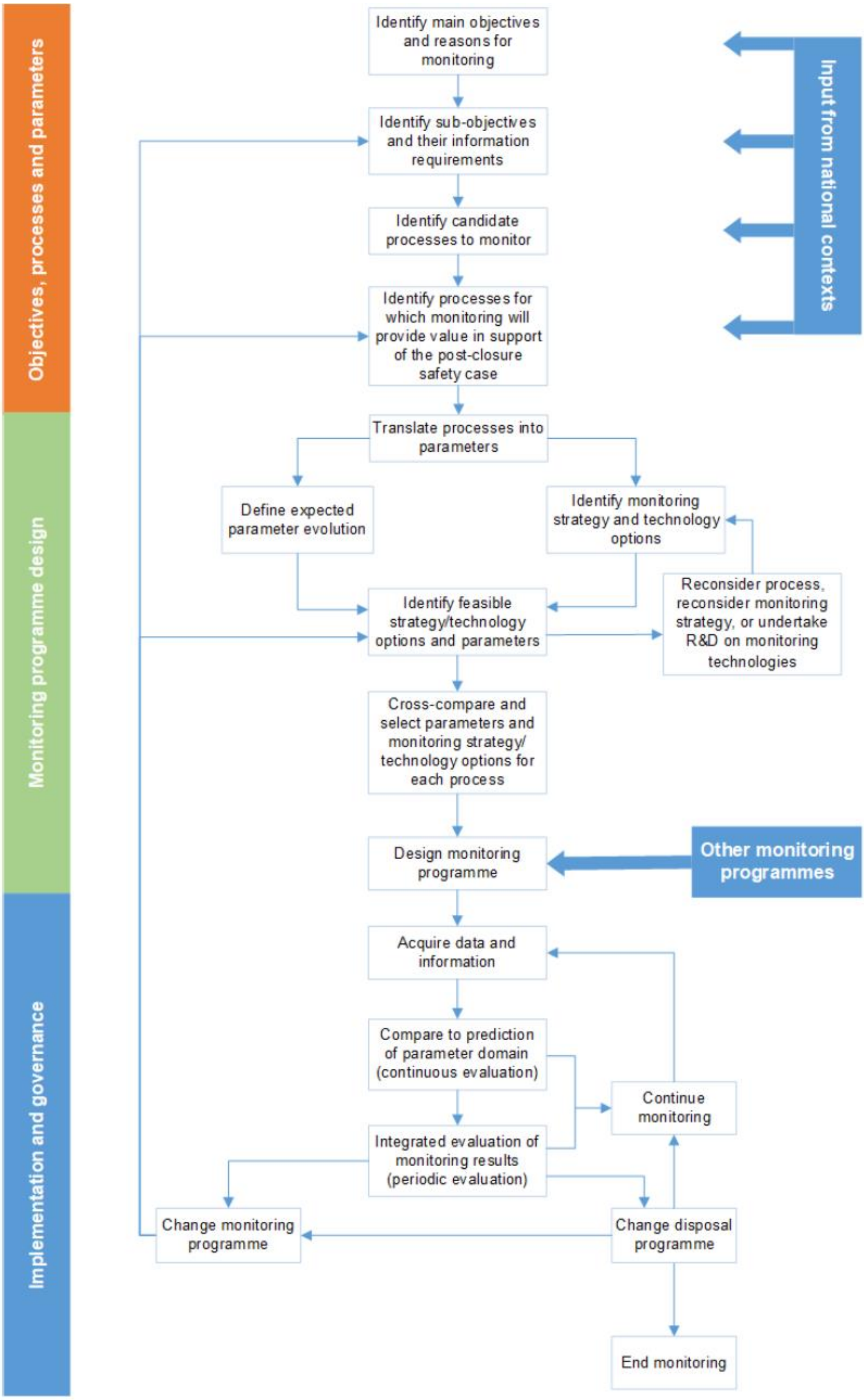


Figure 3-8 - The Modern2020 Monitoring Workflow [3], modified from the MoDeRn Monitoring Workflow.

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 [23]**Erreur ! Signet non défini.** § 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 [[24]§ 4.11.1].

Relating to the objectives of their monitoring programme, SKB state that "*monitoring will help to* [[24] § 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.

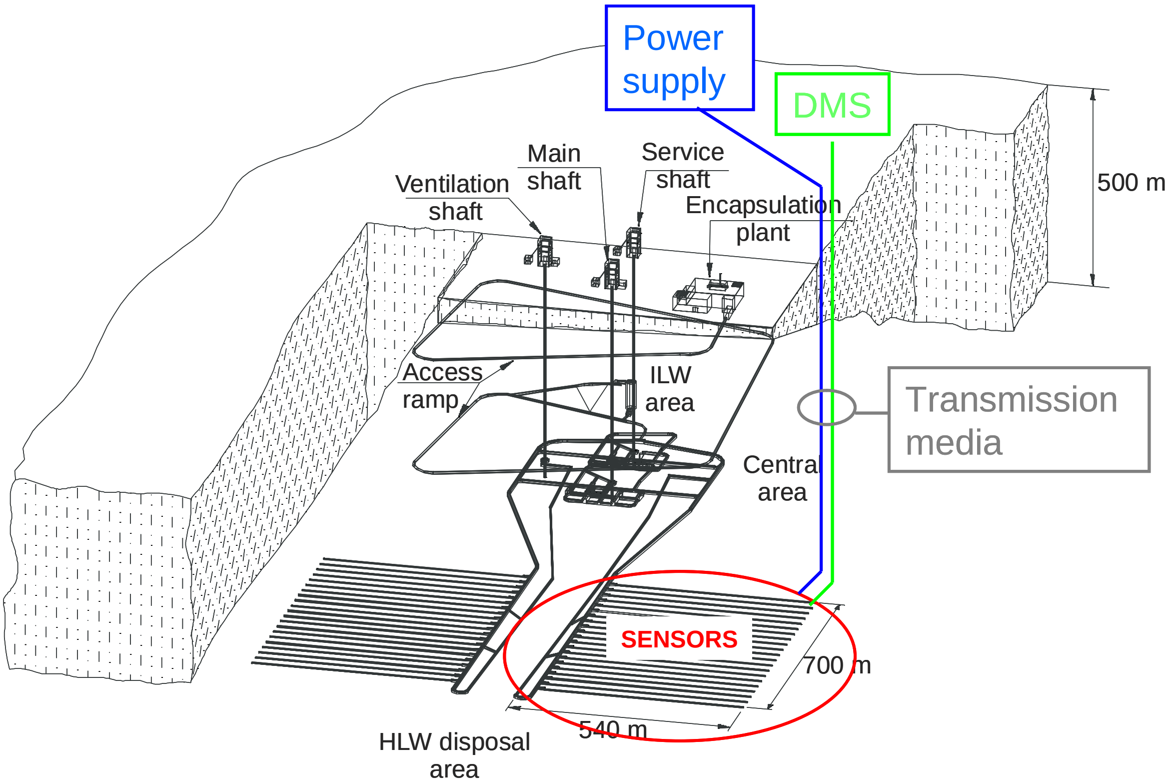


Figure 4-1 - Layout of a generic monitoring system. [25].

Technologies exist for most 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, 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 Requirement

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 [25] 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 [[26] § 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 [[26] § 1.6].

The technical and/or operational requirements that may be imposed on monitoring systems may be attributed to several factors [[25] § 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 [[25] § 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) [[25] § 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 [25]. 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.

4.2 Wireless Data Transmission

Wireless systems allow transmitting monitoring data over natural and engineered barriers without the use of cables that may impair the safety function of those barriers. The barriers of interest could be anything from the concrete buffer of a supercontainer design, a borehole plug, sealings of disposal sections or a shaft sealing: wireless solutions are necessary that can bridge distances from less than a meter up to several hundred meters.

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], [32] § 3.1 and [33].

4.3 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], [32] § 3.1 and [34]

4.4 Optical fiber sensors

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], [32] § 3.1 and [35]

Optical fibre sensors (OFS) are found to be exceptional tools, as they enable distributed measurements, thus providing data over the entire structure. Monitoring with a single fibre can provide information all along the structure behaviour, and thus overcome limitations of traditional sensors, whose information is restricted to local effects. Moreover, optical fibre's small size enables one to reduce invasiveness. Remote sensing would enable the maintenance of the optoelectronic devices during the facility lifetime; only the optical fibre, that is known to be more resistant than electronics, can be exposed to the harsh conditions during the operating period. laboratories. While some of these techniques have already been explored successfully for repository monitoring in MoDeRn [31] and Modern2020 [35].

The OFS offer different levels of sensitivity, spatial resolution, and suitability for various applications. Fibre sensing technology continues to evolve, leading to innovations in sensor design and performance. The key aspect is to guarantee the long-term stability of the sensor in the geological disposal condition [25] and determine if we can measure other parameters like chemical with OFS

Measuring temperature and strain around the radioactive waste cells with accuracies of < 1 °C and 20 με are the two parameters measured by this fiber optic application. Key parameters to develop such sensors under irradiation are Radiation Induced Attenuation (RIA) levels and kinetics determining the sensing length and the lifetime of the sensing capabilities. Radiation Induced Brillouin Gain Attenuation, Radiation Induced Brillouin Frequency Shift (RI-BFS) and radiation induced temperature and strain sensitivity changes, before during and after irradiation and Radiation Induced Rayleigh Frequency Shift (RI-RFS). The latter parameters provide information on the measurement lifetime, sensing length, temperature and strain accuracies, and radiation induced measurement errors. Other parameters are considered linked to coatings of the fiber cable: fiber permeability to H_2 diffusion, cable resistance to gamma and neutron exposures and cable structure influence on the measurement. Results obtained on commercial and research cables has been shown in [38].

Optical pH sensors (pH optodes) are based upon pH-dependent changes of the optical properties of thin proton-permeable layers.The development of these optical probes is based on a simple concept involving the immobilization of a chemical recognition phase sensitive to pH variation on a surface part of the optical chain. These methods use light to measure variations in optical properties resulting from interaction between the aqueous system to be analyzed and the chemical recognition phase of the probe. The immobilization technique for this chemical recognition phase is an important step in the development of these optical probes.

The first results obtained in Bure for the two optical set up lead to a measured value of pH~6 for poral water. These preliminary results are very encouraging because they are independent of the localization of the grafting (fibre or mirror) and are very close to the value pH ~7 measured by conventional on-site pH sensors. This technology is really promising for the future [38].

4.5 Geophysical techniques

In modern2020, 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], [32] § 3.1 and [36].

For repository monitoring, knowledge of the spatial and temporal variations of key parameters, such as temperature, pressure, moisture, porosity, etc. may be needed. In principle, this can be obtained with a sensor network, in which all these parameters can be measured directly. However, this imposes challenges. Firstly, the placement of the sensors could have an impact on the passive safety of the multi-barrier system. Furthermore, the placement of a sensor may locally disturb the embedding material, and the measurements may be therefore not representative. Finally, the sensor data corresponds to point information only, which may be not representative for the entire volume of interest. With geophysical methods the problems mentioned above can be addressed. They can be performed in a non-destructive fashion. Therefore, the integrity of the multi-barrier system remains unaffected, and the embedding material is not disturbed locally. Repeated geophysical measurements also allow spatial and temporal changes to be monitored over larger volumes.

4.6 News and innovative 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], [32] § 3.1 and [35]

In modats WP, the standard thermal imaging is able to see and to detect different type of inflows in conditions where different structures like shotcrete, steel mesh reinforcement and other tunnel infra may disturb the results. Even though the thermal imaging has some challenges, it could be applied to assist human logger. IR-image/recording could be used to automatically identify the leakages and to digitize them. In practice, this would mean taking IR-images and using photogrammetry [39] and pattern recognition to map the anomalies to tunnel profile. After anomalies are digitized, the logging personnel could then determine the amount of water (five different classes) in each anomaly by other means, for example by visual observation (which is the procedure currently anyway.

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 [28].

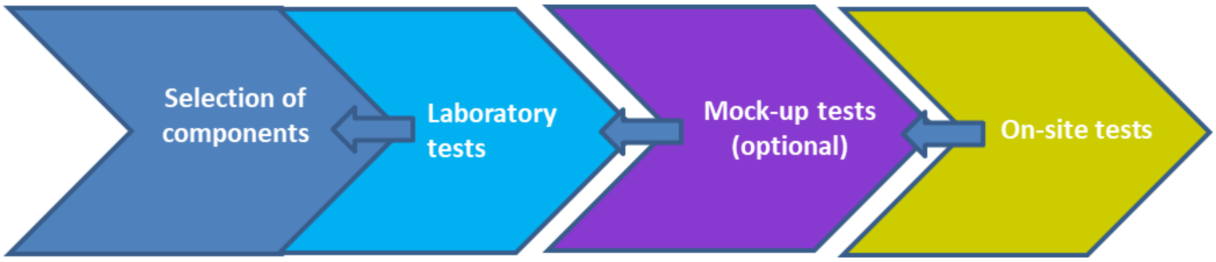
Corrosion sensors that can measure in situ corrosion rates were developed and tested in surface facilities [28].

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].

4.7 Monitoring System Qualification Methodology

The ability to ensure reliable and durable monitoring system with repeatable quality through the time life is critical for DGR implementation. However, as there is still no DGR implemented existing analogies can also be a way for qualifying the MCs and obtain reliable equipment over the long term. This can be done considering the feedback from industries working in harsh environments such as the energy and space fields. Finally, it is acknowledged that another way for qualification and reliability of monitoring components is to consider the lessons learned through long-term experiments conducted at underground research laboratory.

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], [32] § 3.1 and [37]WP.



Global sketch for the qualification of monitoring components in **DGR**s

4.8 Interactions Between 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. Most knowledge of potential interactions is derived from URL experiments.

In MODATS, RD&D was undertaken to identify and describe ways in which monitoring equipment used during the operational phase could impact the long-term performance of a repository, leading to the development of a catalogue of monitoring FEPS. The catalogue was developed using a structured process involving experts from WMOs and research entities. This process included the following steps:

- Identification of generic monitoring components on the basis of their size, location, distribution, and composition.
- Consideration of each generic monitoring component to identify possible thermal, hydraulic, mechanical, chemical, gas generation and migration, biological and electromagnetic impacts of the component on post-closure safety.
- Description of each Monitoring FEP using a standard template.

Eighteen monitoring FEPs were identified through this process [57]. Owing to the differences in monitoring strategies and potential monitoring system designs between different repository programmes, the monitoring FEPs catalogue is generic.

The impact of monitoring equipment on long term performance will ultimately depend on the specific disposal concept and monitoring system design as defined by a WMO. Therefore, the monitoring FEPs catalogue does not provide conclusions on the significance of any of the potential FEPs. The catalogue is envisaged as a starting point for WMOs to develop their own programme-specific monitoring FEPs to support the designs of their monitoring systems.

4.9 Roadmap for Future Technological Development Needs

At the end of MODATS, RD&D was conducted to identify the monitoring technology issues that may need to be addressed before confident implementation of repository monitoring programmes commence. Confidence is a critical consideration because it is recognised that some desired technology performances are difficult to demonstrate before their deployment in a repository. This is particularly true for long lifetimes desired for some technologies.

A matrix analysis approach was used to cross-compare generic technology performance information with generic monitoring requirements for illustrative technologies relating to parameters that may be monitored in the repository (e.g. Table 3-1). Technology performance information was collated from a range of resources (e.g. ongoing research in WMOs, the MODATS Reference Experiments and the MODATS survey of URL experiments; [6], whereas the monitoring requirements were derived from previous requirements research in MoDeRn and Modern2020 (**Erreur ! Source du renvoi**

introuvable.). This approach resulted in the identification of 4 broad categories of implementation issues and 16 sub-categories (Table 4-1).

Table 4-1 - Summary of monitoring technology implementation issues.

Broad categories of issues	Issues
Issues with harsh conditions	Unable to withstand high temperature
	Unable to withstand high pressure
	Unable to withstand high relative humidity
	Unable to withstand high salinity
	Suffer from Radiation induced attenuation
Not fulfilling the data quality objectives	Unsuitable Accuracy
	Significant Drift
	Unsufficent Lifetime
	Require Specific calibration and constitutive relationships
Issues with operational suitability	Unsuitable Sensor attachment
	Cannot measure expected range
	Unsatisfactory Measurement repeatability
	Unsuitable Sampling
	Unsuitable Power supply
	Require Regular Maintenance
Extensive Lack of Knowledge	Extensive Lack of Knowledge

These issues were used to develop a technology development roadmap, highlighting the generic steps that are required to address these issues. The roadmap is designed to interface with the Modern2020 Screening Workflow (relating to questions PRO6 and PRO7; Figure 3-7).

The roadmap is subdivided into four sequential phases, the first of which relates to developing a technological proof-of-concept, if not already available. The other three phases are development activities associated with demonstrating the readiness of the technology in different conditions (laboratory, repository-like environment and site-specific repository).

Each of these activities is linked to a gate assessment. The gate assessments are designed around the matrix analysis approach, described above. They involve the comparison of the available technology performance information to the monitoring requirements to assess technology development against the following questions:

- Can the technology fulfil the data quality objectives?
- Can the technology be installed and operated?

- Can the technology withstand the relevant expected conditions within the repository?

Positive responses lead to the next phase in the roadmap and ultimately, confident deployment in a repository. Negative responses initiate sub-activities, including identification of reasons for failure, proposition and selection of development options, and actual development, with the possibility of reconnection upstream for re-testing and re-assessment. The option can be parked if the development options are deemed unfeasible.

In summary, the roadmap is a versatile tool to demonstrate confidence that a monitoring technology can fulfil the data quality objectives, be installed and operated, and withstand the relevant expected conditions within the repository.

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 repository monitoring data, specifically focussing on the management and use of repository monitoring data.

Relevant understanding of repository monitoring data management and use can be gained from monitoring programmes in URLs, particularly multi-decade experiments, such as the FE experiment [40], where, similar to repository monitoring, there is a need to ensure data integrity over long periods of time. The survey of monitoring in URL experiments, conducted in the MODATS WP, provided lessons for repository monitoring data management and use [6].

Additionally, RD&D was conducted in MODATS to develop tools, methods and guidance 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, MODATS focussed on the processing and storage of repository monitoring data to ensure its accuracy and allow its effective and efficient use in the long term. MODATS also investigated the application of data science approaches to modelling of monitoring data, including digital twins, as well as visualisation tools to communicate the outcomes from repository monitoring. The different RD&D activities were integrated to develop a generic data workflow that considers data management processes and uses from the start of monitoring through quality control of monitoring data through to decision making (Figure 5-5).

Generic guidance documentation on quality aspects of monitoring programmes was also developed in MODATS [44]. This guidance documentation, which is termed a quality assurance programme plan (QAPP), covers the planning, implementation, and assessment procedures for a particular monitoring programme, as well as any specific quality assurance and quality control activities undertaken within it.

This section first describes of SOTA on data management and use, and then uses this understanding to summarise the generic workflow diagram and guidance documentation.

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 processing of the data, organisation and storage of the data (including metadata) into databases with appropriate formats and structures, and supply of data for modelling and visualisation, and so that it can be used to support decision making. Data processing is the manipulation of raw data to make it suitable for its intended use, whereas data storage is the organisation of data and metadata to make it available for its intended use [7] . Effective and efficient data processing and storage processes will ensure the data can be used to fulfil the objectives of monitoring programmes. 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].

5.1.1 Data Processing

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].

Monitoring data are prone to errors. 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 [**Erreur ! Signet non défini.** § 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) [[20] § 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 [[20] § 7.2]. Building on this, invalid data types, referred to as anomalies, were identified in MODATS (Table 5-1).

Table 5-1 - Summary of the main types of monitoring data anomaly (ADD REFERENCE).

Category	Characteristic (and example, if available)
NaN	No value is recorded for a particular timestep or for a specific period within the monitoring data set
Null Value	Value recorded for a particular timestep is zero
Duplicate Values	The data file includes more than one value for a time step in a specific location or for a specific sensor
Non-Physical Value	Value recorded is not possible (e.g., negative relative humidity)
Implausible Value	Value recorded is not reasonably expected (e.g., negative temperature)
Unexpected Constant Values	The values returned by a sensor do not change over time
Spikes	A sharp change in measured value, followed by a sharp change in opposite direction for the subsequent value(s). Spikes can be single values or occur over a short period relative to the monitoring period.
Temporary Step Change	Data records show a sharp change in values, before a similar sharp change in the opposite direction, and then progressing at a similar rate of change as previously

Category	Characteristic (and example, if available)
Permanent Step Change	Data records show a sharp change in values, before progressing at a similar rate of change as previously
Noise	Noise is characterised by a scattering of values around a central trend
Outliers	The values recorded by one sensor are inconsistent with values recorded by close-by sensors measuring the parameter in the same way in the same medium
Unexpected Data Trends	Data trend is inconsistent with model prediction

Invalid data have to be identified and treated. The MoDeRn research 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 [[20] § 7.2 and 7.3].

Data processing methods to identify and treat invalid data are routinely applied in the URL experiments using a range of bespoke methods. 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 [[20] § 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.

These methods are typically developed for the specific experiment or for a specific sensor used in an experiment. Such bespoke methods may not be appropriate for repository monitoring data sets. In particular, repository monitoring data need to be analysed in a way that allows for the systematic identification of anomalies related to sensor ageing and malfunction, outside influences, and deviations of the repository system from expected behaviour. The processing need to provide data for modelling and visualisation in a quality-assured manner. Using the Reference Experiment datasets, RD&D conducted in MODATS has resulted in the development of several processing tools for repository monitoring data (REFERENCE Table 6-2), and the following general conclusions:

Based on the RD&D in MODATS, the following conclusions were drawn on data processing:

- Data processing should be undertaken with reference to user requirements; processing does not have just one end goal; data sets after processing will differ according to the user requesting the data.
- Good practice in data processing is for software to provide visualisation of time series data to give the expert optimal insight into the data, and basic statistical analyses to indicate signal quality (e.g. daily averages and standard deviations to indicate signal-to-noise ratio or repeatability).
- Data processing is a hybrid process; one or many algorithms perform the screening and preliminary labelling of the measurement data, which is then confirmed, rejected or altered using expert judgement. Automatic checking of data is undertaken on a data-point-by-data-point

basis, using *a priori* physics-based knowledge (e.g., identification of non-physical and implausible values) and statistical tests (e.g., standard deviation from median values to identify outliers). Data processing should not remove data.

- To make computed results traceable, all data processing steps should be based on a quality assurance procedure that defines how the process should be conducted, and recorded in a version control system.
- In addition to identification and treatment of invalid data, data processing requires amalgamation of data from different sensors (potentially including sensors monitoring the same parameter using different technologies) into integrated data sets for analysis.
    - This includes data reduction so that modelling and visualisation can proceed efficiently.
    - Temporal sampling of sensor data should be as homogeneous across sensors and time as possible to allow easy comparison across several sensors.
    - The temporal resolution must be high enough to cover all relevant phenomena (e.g. porewater pressure can change more rapidly than temperature, so sampling of pressure data should be performed at a higher frequency than sampling of temperature data).
- Data sets from several sensors should be processed together, alongside metadata, to cross-check conclusions. Applying domain knowledge of the whole environment and of the used sensors and data acquisition setup is also crucial to ensure correct processing.
- Multidisciplinary domain expertise is required at all stages of data management, not just at the analysis stage by the data users.

5.1.2 Data Storage

As with data processing, URL experiments can provide insights into storage approaches for repository monitoring data. 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 [[40] § Appendix 3].

It is important to recognise that 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.

Repository monitoring data storage RD&D was conducted in MODATS using the Reference Experiment datasets. The following general conclusions were made:

- It is necessary to clearly establish the ownership and responsibility for different parts of the monitoring database.
    - These include the data, the metadata, and the expertise required to use the data, including the understanding of how the database has been designed and constructed.

- Owing to the range of types of information that need to be included in a monitoring database, it is a challenge to organise and structure the database in a way that facilitates easy access for data users. The design of the database should be undertaken from the perspective of the data users rather than the data providers.
- Harmonised ontologies[c] and metadata conventions would promote efficient and transparent storage of monitoring data.
  - Work in MODATS has highlighted the application of outcomes from the OECD NEA RepMet initiative [[42]]; high-level guidance provided in the RepMet reports should be followed when planning for the storage of metadata in a repository monitoring programme.
  - Data standards and shared application programming interfaces (APIs) should be agreed and used to facilitate the implementation and use of shared digital infrastructure and to exploit the full capacities of automatization. This standardisation should also cover metadata, which needs to be structured in a uniform and consistent way, through time and by the different data sources.
- During the construction and operational phase of the repository, there will be many activities on-going simultaneously that might generate responses in the monitoring system. It is necessary to include documentation of all relevant activities in the database to support data interpretation and root-cause analysis.
- Monitoring data and metadata need to be available for decades to support repository operation and closure. Flexibility is required in the manner in which data is stored to allow for different ways of processing and analysing data in the future.
  - There needs to be a plan for regular updates to hardware and software, as it is likely that databases and data management tools will change over the lifetime of repository monitoring programmes.
  - Standardised file formats can be used to support sharing of information. They can provide resilient to future software developments because they are founded on the technical support of a large number of users and are less likely to be replaced by new formats.

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"* [[8] § 4.4].

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

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[c] An ontology is the classification and explanation of entities such as (in this context) the information in a database.

> "*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*" [[8] § 3.5].

The ETN also discusses the responses to unexpected monitoring results and corrective actions [[8]§ 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.*" [[8] § 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 [[45] § 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 [[45] § 4.1] (Figure 5-1).

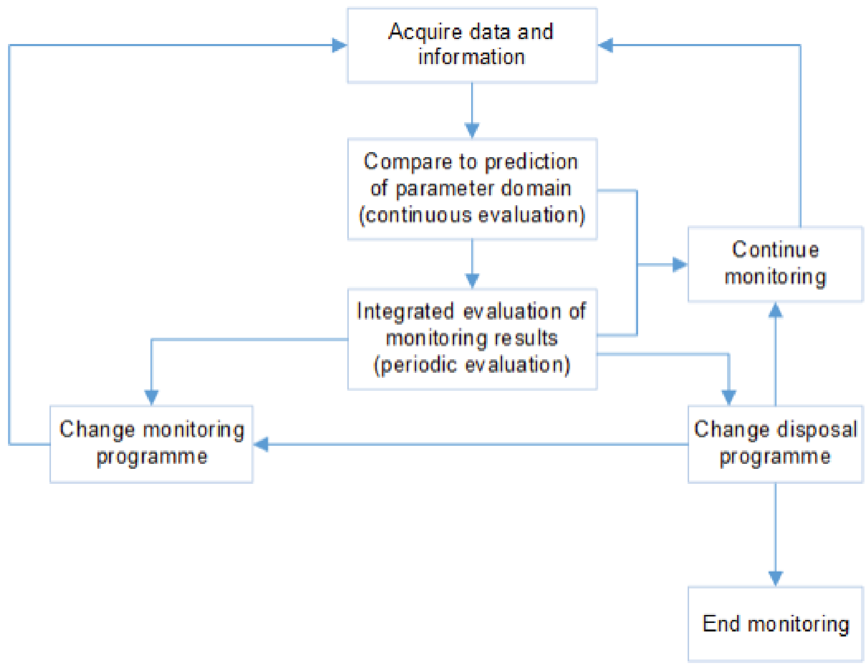

*Figure 5-1 - Workflow for responding to monitoring results [45].*The main steps in the process are:

- 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**Erreur ! Source du renvoi introuvable.**) 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 Modelling

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 [46].

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.

Work in the EURAD Mechanistic Understanding of Gas Transport in Clayey Materials (GAS) and Influence of Temperature on Clay-Based Material Behaviour (HITEC) WPs of EURAD used a combination of experimental and modelling approaches to increase the understanding and predictability of the impact of coupled gas and heat transport on clay barriers [ADD REFERENCE]. 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 [47], which provides a wealth of knowledge and experience on this subject. Summaries of recent research in DECOVALEX are presented in [46], [47] and [48].

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**Erreur ! Source du renvoi introuvable.**).

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 [46]. Further details of the modelling approaches are presented in [46].

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. Some comparisons of model predictions and monitoring data from the FEBEX experiments are presented in Figure 5-3.

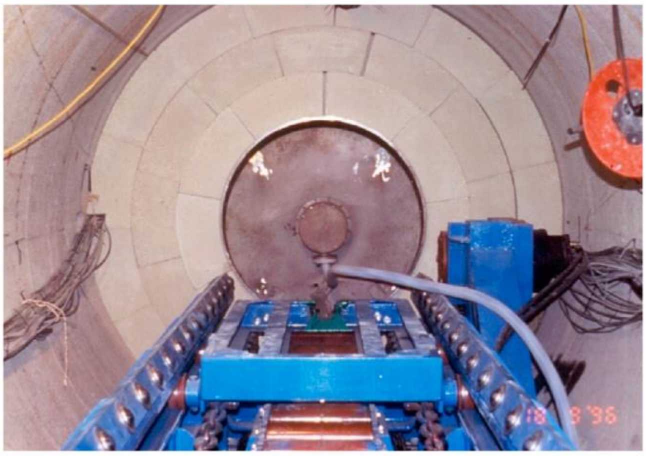

Figure 5-2 - Cross section of the FEBEX experiment during installation showing the heater surrounded by compacted bentonite blocks [48]].

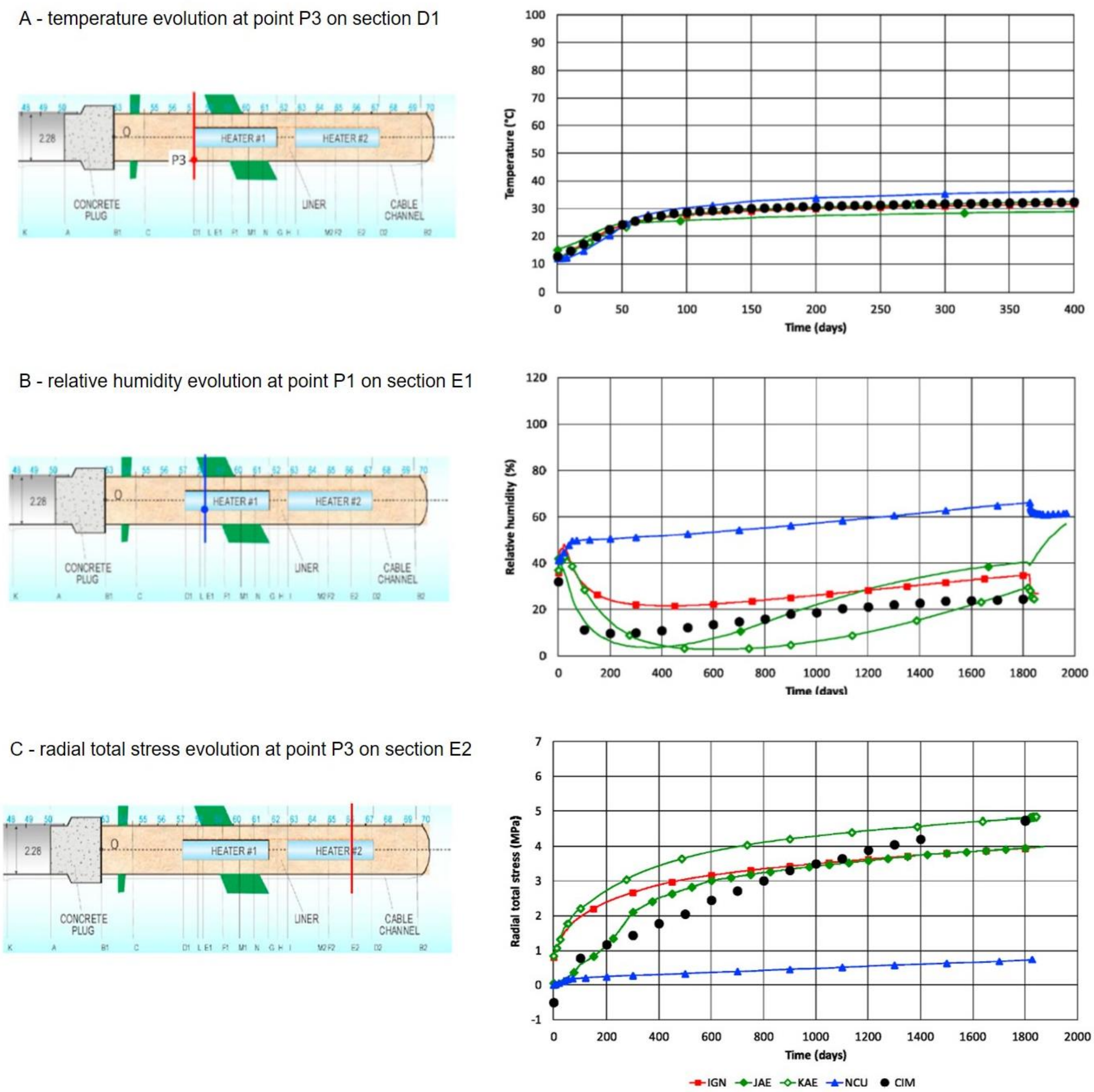

Figure 5-3 - Example comparisons of monitoring data (black dots) and 4 different modelling predictions (red, green and blue curves) for A) temperature, B) relative humidity and C) radial total stress in selected locations the FEBEX experiment, based on work in the INBEB ask in DECOVALEX 2019, modified from [48].

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.

In MODATS, the application of data science approaches to modelling of monitoring data has been investigated in the ALC1605 and the FE Reference Experiments [41].

In the ALC1605 experiment, it has been demonstrated that hybrid twin models are a promising approach for modelling the thermal evolution of a HLW disposal cell. In the hybrid twin approach, a physics-based (surrogate) model using only heat conduction is first applied to the model domain. Monitoring data are then used to quantify the uncertainty in the model (the ignorance), which, when applied to the surrogate model, provides the ability to rapidly and accurately model the data from the ALC1605 experiment. The use of a hybrid twin, rather than a purely data-driven model has several advantages, particularly in modelling of the thermal evolution of the disposal system over the operational period, as it grounds predictions in well-established physics, enhancing the reliability of our results.

The FE Reference Experiment came to a similar conclusion as ALC1605, i.e. that a hybrid modelling approach combining the physical model with a data-driven model provided the best modelling results. In this example, a physics-informed machine learning model was preferred, which combines the k-nearest neighbour algorithm with data on the heat power or power density heat source.

In summary, MODATS has demonstrated the potential for hybrid models that combine physics-based and data-driven-modelling to provide a basis for analysis of monitoring data during repository operation.

5.2.2 Visualisation

Repository monitoring data (and the models generated from the data) can also be used for communication purposes. Using the FE Reference Experiment, a digital model of the Mont Terri URL was generated in MODATS for the purposes of visualisation and communication. This model is known as the Virtual Experiment Information System (VEIS).

It is an integrated information system for domain experts, that includes the geometry of the tunnel system, the geological environment (such as stratigraphic layers and the major tectonic faults; Figure 5-4) and information associated with experiments undertaken in the Mont Terri URL. VEIS automatically updates the when underlying data change, and can therefore be considered a digital twin prototype with a focus on visualisation (section 6.1).

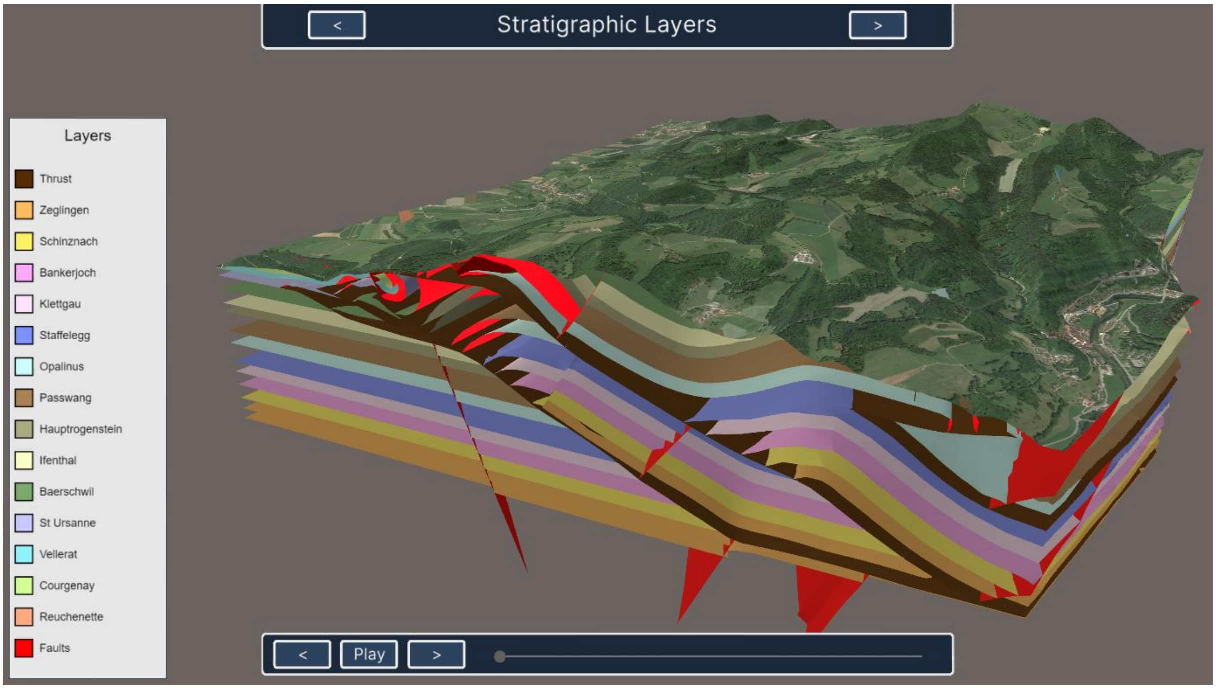

Figure 5-4 - Screenshot from the Virtual Experiment Information System (VEIS) in the Mont Terri URL illustrating the geological context in form of the stratigraphic layers and major faults.

The application of the VEIS was extended for use by university students in MODATS. To extend the use of visualisation systems for these actors, additional features were required to facilitate independent exploration of the information. These included contextual information and tasks to be performed at each viewpoint. The inclusion of tasks is particularly important, as undertaking these tasks provides the user with a more interactive experience, increasing their learning from the process. Evaluation of the use of the VEIS in this way in a trial demonstrated the effectiveness of the approach in communication and education.

This RD&D also showed that visualisation can be of significant benefit when comparing simulation results from different numerical models of THMC processes. The approach adopted involved a two-step process. The first step is combining the data into a common file format, which allows spatial and temporal differences in the data to be reconciled. The second step is to view the data and allow for contouring, slicing, selecting and filtering (based on conditions) of timesteps.

5.3 Generic Data Workflow for Conformance Verification

Using relevant understanding from URL experiments, as well as data and understanding from the Reference Experiments, MODATS developed a generic data workflow as guidance on data management and uses from the start of monitoring, through quality control of monitoring data to decision making (Figure 5-5). The workflow includes five main steps:

1. Data acquisition
2. Data screening
3. Anomaly interpretation
4. Comprehensive data analytics
5. Decision support

Steps 1 to 3 relate to repository monitoring data management, while steps 4 and 5 correspond to analysis, as well as management of the resulting data. The next section describes each of the main steps in detail.

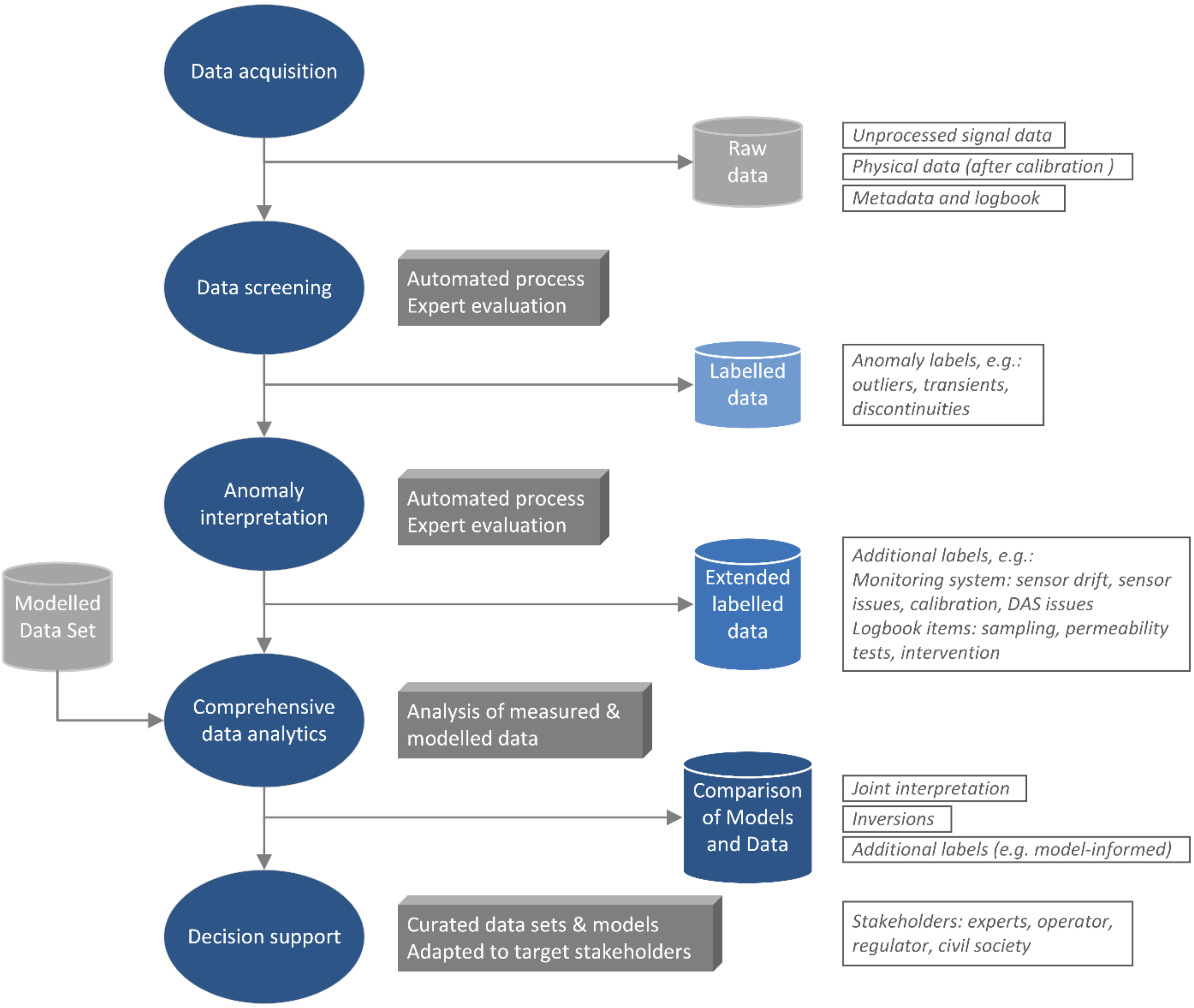

Figure 5-5 - Repository monitoring data workflow from acquisition to decision support.

5.3.1 Data Acquisition

In general, data acquisition needs to be conducted adhering to quality control standards and good practices.

Data needs to be stored in a database, obtaining the most recent data in regular intervals or through live streams. Intervals of no greater than one day are suggested but shorter intervals will be generally preferable. Raw data should be kept for at least the duration of the monitoring programme and not modified in any kind of way.

The database needs to store the unprocessed signal data that are measured by the sensor (e.g. in units of millivolts) as far as reasonable, as well as converted data based on the sensor calibration certificate. Depending on sensor type and manufacturer it could be that the unprocessed signal data is not available, i.e. the output is already a product of a calibration performed in the laboratory. In both cases a complete definition of the sensor response characteristics including the calibration certificates needs to be stored as part of the metadata.

A complete set of metadata that describes the installed sensor network and any changes made to it during the monitoring period need to be maintained throughout and stored alongside the raw data. It is also important to store pertinent information on the overall system (e.g. repository operations affecting the monitored data) in a logbook for later reference. This logbook information is considered to be raw (meta) data and thus should be created and maintained close to real-time for consistency.

5.3.2 Data Screening

Based on the raw data, a (periodical) basic data screening should occur. The goals of the data screening are to evaluate the general quality of the raw data. Specifically, anomalies such as sensor failure, outliers, or gaps and discontinuities in the data should be labelled (Figure 5-5). Because the type of anomalies to be identified in this step is fairly easy to identify, often an automated process may be suitable for this type of screening. In addition, expert evaluation could be employed to verify the automated processes or add additional labels.

The product of the data screening step is a set of labelled data that identifies anomalies in the monitoring data that are not associated with the system monitored but are invalid data (i.e. spurious errors of the monitoring system). The premise of adding labels to the data is to identify sections of the data that are deemed reliably and to identify sections of the data for which confidence is reduced and which shall be excluded from further interpretation. Importantly, the process of labelling does not alter the data in any way and all data is maintained throughout the monitoring programme.

5.3.3 Anomaly Interpretation

Additional analysis is likely to be required to identify and label further anomalies that may not be as obvious as the ones identified in the data screening step. The anomaly interpretation step aims to verify the data in more detail and to use analytical methods to identify potential issues with the data that are less obvious, but that could still impact system understanding. Examples of sensor issues that should be identified are drift, calibration or other unexpected behaviour. There is potential for automated analysis in this step in the future, however, currently this kind of processing requires expert evaluation.

Events documented in the logbook, such as specific interventions that will impact the system behaviour, should also be labelled in the data in this step. Using a well-specified format for the metadata facilitates the implementation of automated processes that aid in the labelling of such events in the data [41].

5.3.4 Comprehensive Data Analytics

The labels created in the previous steps provides a quality-controlled data set (“extended labelled data”) for which confidence is created to conduct further analysis steps and ultimately lead into decision support. In addition to the monitoring data, modelled data sets need to be used in order to evaluate the monitoring data. Labelled data can then be treated properly, depending on the specific requirements of the analysis. While some methods are robust to outliers, others may not be. If labelled data points are removed for specific analyses, a decision needs to be made to fill the gap or leave it blank.

Modelled data should provide the baseline of our understanding of the monitored system. Hence, a meaningful comparison of the modelled data with the monitored data would lead to an understanding of whether the system behaviour is in conformance with predictions. In order to get to a meaningful comparison, it is important to understand the quality of the data and the limitations of the numerical models. The first three steps described above ensure that the data has been adequately quality controlled.

Numerical models are always an approximation of the real system. Differences may be due to approximations in the input data such as simplified time histories of modelled loads, discretization of the spatial domain and of the distribution of material parameters. Furthermore, there may also be (coupled) processes that are not captured by the numerical model. Hence, there will always be some level of mismatch between the results of numerical modelling and monitoring data. This mismatch can also be used to create additional labels and potentially identify (or confirm) faulty sensors through physical reasoning. Comparisons of modelling and monitoring data thus need to consider possible sources of differences before determining conformance.

Advanced analysis may include computational methods such as inversions. These techniques have their own sources of uncertainty and may include biases from the analyst. For example, the specific choice of parameters, e.g. damping parameters, used to control the convergence of a solver will lead to different results and probability distributions of the target solution. Typically, inversions deal with non-uniqueness problems, which means that there are several configurations in the solution space that equally fit the observation.

5.3.5 Decision Support

The ultimate goal of monitoring efforts is to aid in decision making. To that end, suitable, curated data sets and models need to be created. There are different decisions that will need to be made, by different stakeholders during the repository programme. This will range from decisions associated with the way in which disposal is implemented, including modifications to initial plans, to major decisions to progress from one stage of the programme to the next. A range of stakeholders will be involved in, or interested in, these decisions, and will require different information to address the questions that they have. It is important to tailor the presentation of materials with the target audience or specific stakeholders in mind. However, it is stressed here that decisions will be informed by the safety case, and the monitoring programme can be considered as a component of the safety case. In this instance, monitoring data will feed into decision making through the safety case, rather than directly.

5.4 Quality Assurance Programme Plans

To support the demonstration that monitoring data can be used to fulfil the objectives of monitoring programmes, MODATS proposed that the quality aspects of a monitoring programme are described in a document referred to as a quality assurance programme plan (QAPP). A QAPP documents the planning, implementation, and assessment procedures for a particular monitoring programme, as well as any specific quality assurance and quality control activities. It integrates all the technical and quality aspects of the programme in order to provide a "blueprint" for obtaining the type and quality of monitoring data and information needed for a specific decision or use. The term and concept for a QAPP were developed by the United States (US) Environmental Protection Agency (EPA) to control operations related to environmental monitoring performed by, or for, the US EPA

Quality assurance guidance and requirements from published literature [44], along with learning from structured discussions with experts, were used in MODATS to develop guidance on the structure and content of QAPPs for repository monitoring [44].

Figure 5-6 shows how a QAPP could interface other documentation produced by a monitoring programme. The proposed guidance assumed that a QAPP would identify the procedures and protocols to be followed in the repository monitoring programme, and provide information on how to access them (e.g., for most programmes this would be through links to a database or document management system).

The guidance proposed that a QAPP would contain five main sections that correspond to the plan, do, check and act cycle, which underpins generic quality assurance guidance:

Plan:

- Organisation of the Repository Monitoring Programme, including description of the monitoring objectives; monitoring processes, parameters, and technologies; the monitoring programme schedule; monitoring roles and responsibilities; and monitoring programme documentation.
- Design of the Repository Monitoring Programme, including descriptions of the knowledge on which the design has been based; the requirements on the monitoring system, including data quality objectives; the process used to design the monitoring system; and a description of the monitoring system itself.

Do:

- Implementing the Repository Monitoring System, including guidance on the receipt and testing of monitoring equipment; its calibration; installation of the equipment; operation of the equipment; and its eventual decommissioning.

Check

- o Checking the Monitoring Data, including guidance on processing, storing and auditing data.

Act

- o Feedback to the Monitoring Programme, which would provide guidance on the evaluation of operational experience and the data provided by the monitoring system, and would feed back to changes to the programme reflecting a commitment to continuous improvement.

This guidance provides a framework for addressing some of the challenges posed by repository monitoring. It is designed to support reliable, long-term monitoring data acquisition, management and use, fostering confidence in the data provided by the programme.

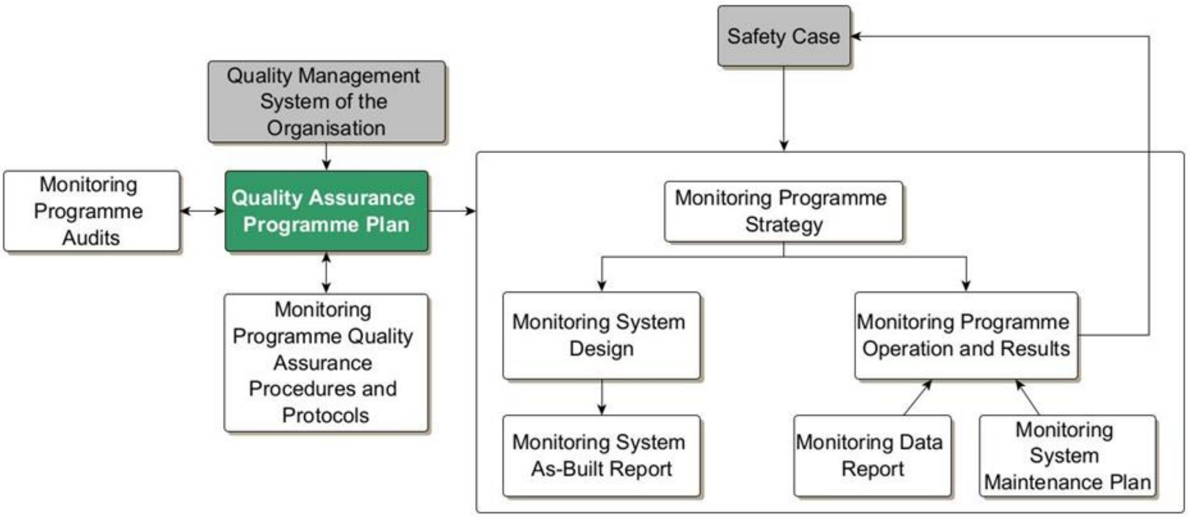

Figure 5-6: Proposed structure of monitoring programme documentation for a repository monitoring programme. The QAPP is highlighted in green. Grey-coloured documents (or suites of documents), including the Safety Case and the Quality Management System, provide overall requirements on the monitoring programme regarding the repository programme quality management

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6. Digital Twins

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. Digital twins have most frequently been used to support the production and maintenance of structures, especially engineered structures such as aircraft, bridges and machinery. The coupling of digital twins with data science applications such as artificial intelligence (AI) provides significant opportunities for expansion of the use of digital twins, including the geological disposal of radioactive waste [49].

Digital twins have the potential to support monitoring programmes in demonstration of compliance with requirements and conditions linked to long-term safety. These requirements and conditions differ between each repository programme are yet to be fully developed in some cases. However, monitoring during repository operation is not expected to be based on extensive sensor networks as currently employed in URL experiments. The extensive networks used in URL experiments are deployed to develop understanding of coupled processes occurring in the EBS and geosphere, and this understanding is fed into the safety case. Monitoring during repository operation is anticipated to be more focused on support of limited modelling used to check system behaviour (for example to confirm the absence of any conditions that could affect the safety of the facility after closure), and has to be implemented such that it does not impact passive safety. Hence, approaches to developing digital twins for monitoring repository processes during the operational period will most likely have to be developed with much sparser data sets than digital twins of URL experiments. Likewise, measured gradients might be smaller since sensors will generally be placed at a significant distance from the waste packages.

Digital twins can support monitoring by developing surrogate models that are able to recreate spatially-distributed time series data without the need for resource-expensive and time-consuming coupled process modelling. To achieve this aim, surrogate models require a PBM that incorporates the processes of greatest significance to the objective of the model, and the use of a DDM that incorporates ML approaches such as neural networks to train the model to deliver accurate results (e.g. AL1605 and FE Reference Experiment digital twins; section 5.2.1).

6.1 MODATS Opinion on Definition and Uses

MODATS developed the following definition of a repository digital twin:

> *A repository digital twin is a virtual model of part of a repository that is updated automatically to address specific objectives.*

In the context of repository monitoring, a key feature of a digital twin is the automatic feedback of monitoring information to better meet the objectives. It is the feedback from monitoring information that distinguishes digital twins from other types of models (e.g., geological interpretations, building information modelling representations of infrastructure, and coupled process models).

Furthermore, as justified above, digital twins are built with a specific objective in mind and cannot replicate the full reality of the repository. Therefore, it is the opinion of MODATS that repository digital twins are not "one size fits all", but come in different forms depending on the objective for which they are developed. Several digital twins might be created for one repository, each with a different purpose, but, potentially, all with a common data architecture to enhance interoperability. Discussions within the MODATS WP identified the following potential applications of digital twins in repository programmes:

- Demonstration of retrievability.
- Communication through visualisation.
- Checking sensor performance.
- Modelling coupled processes using surrogate models.
- Prediction of repository processes and evolution.

It is recognised that repository digital twins constitute an emerging technology with a range of potential use cases, including applications such as optimisation and communication. These discussions have not focused on a comprehensive evaluation of the potential purposes of digital twins in repository programmes or in support of repository monitoring, nor on the requirements of digital twins with respect to each purpose.

7. Future RD&D in Repository Monitoring

The final section of this SOTA report summarises some of the gaps in repository monitoring knowledge, and in doing so highlights potential future repository monitoring RD&D.

7.1 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 enhanced through development of novel and innovative technologies. The present state-of-art of industrial sensors features a variety of sensing devices nevertheless, there is still a need in the following domains:

Emerging Sensing Technologies (Non-destructive/non-invasive)

It is important to continue to support New and emerging sensing methods that may change the paradigm of how to monitor waste repositories. Especially, it is important to support non-destructive techniques and non-invasive inspections.

Corrosion sensors

Currently there are also knowledge and technological gaps that limit the ability of engineers to effectively, reliably and proactively detect and control localised corrosion. Many of these gaps, challenges and needs have been discussed [58][59]. An ‘ideal’ corrosion monitoring and control system should be one that not only provides in-situ and site-specific corrosion data required to visualise localised corrosion in variable corrosion environments, but also to use such data to inform corrosion predictive modelling, mitigation and management actions that may need to be adjusted smartly and dynamically based on the prevailing corrosion condition and mechanism.

Harsh environments sensors

There is currently a strong demand, from many fields, for the realization of sensors capable of operating in harsh environments. Sensors exist to measure many parameters now but they need to be improve to support the condition of the geological disposal.

Integration with AI/ML

Advancements in AI/ML technologies will redefine many aspects of monitoring approach. Advanced sensor readings coupled with cutting-edge AI and ML computing capabilities have immense transformative potential.

Rise of Robotics in NDE Applications

Robotics introduces unprecedented accessibility to confined spaces, mitigating the need for human exposure to hazardous environments. Equipped with advanced sensors, robotic systems offer a level of precision and thoroughness that surpasses traditional inspection methods. The ascent of robotics in Non-destructive Examination heralds a paradigm shift in inspection methodologies.

7.2 Future Near-Term Requirements on Digital Twin EC Research

MODATS concluded that future RD&D work should focus on achievable goals rather than looking for global solutions to the application of digital twins in repository programmes. There is no requirement to harmonize approaches (e.g., focusing on open-source software or bespoke solutions). Instead, the existing approach of undertaking a range of exploratory projects looking at different aspects of digital twins should continue. This approach should make use of the MODATS Reference Experiments and active digital twin research programmes. There should be further integration between groups working on digital twins in different spheres of radioactive waste management (e.g., EURAD and PREDIS).

At the end of MODATS, it was proposed that future European-level collaborative research on digital twins should be structured into application and technology themes. The potential activities in each theme are discussed below.

- Application Theme: research into the use of digital twins in repository programmes to identify the benefits that could be delivered through their development and application.
- Technology Theme: further development of the capabilities of digital twins, especially the prototype digital twins developed in MODATS.

Application Theme

Consideration of the application of digital twins could include further analysis and a review of the potential applications of digital twins in repository programmes. This would provide a reference document for understanding how different types of digital twins could be developed and applied across the broad spectrum of activities required to support geological disposal of radioactive waste. It would also support a more evolved and more harmonised understanding of the digital twin concept.

This review could be coupled with specific research into the application of digital twins associated with monitoring programmes. The outcome would be to understand the needs of digital twins linked to repository monitoring programmes, e.g., exploring how much data is required by the digital twin, would the associated data requirements impact on the passive safety of a repository, and how would information supplied by digital twins support periodic updates to the safety case during operations (i.e., address uncertainties in the safety case recognised during the licence application)?

As digital twins are still an emerging technology, there is a lack of clear understanding about the value it can bring to the geological disposal field. There is a lack of case studies of successful practices. Extension of the MODATS Reference Experiments and development of digital twins and their underlying surrogate models could be used to communicate the manner in which digital twins can be applied during repository monitoring, and to identify the benefits and challenges of doing so. This would include implementation of recommendations developed from ongoing work on digital twins in the MODATS WP.

There is also a need to communicate the potential for digital twins to different stakeholders. This would include developing guidance/understanding on the challenges and difficulties with using digital twins for discussions with civil society (for example, explaining the complex science associated with PBMs and surrogate models, and the different modelling approaches undertaken in safety assessment calculations used to support safety case arguments).

7.2.1 Technology Theme

Current digital twin development is looking at sub-systems of the repository, whereas the ultimate ambition of digital twins could be to develop representations of the entire underground system. This would require research into the aggregation of digital twins into a single entity (so-called meta digital twin), or in other words, a digital twin made up of other digital twins that represent various aspects of the system. For example, work in MODATS investigated digital twins of single drifts or deposition modules, research is required to consider how to integrate hundreds of these individual models into a meta digital twin.

The digital twin concept has the opportunity to change how we view system design, manufacturing and operation, and to augment systems engineering approaches. In a repository context, digital twins have the potential to have a role in optimisation processes and support changes to design during the operational period. This would require code and algorithm development for computational efficiency leading to the deployment of ExaScale Computing[d].

Deployment of digital twins also requires the development of data standards to improve the feasibility to develop more comprehensive systems, and the improvement of numerical models for computational

[d] See Kogge *et al*. (2008) for a discussion of the term ExaScale Computing.

efficiency, e.g., by improving parallelization schemes and using novel hardware developments, especially to manage multiphysics couplings on increasingly integrated systems.

To apply digital twins in support of monitoring programmes requires developments in the integration of DDMs and PBMs. The digital twin has to be calibrated, and an “ignorance” model will be crucial to assess the root cause of the divergence of data from values anticipated by the early versions of the PBMs and DDMs.

Finally, with future cumulative monitoring data, coupling digital twin with data mining through machine and deep learning technologies may well be the most promising path towards understanding and predicting the processes occurring in the multi-barrier system during the operational period. To date, the demonstration and validation of such approaches have yet to be performed on real and representative use cases.

7.3 Confidence

The objective of MODATS was to consolidate the implementation strategy for monitoring systems by developing methods through which confidence can be demonstrated in the data acquired and benefits derived for repository implementation. The focus, therefore, was confidence in monitoring data. MODATS undertook a series of focused developments that improve the ability to acquire, manage and use monitoring data.

The approach can be considered consistent with approaches proposed for building confidence in the safety case. For example, in the NEA international project on Approaches and Methods for Integrating Geological Information in the Safety Case (AMIGO), it was recognised that multiple lines of evidence are required to build confidence in the geoscientific understanding that underlies the safety case (ADD REFERENCE). These relate to, for example, groundwater flow rates or groundwater travel times, diffusion properties, sorption properties and the stability of geochemical conditions within a host rock.

In the same way, MODATS focussed on multiple aspects of monitoring data acquisition, management and use. It is the sum of these activities that could be used to build confidence in monitoring data; ensuring that the acquisition, management and use of monitoring data is undertaken in a reliable and high-quality fashion, and communicating this effectively, could help to create confidence in the data by those not directly involved in the monitoring programme.

Within MODATS, there was no attempt to quantify confidence, because it requires a broad, multi-disciplinary RD&D activity. The work in MODATS was generic, and focused on providing methodological improvements in monitoring data acquisition, management and use, rather than advancements in the monitoring data associated with one repository programme. To quantify confidence would have required focus on one or more actual repository monitoring programmes. Furthermore, there are challenges in quantifying confidence. Confidence has been defined as a belief about the validity of our own thoughts, knowledge or performance, and might therefore be considered as relying on a subjective feeling (ADD REFERENCE). Methods have been developed to measure confidence objectively (ADD REFERENCE) The most commonly used is confidence rating. In this scale, the subject is asked to report confidence on a continuous scale ranging from 0% or complete uncertainty to 100% or complete certainty. Alternatively, confidence can be assessed with discrete fixed levels, or a simple binary choice between confident and not confident [61]. Such approaches could be considered in future international collaborative work on confidence.

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