Deliverable 17.9: MODATS Synthesis: Confidence in Monitoring Data

Work Package 17 (MODATS)

This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014-2018 under grant agreement N°847593.

http://www.ejp-eurad.eu/

Document information

Project Acronym	**EURAD**
Project Title	**European Joint Programme on Radioactive Waste Management**
Project Type	**European Joint Programme (EJP)**
EC grant agreement No.	**847593**
Project starting / end date	**1 June 2019 – 31 May 2024**
Work Package No.	**17**
Work Package Title	**Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure**
Work Package Acronym	**MODATS**
Deliverable No.	**D17.9**
Deliverable Title	**MODATS Synthesis: Confidence in Monitoring Data**
Lead Beneficiary	**Galson Sciences Limited**
Contractual Delivery Date	**31 May 2024**
Actual Delivery Date	**7 May 2024**
Type	**Deliverable**
Dissemination level	**Public**
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To be cited as:

M. White, T. Haines, J. Bertrand (2024): MODATS Synthesis: Confidence in Monitoring Data. Deliverable D17.9 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

Acknowledgement

This document is a deliverable of the European Joint Programme on Radioactive Waste Management (EURAD). EURAD has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Status of deliverable		
	By	Date
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Submitted to EC (Coordinator)	Andra (Coordinator)	17.05.2024

Executive Summary

International collaborative work on monitoring has been undertaken under the auspices of the International Atomic Energy Authority (IAEA), the Nuclear Energy Agency and the European Commission. It has included consideration of monitoring strategies and the role of monitoring in decision making; research and development 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.

The data provided by repository monitoring programmes will be used in the iterative development of the safety case in order to support decision making. To allow for this, there must be confidence in the data provided by the monitoring programme, and confidence that it can be used for the purpose for which it was acquired. 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 established to address the issue of confidence in monitoring data used in support of the post-closure safety case. This has been achieved through RD&D on:

- Data acquisition and management.
- The use of the data to enhance system understanding.
- Further development of specific monitoring technologies.
- Consideration of how interactions with civil society on repository monitoring can proceed.

This document integrates the work undertaken across the different activities in MODATS to demonstrate how the results of the RD&D undertaken 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.

Confidence in monitoring data can be achieved if the acquisition, management and use of the data is appropriate for the purpose for which it has been acquired. Therefore, in terms of providing confidence in monitoring data associated with long-term safety, confidence in monitoring data can be built if the methods and technologies used to acquire, manage and use it contribute to meeting the purposes of monitoring identified by the IAEA that are linked to long-term safety:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure. This purpose relates to decisions to adjust and modify the way geological disposal is undertaken during the operational period to take advantage of ongoing scientific and engineering developments, and what is learned from concurrent monitoring information.
- 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. This purpose relates to the opportunity to test and strengthen understanding of some aspects of thermal, hydraulic, mechanical, chemical and gas transport behaviour during the long period, probably several decades, prior to repository closure.
- 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. This purpose relates to critical points in a repository development programme that are likely to require input from a broader range of societal groups than the repository operators and regulators alone.

MODATS has undertaken a series of focused developments that improve the ability to acquire, manage and use monitoring data (including use of monitoring data in modelling and forecasting, and the use monitoring data as part of engagement activities). This work has included the development of guidance,

tools and methods. MODATS provides the means for specific repository monitoring programmes to apply the outcomes and use them as appropriate to build confidence in their programme. The manner in which the guidance, tools and methods produced in MODATS can be used in repository programmes will reflect the different contexts of each programme, including: the relevant laws and regulations; the wastes to be disposed of and their characteristics, including packaging; the geological environment; the disposal facility design; decision-making practices used in the programme; and the socio-political environment. These contexts vary significantly in each programme; hence, it is appropriate for the generic guidance developed in MODATS to be taken forward within each repository programme. Continued discussion and collaboration between programmes would support and enhance the development of specific monitoring programmes.

MODATS has focused 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, on behalf of both individuals involved in the monitoring programme and stakeholders not involved in the programme.

In addition to having guidance, tools and methods to develop confidence in monitoring data, there needs to be confidence that these products from MODATS are robust, can be implemented effectively, and reflect good practice. MODATS has ensured that products delivered through the work package are indeed robust, can be implemented effectively and reflect good practice by adopting an inclusive approach encompassing actors from different EURAD colleges and representing a broad range of repository programmes, and engaging with experts from outside of the WP.

MODATS results can be used to build confidence in monitoring data by contributing to the three purposes of monitoring data recognised by the IAEA. This report illustrates examples of how the work contributes to each monitoring purpose, although it is recognised and acknowledged that the activities undertaken in MODATS and the results achieved are likely to contribute to more than one purpose:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure:
  - Development of guidance on Quality Assurance Programme Plans (QAPPs).
  - Development of reliable and robust data management processes.
  - Development of a Monitoring Features, Events and Processes (FEPs) catalogue.
- 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:
  - Development of enhanced monitoring technologies, and development of a roadmap for future technology developments.
  - Identification and classification of data anomalies, and development of methods and tools for treating these anomalies.
  - Elaboration of the importance of metadata in interpretation of monitoring results.
  - Enhanced modelling approaches and development of prototype digital twins.
- 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:
  - Multi-party dialogue was undertaken to collect participants views on monitoring, including specific topics associated with monitoring data.
  - Good practice was established in data management:

        - Lessons for repository monitoring were developed in the URL survey, this can be used to demonstrate that good practice has been used in the design and operation of a repository monitoring system.
        - Knowledge management work has contributed to the description and availability of good practice in repository monitoring.
    - Development of open-source tools for data analysis contributes to the provision of traceable and transparent data.
    - The Pathway Evaluation Process used for multi-party dialogue provides a methodology for engaging with different actors on monitoring.
    - Visualisation can help members of society to develop an understanding of complex data and can support knowledge transfer; good practice in the use of visualisation for these purposes has been demonstrated through the development of digital twins of Mont Terri.

MODATS has provided developments that indicate how confidence in monitoring data can be achieved, and approaches that could be adopted within different programmes. Having an overall robust and reliable approach to the acquisition, management and use of monitoring data is the main way in which confidence can be built. The comprehensive approach adopted in MODATS contributes to this. Good management practices were identified for all aspects of the data lifecycle, including acquisition, management (processing and storage), use of the data (modelling) and communication of the data for decision making. The guidance provided from MODATS is generic and needs to be tailored to specific repository programmes, which respond to their specific boundary conditions. Tailoring the outcomes from MODATS to the specific context of each monitoring programme would provide a sound technical, scientific and sociological basis for developing and maintaining confidence in monitoring data.

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Acronyms[1]

BOTDA:	Brillouin optical time-domain analysis
BOTDR:	Brillouin optical time-domain reflectometry
CHENILE:	Coupled beHaviour undErstaNdIng of fauLts
CNN:	Convolutional neural networks
CSO:	Civil society organisation
DDM:	data-driven modelling
EBS:	Engineered barrier system
EC:	European Commission
EPA:	Environmental Protection Agency
ESS:	European Statistical System
ETN:	European Thematic Network
EURAD:	European Joint Programme on Radioactive Waste Management
FE:	Full-Scale Emplacement
FEIS:	FE Information System
FEPs:	Features, events and processes
GAS:	Mechanistic Understanding of Gas Transport in Clayey Materials
HADES:	High Activity Disposal Experimental Site
HITEC:	Influence of Temperature on Clay-Based Material Behaviour
HRL:	Hard Rock Laboratory
HLW:	High-level waste
IAEA:	International Atomic Energy Authority
IGD-TP:	Implementing geological disposal of radioactive waste technology platform
IMS:	Institute of Mine Seismology
IR:	Infrared
IP:	Induced polarization
ISO:	International Organization for Standardization
LED:	Light-emitting diode
LILW:	Low- and intermediate-level waste
LSTM:	Long short-term memory
MODATS:	Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure

[1] Partner acronyms are provided in Table 2-1.

NEA:	Nuclear Energy Agency
OBR:	Optical backscatter reflectometry
PBM:	Physics-based modelling
PDCA:	Plan, do, check and act
PIML:	Physics-informed machine learning
POPLU:	Posiva Plug
PRACLAY:	Preliminary Demonstration Test for Clay Disposal
QA:	Quality assurance
QAPP:	Quality Assurance Programme Plan
QC:	Quality control
QMS:	Quality management system
R&D:	Research and development
RD&D:	Research, development and demonstration
RE:	Research entity
RIA:	Radiation-induced attenuation
RNN:	Recurrent neural network
SIP:	Spectral-induced polarization
SITEX:	Sustainable Network for Independent Technical Expertise on Radioactive Waste Management
SOTA:	State-of-the-art
SUS:	System Usability Scale
THM:	Thermal, hydraulic and mechanical
THMCG:	Thermal, hydraulic and mechanical, chemical and gas
TSO:	Technical support organisation
URL:	Underground research laboratory
US:	United States
VEIS:	Virtual Experiment Information System
VTK:	Visualization Toolkit
WMO:	Waste management organisation
WP:	Work package

1. Introduction

1.1 Background

1.1.1 Objectives of Monitoring

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 [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. Monitoring can form part of a repository safety strategy; it can contribute to understanding of processes occurring in the repository, and it can 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. The key purposes of monitoring of repository systems are seen to be [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.
- For operational reasons:
    - To determine any radiological impacts of the operational disposal system (as with a nuclear installation, like a power plant) on the personnel and on the general population, in order to comply with statutory and regulatory requirements.
    - To determine non-radiological impacts on the environment surrounding the repository, to comply with environmental regulatory requirements (e.g., impacts of excavation and surface construction on local water supply rates and water quality).
    - To ensure compliance with non-nuclear industrial safety requirements for an underground facility (e.g., dust, gas and noise).

1.1.2 International Collaborative Work and Guidance on Monitoring

International collaborative work on monitoring 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 and development (R&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.

Some of the key activities include:

- Production of an IAEA TECDOC on monitoring of geological repositories for high-level waste [2].
- A European Thematic Network (ETN) on the role of monitoring in a phased approach to geological disposal of radioactive waste [3].
- The EC Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) project [4].
- The Modern2020 project [5].
- A study into the technical and societal aspects of repository monitoring [6].

A requirement to conduct a programme of monitoring prior to, and during, the construction and operation of a disposal facility and after its closure, if this is part of the safety case, is included in the IAEA Specific Safety Requirements on disposal of radioactive waste [7]. Recommendations and guidance on how to comply with the safety requirements is provided in the IAEA Specific Safety Guide on geological disposal facilities for radioactive waste [8], and in the IAEA Specific Safety Guide on Monitoring and Surveillance of Radioactive Waste Disposal Facilities [9]. Further details on these requirements, recommendations and guidance are provided in a state-of-the-art (SOTA) report on repository monitoring [10].

This international collaborative effort has developed a common understanding of the strategic aspects of repository monitoring, in particular in relation to the role of monitoring in building further confidence in long-term safety during the operational period. For example, an overall strategic framework has been elaborated and captured within the Modern2020 Monitoring Workflow (Figure 1-1), a generic screening process, referred to as the Modern2020 Screening Methodology, has been developed for identifying monitoring parameters (Figure 1-2), and the high-level requirements and objectives of specific repository monitoring programmes have been described [10]. This work has emphasised that monitoring parameters should be selected with respect to the value that the results could provide to iterative development of the safety case; it is the safety case that provides demonstration of long-term safety [11]. Parameter selection should also consider the impacts of monitoring, including impacts to the safety case, to the environment, to worker safety and to the logistics of repository operation.

Extensive research, development and demonstration (RD&D) activities have been undertaken to enhance the toolbox of monitoring techniques from which a monitoring programme can be developed [4, 5]. This has included, for example, developments related to fibre optic sensors and monitoring using geophysical methods (both of which have the potential for distributed monitoring with minimal impact on repository behaviour), development of several new sensors, development and demonstration of wireless data transmission [12, 13], and research into long-term power supplies [14]. Some of these RD&D activities have provided technological developments that are ready to be implemented within an operational repository, for example, distributed strain and temperature monitoring using fibre optics. Other activities have provided *proof-of-principle* developments, for example related to geophysical techniques implemented in various experiments but still suffering from some deficiencies.

In addition, the MoDeRn and Modern2020 projects have included significant research into the role of monitoring in decision making, and stakeholder engagement on monitoring and in European-level RD&D [10]. In terms of decision making, Modern2020 concluded that responding to monitoring results must be flexible to allow for unexpected repository evolutions, and, therefore, specific actions and response plans cannot be defined ahead of the acquisition of monitoring data [5]. Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the entire dataset. Furthermore, the Modern2020 project concluded that decision making during implementation of geological disposal is a complex process where monitoring is only one input.

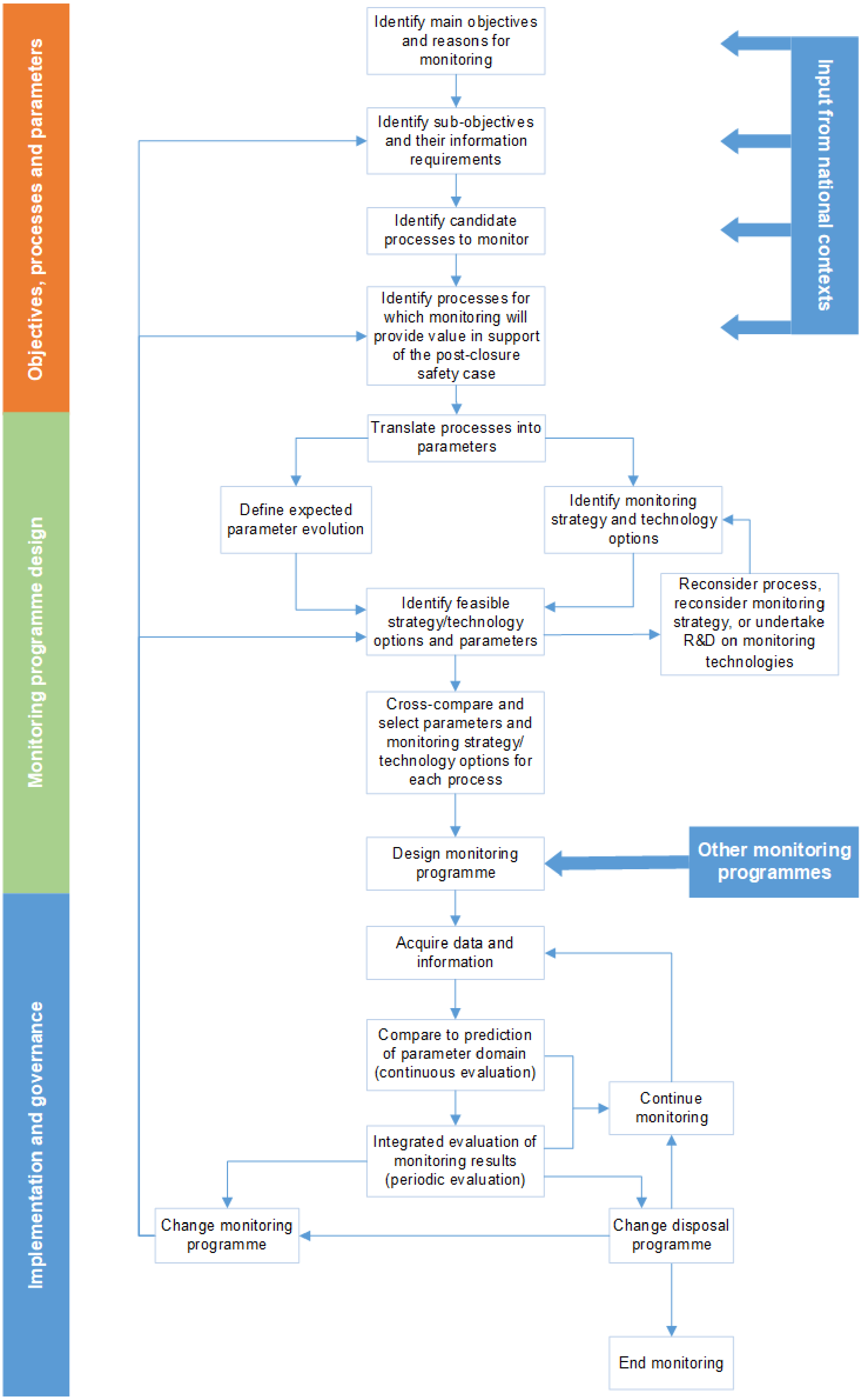

Figure 1-1 – The Modern Monitoring Workflow.

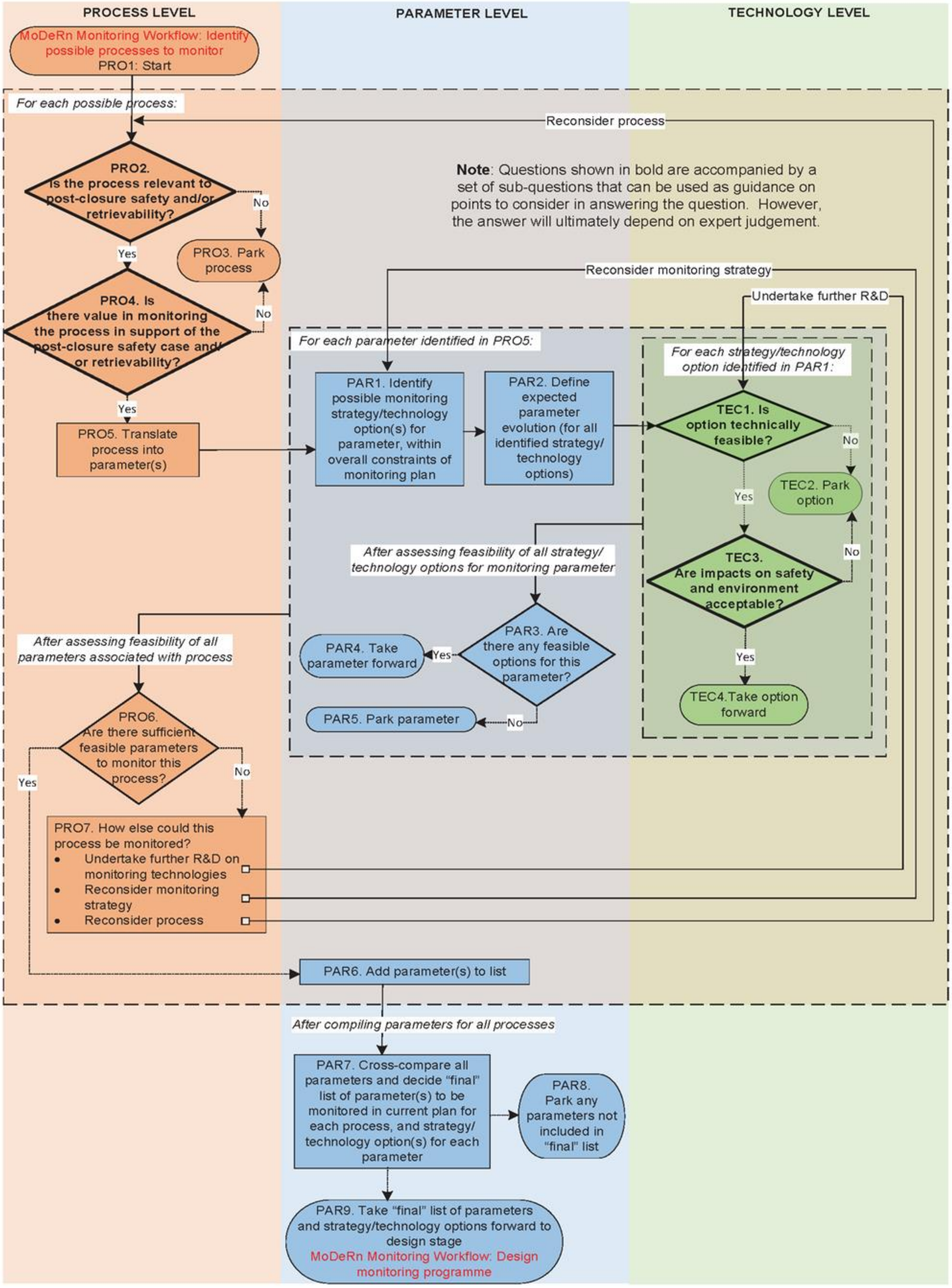

Figure 1-2 – The Modern Screening Methodology.

Engagement with civil society was a significant part of both the MoDeRn and Modern2020 projects, with local stakeholders participating throughout the project. The work developed an understanding of the views of public stakeholders on a European level, and concluded that monitoring could potentially contribute to building the confidence of public stakeholders in the safety of a particular repository project, though not by itself [10]. Many other factors will also play a role in building stakeholder confidence, such as the approach to decision making, and the level of public and stakeholder engagement. Monitoring can contribute to implementation of geological disposal 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 technical evolution in monitoring techniques during the monitoring period [4].

In addition, some organisations have begun monitoring programmes associated with construction of geological repositories (e.g., [15]), and monitoring experience and expertise has been gained during the construction and operation of low- and intermediate-level waste (LILW) repositories [16].

1.1.3 Remaining Monitoring Issues at the Start of MODATS

Although extensive work on the strategic aspects of monitoring has been undertaken, on completion of these initiatives, there was a recognised need for further RD&D into monitoring of geological repositories. In particular, it was recognised that monitoring has specific challenges compared to current standard monitoring activities, for example those associated with infrastructure projects. These include challenges associated with monitoring of the near field (for a definition of the near field, see [17][2]), in support of the post-closure safety case during the operation of the repository. Many of these novel issues are also relevant to programmes focused on monitoring of the geosphere in the far field and the surface environment, monitoring to establish baseline conditions, and monitoring to support repository design.

Specific challenges are primarily associated with the long timeframes envisaged for monitoring programmes (several decades), the requirement that monitoring programmes are designed and implemented so as not to reduce the overall level of safety of the facility after closure [7], and the operation of monitoring equipment in potentially harsh environmental conditions such as high-pressure, high-salinity and high-radiation. The data provided by repository monitoring programmes will be used in the iterative development of the safety case in order to support decision making. To allow for this, there must be confidence in the data provided by the monitoring programme, and confidence that it can be used for the purpose for which it was acquired.

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 established to address the issue of confidence in monitoring data used in support of the post-closure safety case. This has been achieved through RD&D on:

- Data acquisition and management.
- The use of the data to enhance system understanding.
- Further development of specific monitoring technologies.
- Consideration of how interactions with civil society on repository monitoring can proceed.

This document provides a synthesis of the outputs from the MODATS WP of EURAD (referred to as MODATS hereafter) and evaluates the impacts in terms of building confidence in monitoring data.

[2] The "near field" (as defined by the NEA and EC) includes the engineered barrier system as well as the host rock within which the repository is situated, to whatever distance the properties of the host rock have been affected by the presence of the repository.

1.2 Objectives of this Document

This document integrates the work undertaken across the different activities in MODATS to demonstrate how the results of the RD&D undertaken 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 objective of this document is to describe the contribution of different activities undertaken in MODATS to building, demonstrating and maintaining confidence in monitoring data.

Activities are not described in detail. Instead, the outcomes of the work are described with respect to their contribution to confidence in monitoring data. References are provided to reports describing the work, where more details can be found on the objectives, methods, results and conclusions from each activity.

1.3 What is Confidence in Monitoring Data?

The issue of confidence in geological disposal of radioactive waste has previously been considered from the perspective of the safety case and how confidence can be built in the safety assessment (see, for example, [18]). IAEA guidance on geological disposal facilities for radioactive waste [8] notes that scientists, regulatory bodies, decision makers and other interested parties should all have confidence in the information, insights and results provided by safety assessments, and has listed the activities contributing to confidence building, as follows:

- Verification, calibration and, if possible, validation of models.
- Investigation of relevant natural analogues.
- Quality assurance (QA).
- Peer review.

The concept of confidence building has different aspects; development of any plan to build confidence should define whose confidence is under discussion, since different actors might have different foci in relation to confidence. The implementing organisation has to be confident that its work meets established criteria, the regulator has to be confident in the work carried out by the implementer, and the public has to be confident that both are doing their job properly and thus ensuring that waste can be disposed of safely [19].

As noted in Section 1.1, the subject of MODATS is monitoring, and, more specifically, confidence in monitoring data acquired during the operational phase and used in support of the long-term safety case. Work has mainly focused on confidence from a technical perspective, although MODATS has also undertaken some work on civil society dialogue using monitoring data.

Having confidence in data is the precondition for using the monitoring results to support ongoing implementation of geological disposal, for example, in periodic updates to the safety case and, via the safety case, in decision making. Obtaining highly-credible data from the monitoring programme will allow responses to the results to be defined with confidence and will build greater trust in the strengthened understanding of the behaviour of the disposal system.

Parallels can be drawn between approaches used to build confidence in the safety case and developing confidence in the monitoring data that support it. Monitoring data must be checked (verified) with reference to defined protocols, calibrated according to manufacturer specifications, and compared with scientific understanding to ensure validity of data (validation). Monitoring data must be acquired, managed and used according to pre-defined QA requirements, and be subject to peer review.

Furthermore, confidence in monitoring data can be achieved if the acquisition, management and use of the data is appropriate for the purpose for which it has been acquired. Therefore, in terms of providing confidence in monitoring data associated with long-term safety, confidence in monitoring data can be built if the methods and technologies used to acquire, manage and use it contribute to meeting the purposes of monitoring identified by the IAEA [2] that are linked to long-term safety:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure; that is, confidence that monitoring data used in the analyses and assessments that underpin management decisions are fit-for-purpose.
- 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.

Confidence in monitoring data is a belief that the data are valid for the application for which they are intended.

MODATS has undertaken work that contributes to confidence in monitoring data associated with each of these three objectives of repository monitoring, as described in this report.

1.4 Document Scope and Audience

This document is written at a high level of detail for an audience with an interest and involvement in geological disposal of radioactive waste. As such, it is anticipated that the summary presented in this document will be useful to all actors in the EURAD community, including WMO staff, technical support organisation (TSO) staff and members of other regulatory bodies, researchers in research entities (REs), and members of civil society and civil society organisations (CSOs). Extensive referencing to underpinning reports is provided, and it is intended that this document acts as a gateway to reports produced in MODATS that provide the detail of the work undertaken and the results obtained. The wider context of repository monitoring is summarised in the MODATS SOTA report [10].

1.5 Document Structure

As noted above, the focus of this document is confidence in monitoring data. Therefore, the synthesis of MODATS is focused on the use of the WP results for this purpose rather than presentation of the results of each activity independently. In support of this focus, in Section 2, a summary of the objectives, scope and structure of MODATS is provided, and the objectives of each activity undertaken and the reports published are described. This provides the context for the subsequent discussion of the contribution of MODATS results to confidence in monitoring data.

Separate sections then discuss how the outcomes of MODATS contribute to confidence in data used for decision making and to strengthen understanding, and confidence in information provided to society (Sections 3-5). In each of these sections, we first discuss what is required to have confidence in data used for each specific purpose, and then we present outcomes and conclusions from the MODATS activities that contribute to this aim.

Monitoring data are typically not acquired for just one purpose and similarly, many of the results from MODATS contribute to confidence in monitoring data used for all three purposes identified by the IAEA. However, to avoid repetition in this document, we have described the principal ways in which each result from the work in MODATS contributes to building confidence. As explained in this document, having an overall robust and reliable approach to the acquisition, management and use of monitoring data is the main way in which confidence can be built.

Section 5 provides a discussion of the contribution of MODATS to confidence in monitoring data.

Section 6 presents the conclusions from MODATS.

2. MODATS Overview

This section provides an overview of MODATS in three sections:

- Section 2.1 provides the context of the EURAD programme.
- Section 2.2 presents the objectives and scope of MODATS.
- Section 2.3 presents the structure of the WP and the activities undertaken within it.

2.1 EURAD Programme

As noted in Section 1.1.3, MODATS was undertaken as a WP with EURAD. EURAD supports the implementation of the Waste Directive [1] in European Union Member States, taking into account the various stages of advancement of repository programmes. The goals of EURAD are to [20]:

- Support Member States in developing and implementing their national RD&D programmes for the safe long-term management of their full range of different types of radioactive waste through participation in the radioactive waste management Joint Programme.
- Develop and consolidate existing knowledge for the safe start of operation of the first geological disposal facilities for spent fuel, HLW, and other long-lived radioactive waste, and supporting optimisation linked with the stepwise implementation of geological disposal.
- Enhance knowledge management and transfer between organisations, Member States and generations.

MODATS was one of the WPs selected for funding during the EURAD 1 period from 2020-2024.

2.2 Objectives and Scope of MODATS

MODATS conducted RD&D into: monitoring data acquisition 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. MODATS built on the previous international collaborative RD&D activities described in Section 1.1, including the ETN [3], and the MoDeRn [4] and Modern2020 [5] projects.

The RD&D in MODATS was supported by existing information and data from underground research laboratory (URL) experiments, including five Reference Experiments:

- ALC1605: A demonstration of the reference disposal concept for HLW led by Andra in the Bure URL, France.
- The Full-Scale Emplacement (FE) experiment: The FE experiment investigates repository-induced thermal, hydraulic and mechanical (THM) coupled processes at full scale to validate existing models, and also aims to verify the technical feasibility of constructing a disposal tunnel using standard industrial equipment. It is led by Nagra in the Mont Terri URL, Switzerland.
- The Posiva Plug (POPLU) experiment: The POPLU experiment was a full-scale test of a possible design for a disposal tunnel end plug component in the disposal concept for the spent fuel repository in Olkiluoto (Finland) and Forsmark (Sweden). It was led by Posiva and SKB in the ONKALO Facility, Finland.
- The Prototype Repository: The Prototype Repository is a full-scale field experiment in crystalline rock. The experiment aims to simulate conditions that are largely relevant to the Swedish/Finnish KBS-3V disposal concept for spent fuel. It is led by SKB in the Äspö Hard Rock Laboratory (HRL).

- The Preliminary Demonstration Test for Clay Disposal (PRACLAY) experiment: The PRACLAY experiment is a large-scale experiment designed to study the impact of the heat generated by HLW on the host clay formation. It also looks at how excavation affects the behaviour of the clay. The experiment is conducted by EURIDICE and ONDRAF-NIRAS in the High Activity Disposal Experimental Site (HADES) URL in Mol, Belgium.

The focus of MODATS is monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. In particular, as discussed in the introduction (Section 1), MODATS focused on confidence in monitoring data.

Amongst other activities, MODATS has undertaken work on data management and digital twins, which are defined as follows:

Data management is the processing, storage and supply of data for the use for which it was acquired. Processing includes transferring raw signals to parameter values, combining results from different sensors, and identification and treatment of any anomalies in the data.

Digital twins are a virtual model of part of a repository that is updated automatically to address specific objectives.

MODATS was undertaken by 23 partners (Table 2-1).

Table 2-1 – List of the partners in MODATS and identification of the type of organisation for each partner.

Partner Acronym	Partner Full Name and Country	Type of Organisation
Amvalor	Amvalor, France	RE
Andra	Agence Nationale pour la Gestion des Déchets Radioactifs, France	WMO
CEA	Commissariat à L'énergie Atomique et aux Energies Alternatives, France	RE
CNRS	Centre national de la recherche scientifique, France	RE
CVR	Centrum výzkumu Řež, Czech Republic	RE
EIMV	Elektroinstitut Milan Vidmar, Slovenia	TSO
ESI	Engineering System International, France	RE
ETH Zürich	Eidgenössische Technische Hochschule Zürich, Switzerland	RE
EURIDICE	European Underground Research Infrastructure for Disposal of Nuclear Waste in a Clay Environment, Belgium	RE
GFZ	Deutches GeoForschungsZentrum, Germany	RE
GSL	Galson Sciences Limited, UK	RE
IRSN	L'Institut de Radioprotection et de Sûreté Nucléaire, France	TSO
LHC	Laboratoire Hubert Curien, France	RE

Partner Acronym	Partner Full Name and Country	Type of Organisation
MUTADIS	Mutadis, Paris, France	RE
Nagra	Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Switzerland	WMO
NTW	Nuclear Transparency Watch, France	CSO
NWS	Nuclear Waste Services, UK	WMO
Posiva	Posiva Oy, Finland	WMO
PSI	Paul Scherrer Institute, Switzerland	RE
SKB	Svensk Kärnbränslehantering Aktiebolag, Sweden	WMO
SSTC NRS	State Scientific and Technical Center for Nuclear and Radiation Safety, Ukraine	TSO
UFZ	Helmholtz Zentrum für Umweltforschung, Germany	RE
VTT	Valtion Teknillinen Tutkimuskeskus	TSO

2.3 MODATS Structure and Activities

MODATS was organised into four tasks:

- Task 1 (WP Management) involved ensuring an effective, smooth and high-quality implementation of MODATS, including: communication and integration between partners and the EURAD consortium; monitoring of the WP progress and outputs against the project work plan; and maintaining up-to-date information on the EURAD website. Since this document is focused on the research outcomes from MODATS, Task 1 is not discussed further.
- Task 2 (Data Treatment for Increased Confidence in Repository Monitoring) was split into five sub-tasks:
    - Task 2.1 (Monitoring Programme Experience and Future Needs) undertook integration of activities in Task 2, including conducting a survey on experience from monitoring in URL experiments; development of guidance on QA Programme Plans (QAPPs), identification of future monitoring technology needs, and a series of workshops to discuss progress and to identify conclusions from the Task 2 activities.
    - Task 2.2 (Data Management), Task 2.3 (Development of Enhanced Understanding through Integration of Monitoring Data and Models) and Task 2.4 (Development of the Digital Twin) were conducted in an integrated fashion by undertaking six test cases using the MODATS Reference Experiments, as described below.
    - Task 2.5 (Enhanced System Understanding, Multi-Party Dialogue) aimed to build an integrated vision of how the monitoring devices and corresponding data production will contribute to develop a shared understanding of the repository system along the decision-making process from the early phase of authorisation to subsequent implementation phases and closure.

- Task 3 (Novel and Optimised Monitoring Technology for Repository Monitoring) conducted research into monitoring technologies to improve their ability to be employed during repository operation, and included three sub-tasks:
  - Sub-Task 3.1 (Geophysics and Innovative Sensors) undertook research and further developed innovative sensors and geophysical techniques to measure and infer parameters that are difficult to obtain through other approaches.
  - Sub-Task 3.2 (Advancement of Fibre-Optic Methods) developed and qualified optical sensors to get them ready for a range of applications in the implementation of geological disposal.
  - Sub-Task 3.3 (Interactions between Sensors and the Multi-Barrier System) developed methods to investigate the potential impact of monitoring technology on the performance of a range of disposal systems through development of a features, events and processes (FEP) catalogue linked to monitoring equipment.
- Task 4 (Communication and Project Synthesis) spread excellence and disseminated knowledge and results obtained within MODATS, and integrated these into the knowledge management system developed in EURAD. Task 4 included three sub-tasks:
  - Sub-Task 4.1 (Interaction with Knowledge Management WPs) focused on identification of mutual needs between MODATS and EURAD WPs focused on knowledge management, development of a procedure and roadmap for interaction between EURAD WPs, contribution to knowledge management in EURAD (production of a domain insight document on monitoring [21]), and development and provision of a training school in repository monitoring.
  - Sub-Task 4.2 (Develop Communication Tools of the MODATS WP) focused on dissemination of MODATS work. This included development and maintenance of the MODATS webpage inside the EURAD website, contribution to EURAD newsletters, and collation of information sheets on scientific progress and upcoming plans in MODATS.
  - Sub-Task 4.3 (Project Synthesis) focused on production of this document.

As noted above, the work in Task 2.2, Task 2.3 and Task 2.4 was undertaken as a series of linked test cases based on data available from the five MODATS Reference Experiments. The objectives of the research activities in Task 2 (including Task 2.1 and Task 2.5) are summarised in Table 2-2. Similarly, several activities were undertaken in each of the sub-tasks of Task 3; these are also summarised in Table 2-2.

Table 2-2 – Objectives of the research activities in Tasks 2 and 3 of MODATS.

Sub-Task	Activity Title	Objective	Lead Partner(s)
2.1	URL Survey	Learn lessons for repository monitoring from monitoring of URL experiments. In particular, the survey aimed to identify lessons related to monitoring system design and monitoring data acquisition, management and use.	GSL
2.1	QAPP Guidance	Provide high-level guidance on the structure and content of a QAPP for repository monitoring systems, and provide examples of good practice based on the MODATS Reference Experiments and other URL experience.	GSL

Sub-Task	Activity Title	Objective	Lead Partner(s)
2.1	Technology Roadmap	Identify future RD&D needs for different programmes moving forward and produce a technology development roadmap that defines the steps to ensure that technologies are available for the implementation of repository monitoring when needed.	GSL and NWS
2.2-2.4	ALC1605 Test Case	Develop a digital twin demonstrator of the instrumented heating cell ALC1605, combining both digital simulations and monitoring data from the experiment using machine learning.	Andra, Amvalor and ESI
2.2-2.4	FE Test Case 1	Develop a workflow to assess monitoring data jointly with system modelling, extension of the FE Information System (FEIS) for external access, development of methods for quality control of distributed temperature measurements using fibre optic systems, and development of approaches for cleaning of monitoring data from point sensors.	Nagra
2.2-2.4	FE Test Case 2	Evaluate machine learning models with respect to the forecasting of temperature and relative humidity within the setting of the FE experiment.	PSI
2.2-2.4	FE Test Case 3	Develop a comparison tool for simulation results to facilitate result assessment through comparison of outcomes from different simulation software and parameter studies, and development of data visualisation tools that could also be used for the purpose of communicating understanding of processes occurring in geological repositories.	UFZ
2.2-2.4	POPLU and Prototype Repository Test Case	Develop a transparent and flexible data cleaning methodology, which serves two purposes: (i) to identify and resolve data problems to determine their root cause; and (ii) to improve the quality of data for future use.	VTT, Posiva and SKB
2.2-2.4	PRACLAY Test Case	Define a more structured approach to data management, and thereby establish central storage of all data with a consistent structure for both sensor data and metadata, which allows standard tools to handle the data.	EURIDICE
2.5	Multi-Party Dialogue	Develop an integrated vision of how monitoring devices and data production contribute to the shared understanding of the repository system throughout the decision-making process, from authorisation to implementation phases and closure. Contribute to the development of mutual understanding and common perspectives on the key challenges and topics related to monitoring system and data management. Collect expectations from civil society regarding monitoring activities. Introduce a socio-technical interpretation of monitoring systems, considering the social and technical aspects in conjunction. Contribute to research by identifying RD&D areas to consider for pluralistic monitoring.	IRSN and NTW

Sub-Task	Activity Title	Objective	Lead Partner(s)
3.1	Geophysical Inversion	Develop non-intrusive monitoring techniques to investigate the state of the multi-barrier system; address non-uniqueness in non-linear inversions; and develop constitutive relationships to link seismic data to monitoring parameters.	ETH
3.1	Monitoring Bentonite Saturation using Spectral-Induced Polarization (SIP)	Test the feasibility of using a geoelectrical induced polarisation (IP) method to monitor hydraulic and chemical evolution in bentonite clays, and mixtures of bentonite and sand.	IRSN
3.1	Coupled beHaviour undErstaNdIng of fauLts (CHENILE) Experiment	Understand the coupled THM processes occurring in and around a meso-scale fault in a semi-controlled environment, bridging the knowledge gap between the laboratory and the field scale, and develop novel geophysical monitoring techniques and strategies suitable for strongly-attenuating material (clay rich rocks) in a URL and under non-favourable conditions.	GFZ
3.1	Passive Seismic Monitoring	Automate the classification and identification of seismic events in and around the ONKALO disposal facility.	Posiva
3.1	Automatic Digital Mapping of Leakages	Develop and test a new method for semi-automated or automated mapping of leakages in excavations to reduce observer bias and hence, improve data consistency.	Posiva
3.2	Qualification of Radiation Tolerant Sensors	Understand the impact of radiation on optical fibre sensor performance, specifically the performance of distributed temperature and strain sensors.	LHC
3.2	Advancement of Fibre Optic Strain Sensing Methods for Monitoring Tunnel Linings in Clay Rocks	Improve the application and analysis of fibre optic strain sensing under repository-like conditions.	Nagra
3.2	Development of an Optical pH Sensor for Porewater Monitoring	Develop and characterise an optical pH sensor for the neutral pH range by grafting an acid base indicator onto an optical fibre.	CEA
3.3	Analysis of Harsh Environment Impacts	Evaluate the impacts of the repository environment on the data acquired through long-term monitoring using *in situ* sensors.	SSTC NRS
3.3	Monitoring FEPs: Potential Impacts of Monitoring Equipment on Post-Closure Safety	Identify and describe the FEPs through which monitoring system components could affect the behaviour of the multi-barrier system (known as Monitoring FEPs).	GSL and NWS

Reporting of the work conducted in MODATS was undertaken in a hierarchical fashion, with memoranda describing the work in each activity feeding into task-related reports, and the task reports feeding into this WP synthesis (Figure 2.1). Along with published papers and conference presentations, the task-related reports and the WP synthesis comprise the published outputs from MODATS. The objective of each MODATS deliverable is summarised in Table 2-3. Published papers and conference presentations are listed in Appendix A.

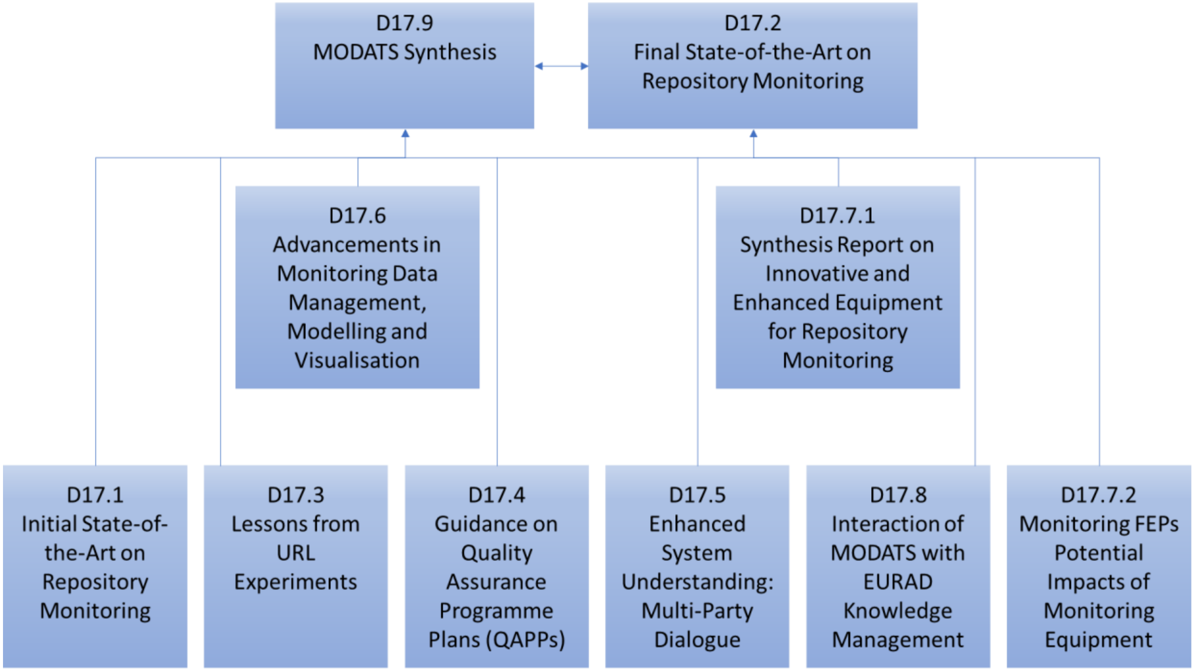

Figure 2-1 - Reporting structure for the MODATS WP. The contents of each deliverable are described in Table 2-3. Although not illustrated in this figure, D17.8 considered inputs from across MODATS during multi-party dialogues activities.

Table 2-3 – The objective of each MODATS deliverable.

Number	Title	Objective	Lead Author or Editor
D17.1	Initial State-of-the-Art on Monitoring in Radioactive Waste Repositories in Support of the Long-Term Safety Case [22]	Describe the current knowledge in repository monitoring, at the start of MODATS	Andra
D17.2	Final State-of-the-Art on Monitoring in Radioactive Waste Repositories in Support of the Long-Term Safety Case [10]	Describe the current knowledge in repository monitoring, at the end of MODATS	Andra
D17.3	Lessons for Repository Monitoring from Underground Research Laboratory Experiments [23]	Document the monitoring-related lessons learnt from the URL Survey undertaken in Task 2.1	GSL

Number	Title	Objective	Lead Author or Editor
D17.4	Guidance on QA Programme Plans for Repository Monitoring [24]	Document the guidance on the structure and content of a QAPP developed in Task 2.1	GSL
D17.5	Enhanced System Understanding, Multi-Party Dialogue [25]	Report on work undertaken in Task 2.5, and present conclusions on processes to be used during dialogue on monitoring and the outcomes of applying those processes in MODATS	IRSN and NTW
D17.6	Advancements in Monitoring Data Management, Modelling and Visualisation [26]	Provide an integrated discussion of the advancements made during the test cases based on data available from the five MODATS Reference Experiments	GSL
D17.7.1	Synthesis Report on Innovative and Enhanced Equipment for Repository Monitoring [27]	Describe developments made in monitoring technology during MODATS	Andra
D17.7.2	Monitoring FEPs: Potential Impacts of Monitoring Equipment on Post-Closure Safety [28]	Present the Monitoring FEPs catalogue developed within MODATS, and provide the context to the catalogue, including: the approach used to develop the catalogue and commentary on the ways in which the Monitoring FEPs catalogue might be used in repository programmes going forward	GSL and NWS
D17.8	Interaction of the MODATS WP with EURAD Knowledge Management Work Packages – Synthesis Report [29]	Describe knowledge management activities undertaken in MODATS including capture and dissemination of the most relevant knowledge and associated uncertainties on monitoring	SSTC NRS
D17.9	MODATS WP Synthesis: Confidence in Monitoring Data	Integrate the work across the different activities in MODATS to demonstrate how the results 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	GSL

3. Contribution of MODATS to Developing Confidence in Monitoring Data used in Support of Management Decisions

This section describes how the results of MODATS contribute to the first purpose of monitoring in support of long-term safety recognised in IAEA TECDOC 1208 [2]:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure.

Section 3.1 identifies what is required in order to have confidence in monitoring data used to support management decisions. Section 3.2 presents the outcomes of MODATS that could be used to build confidence in monitoring data used for this purpose.

3.1 Building Confidence in Monitoring Data used to Support Management Decisions

The IAEA TECDOC recognised that the operators of a repository are likely to make numerous decisions during the operational period [2]. Although the initial plans for a repository will make assumptions about the behaviour of the system during the operational period, it is probable that decades of operational experience will allow early decisions to be adjusted and modified to take advantage of ongoing scientific and engineering developments, and what is learned from concurrent monitoring information. Examples provided in the TECDOC included decisions that could lead to [2]:

- Adjusting the later stages of repository layout or design.
- Modifying waste handling and emplacement procedures.
- Modifying engineered barrier design or material properties.

The extent to which any of these types of decisions would be made in any one repository programme would be dependent on the specific programme. By providing these examples, the TECDOC does not imply that these adjustments or modifications would be undertaken, or that a monitoring programme would have to address each of the examples provided (or only these examples) [2].

The TECDOC noted that these management decisions could be distinguished from major decisions on the implementation of geological disposal (see Section 5). Major decisions, as explained in Section 5, might involve progression of the disposal programme from one phase to the next, and would likely require wider consultation and review than operational management decisions.

The implementing geological disposal of radioactive waste technology platform (IGD-TP) symposium on optimisation supported the concept that there might be adjustments or modifications to some aspects of the disposal system during the operational period. The symposium recognised that optimisation of all aspects of the disposal system could be a continuous activity throughout implementation of geological disposal [30].

Adjustments or modifications to implementation are likely to require consultation with the regulators; the extent of that consultation would be dependent on the nature of the adjustment or modification and the repository programme. The process would be managed through a change control protocol.

The information on which any adjustment or modification to the disposal system was based would not be limited to monitoring data. It could be based on, for example, ongoing RD&D and/or the availability of new materials, as well as monitoring results. Nevertheless, confidence in monitoring data is clearly a prerequisite for using the data to support management decisions. Part of this might be the strengthened understanding in physical and chemical processes that is discussed in Section 4.

In order for monitoring data to be used in support of management decisions there will need to be confidence that the data have been acquired, managed and used in a quality assured manner. It will be necessary for data scientists and repository programme managers to identify and present the most pertinent data for decision making, and to have transparent and traceable methods for doing so (for example, checking that no false or otherwise erroneous data have been included in an analysis dataset and recognising that different users want to see different data). Different actors within WMOs could be recognised, for example, safety assessment staff who might want to have results from monitoring with errors such as spikes or null values removed, and decision makers who might want data presented in common timesteps. Safety assessors, safety case developers and decision makers might want to have access to data to ask 'what if?' questions and/or to gain insights into the behaviour of the repository to date.

Furthermore, any proposed changes to the monitoring programme itself will need to consider the potential impacts of any changes on the multi-barrier system. There will be an ongoing need to maintain the QA processes and procedures used in the monitoring programme during the operational period. This would reflect a commitment to continual improvement, and the use of best available techniques.

3.2 Contribution of MODATS

The results from MODATS contribute to the development of confidence in monitoring data used to support management decisions in several ways. In this section, we highlight three specific activities:

- Development of guidance on QAPPs (Section 3.2.1).
- Development of reliable and robust data management processes (Section 3.2.2).
- Development of the Monitoring FEPs catalogue (Section 3.2.3).

3.2.1 Production of Guidance on QAPPs

To have confidence in monitoring data so that it can be used to support management decisions requires that the data are acquired, managed and used in a quality assured manner, and that the experience of data acquisition, management and use are fed back into a process of continual improvement. To assist in the demonstration that monitoring data are fit-for-purpose, MODATS proposes that the quality aspects of a monitoring programme are identified in a single document, referred to as a QAPP. A QAPP would document the planning, implementation, and assessment procedures for a particular monitoring programme, as well as any specific QA and quality control (QC) activities undertaken within it. Work in Task 2.1 of MODATS included the development of guidance on the structure and content of QAPPs (see [24] for a full description of this work).

The guidance developed in MODATS built on established QA guidance and requirements, including:

- International Organization for Standardization (ISO) 9001:2015 [31], the most widely used quality management system (QMS) standard.
- IAEA TECDOC 1910 on QA and QC in nuclear facilities [32].
- The European Statistical System (ESS) Handbook for Quality and Metadata Reports [33].
- The United States (US) Environmental Protection Agency (EPA) requirements for QA project plans for controlling operations related to environmental monitoring performed by, or for, the US EPA [34].

However, repository monitoring is a novel undertaking, with unique challenges owing to the long timescales and the need to ensure that monitoring programmes do not reduce the overall level of safety of the facility after closure [7]. The guidance on QAPPs developed in Task 2.1 responds to these challenges by proposing a comprehensive approach to quality throughout all stages of the repository programme. In particular, the guidance recognises that development and maintenance of comprehensive documentation to provide a transparent and traceable record of quality-related matters through the lifecycle of the monitoring programme is the key to meeting these challenges. The QAPP would complement other documentation produced by a monitoring programme as illustrated in Figure *3-1*. The guidance assumes 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).

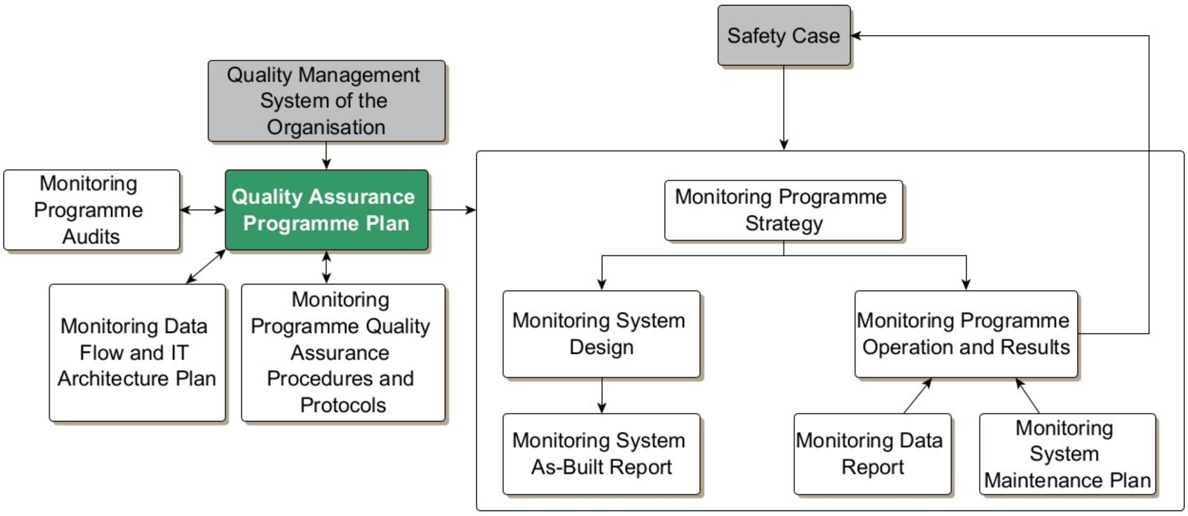

Figure 3-1 – Proposed structure of monitoring programme documentation for a repository monitoring programme. The QAPP is highlighted in green. Grey-coloured documents (or suites of documents), including the Safety Case and the QMS, provide sources of the requirements on the monitoring programme regarding the repository programme quality management.

The guidance proposes that a QAPP would contain five main sections that correspond to the plan, do, check and act (PDCA) cycle, which underpins generic QA guidance [31]:

- 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 (Figure 3-2); 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
  - Checking the Monitoring Data, including guidance on processing, storing and auditing data.
- Act
  - 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.

The guidance on QAPPs offers a framework for addressing some of the challenges posed by repository monitoring. By structuring a QAPP into five main sections linked to the PDCA, and offering flexibility in its implementation, WMOs and other stakeholders could confidently develop programme-specific QA documentation for their monitoring activities. This guidance is designed to support reliable, long-term monitoring data acquisition, and data treatment, fostering confidence in the data provided by the programme. Through continuous improvement, adaptation to technological advancements, and responsive decision-making, a QAPP would ensure that a monitoring programme remains effective, credible, and beneficial over the entire duration of repository operations.

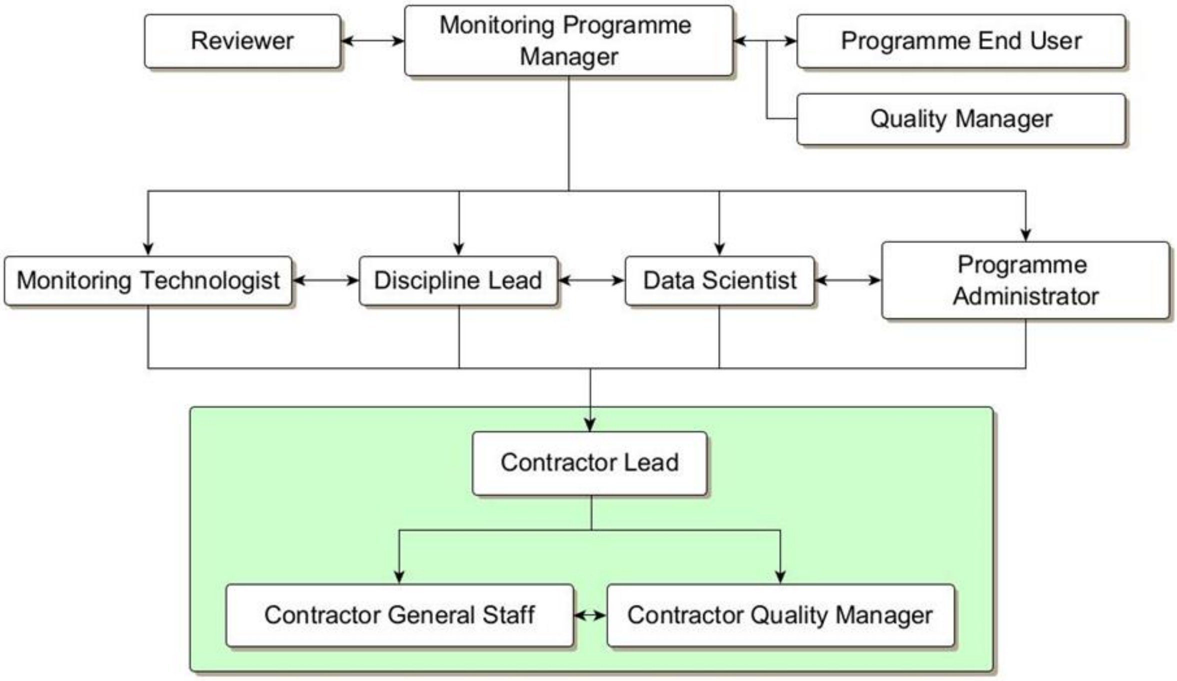

Figure 3-2 – An example of a repository monitoring programme organogram. The green box indicates roles fulfilled by contractors (if contractor staff are used during the planning, design and/or delivery of the repository monitoring programme; which might be undertaken by WMO staff only). The guidance provided on QAPPs is generic and, therefore, the organogram for any specific repository monitoring programme is likely to differ.

3.2.2 Guidance on Reliable and Robust Data Management Processes

The work in MODATS has highlighted that existing monitoring programmes (e.g., monitoring programmes associated with URL experiments) have typically followed a bespoke data management process. As noted in Section 2.2, management of data includes processing, storage and supply of data for the use for which it was acquired. Processing includes transferring raw signals to parameter values, combining results from different sensors, and identification and treatment of any anomalies in the data.

The developments in data management made during the Reference Experiment test cases [26] allowed the elaboration of an overall data management process for processing data so that it is ready for supporting decision making (Figure 3-3). This workflow can provide the basis for preparing data for use in stepwise decision making, and, through its systematic application, for developing confidence that good practice is being followed. This data management process is considered as a common approach that can be applied in all programmes. Development of this process, and application of it during repository monitoring, is expected to improve data management in repository monitoring programmes and thereby improve the reliability of the data produced.

Preparing data to be ready to support decision making requires amalgamation of data from different sensors (potentially including sensors monitoring the same parameter using different technologies) into integrated data sets. 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 Reference Experiment test cases developed a series of tools that can be applied in support of these principles (Appendix B) [26].

Monitoring data and metadata need to be available for decades to support repository operation and closure. As a consequence, 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. To date, tools for data processing and analysis of URL experiments have included spreadsheet applications, where significant manual work has been necessary for data processing, to automated or semi-automated databases with visualisation capabilities. In the future, approaches are likely to include machine learning, as demonstrated by the test cases reported herein (see Section 4.2.4). 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 is also a need for databases to be capable of handling different time systems, to adjust for daylight saving time, and to accommodate different spatial coordinate systems.

Work in MODATS has demonstrated how standardised file formats can be used to support sharing of information and, in this way, to improve robustness against future software developments. The use of a common and widely used data format, such as Visualization Toolkit (VTK), can increase robustness compared to establishing a new and specialised file format used only in the domain. Established formats are founded on the technical support of a large number of users, which increases the expertise and resources applied in their development (bugs are more likely to be identified) and are less likely to be replaced by new formats.

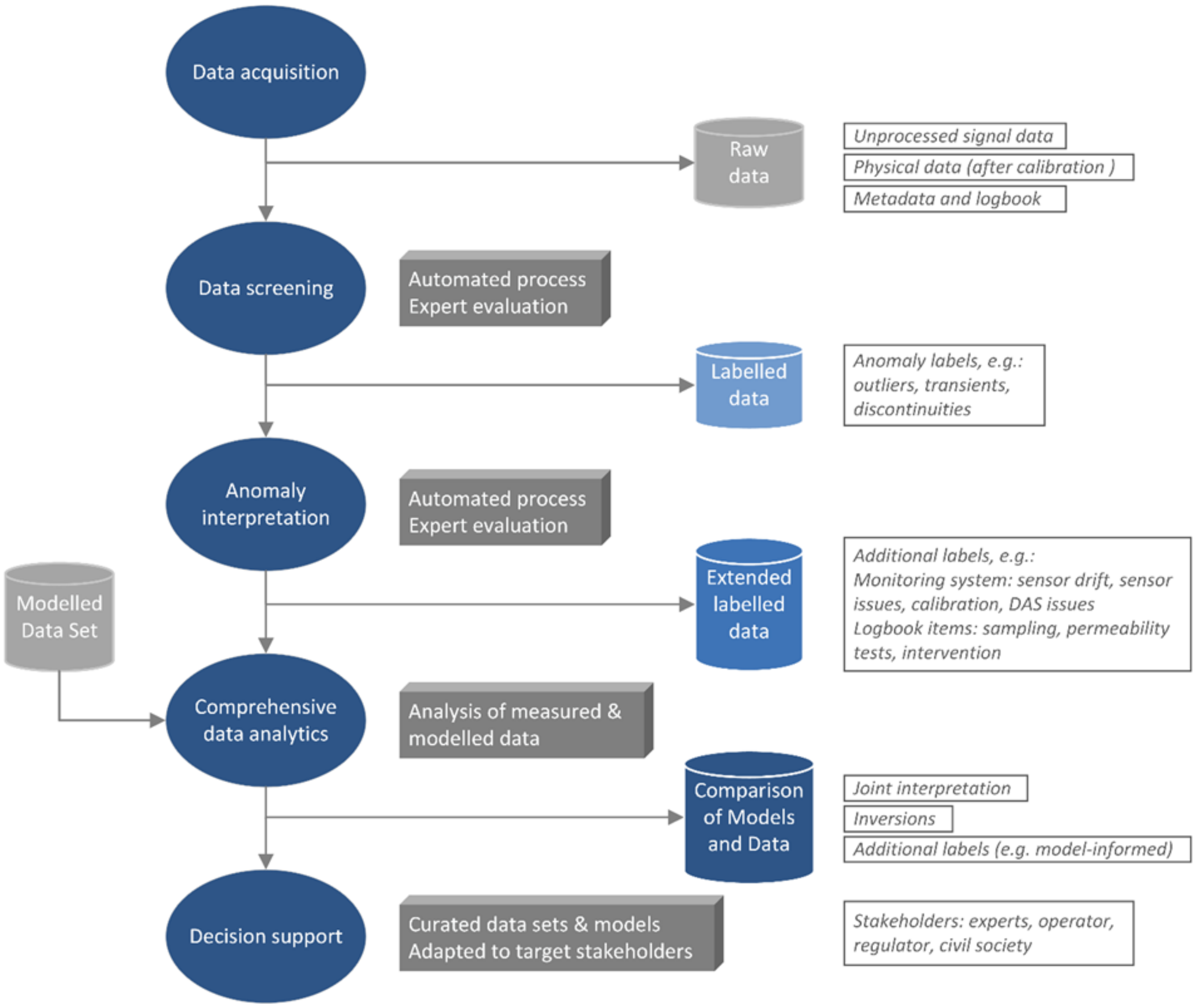

Figure 3-3 – MODATS workflow for data handling from acquisition to decision support.

3.2.3 Understanding the Potential Impact of Alterations to Monitoring Equipment on Post-Closure Performance

As mentioned in Section 3.1, management decisions during operations might lead to adjustments or modifications to the disposal system. These could also include adjustments or modifications to the monitoring programme. Initial design of the monitoring programme would take into account any potential impacts of the monitoring equipment on post-closure safety. This would include post-closure impacts caused by operation of the equipment during operations, and impacts caused following closure should equipment be left *in situ*. Any changes to the monitoring programme or the disposal system would need to assess changes in the potential impact(s) of monitoring equipment on the performance of the system. Sub-Task 3.3 of MODATS provided a contribution to addressing that requirement, through the development of a Monitoring FEPs catalogue. The catalogue identifies and describes ways in which monitoring equipment used during the operational phase could impact the post-closure performance of a repository system.

Monitoring FEPs are expected to have several uses that include:

- Informing the monitoring strategy and design by giving arguments to justify the choice of monitoring system in order to mitigate the potential impacts of monitoring equipment on post-closure safety.
- Providing knowledge to support the development of scenarios involving Monitoring FEPs in order to make robust argumentation in a safety case.
- Identifying future research needs, such as novel monitoring technologies e.g., wireless sensors or monitoring technology test facilities to quantify monitoring FEP impacts.

Development of the Monitoring FEPs catalogue followed a structured process undertaken by experts from WMOs and research entities:

1. Identification of generic monitoring components on the basis of their size, location, distribution, and composition.
2. 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.
3. Description of each Monitoring FEP using a standard template (Table 3-2).

Owing to the current maturity of monitoring programmes, and differences in monitoring strategies between different repository programmes, the Monitoring FEPs catalogue is generic. Therefore, no conclusion is drawn on the significance of any of the potential impacts. Given the current expectation that repository monitoring will not involve the intensive instrumentation of the engineered barrier system (EBS) typically used in URL experiments, it is envisaged that the Monitoring FEPs identified in this work will not result in impacts on post-closure safety.

Eighteen Monitoring FEPs were identified in this work, as captured in the matrix presented in Table 3-2. As noted above, the impact of monitoring equipment on post-closure performance will ultimately depend on the specific disposal concept and the needs of monitoring as defined by a WMO. The Monitoring FEPs catalogue provides support for the design of monitoring systems, and provides knowledge and information that can be used in the development of programme-specific monitoring FEPs and scenarios associated with the impacts of monitoring equipment used during operations or left *in situ* following repository closure.

Table 3-1 – The structure and content of Monitoring FEP descriptions in the Monitoring FEPs catalogue [28].

Title	A short title describing the FEP.
Category	Identify if FEP is a feature, event, or process.
Description	A general description of the feature, event of process. This is a fundamental physical, chemical, biological, or other category of description. The description includes details of what the FEP is, what conditions are required for the FEP to occur, and what components of the multi-barrier system the FEP interacts with.
Relevant Monitoring System Components	A generic description, supported by examples, of the monitoring system component that could cause the FEP to exist or occur. This description could include description of relevant dimensions, compositions, and structure of the monitoring system component.
Potential Relevance to Performance and Long-Term Safety	Description of how the monitoring system component might affect long-term system performance, including uncertainties and concept specific issues where identified.
Examples of the FEP	Examples of the FEP occurring or not occurring. Examples are largely from URL experiments, but other analogues could be included, i.e., groundwater abstraction, mining, and tunnelling.
Mitigations	Description of how any potential impact of the FEP could be mitigated through selection of monitoring component (e.g., use of different materials in the sensor), design of the monitoring system (e.g., sensor positioning) or changes to the multi-barrier system.
Comments	Any other information that may be relevant to the FEP.
References	Any references used to develop the FEP description.

Table 3-2 – Matrix illustrating the Monitoring FEPs and relevant monitoring system components. The number is the number assigned to the FEP in the catalogue.

<table>
<tr><th>Monitoring System Component</th><th>Thermal</th><th>Hydraulic</th><th>Mechanical</th><th>Chemical</th><th>Biological</th><th>Gas</th><th>Electromagnetic</th></tr>
<tr><td>Cuboidal and Cylindrical Centimetre-Scale Sensors</td><td></td><td></td><td rowspan="4">7. Void Introduction
8. Volume Change</td><td>10. Corrosion of Monitoring System Components
11. Electrochemical Effects
12. Degradation
14. Chemical Interactions
15. Contamination</td><td rowspan="4">16. Microbial Activity</td><td rowspan="2">13. Gas Generation</td><td></td></tr>
<tr><td>Metre-Scale Linear Sensors</td><td>1. Heat Transfer</td><td></td><td rowspan="3">10. Corrosion of Monitoring System Components
11. Electrochemical Effects
12. Degradation
14. Chemical Interactions</td><td></td></tr>
<tr><td>Fibre Optic Cables</td><td></td><td>3. Pathway Generation
4. Liquid Transport</td><td>5. Gas Transport
13. Gas Generation</td><td></td></tr>
<tr><td>Accelerometers and Geophones</td><td></td><td></td><td>13. Gas Generation</td><td></td></tr>
<tr><td>Sound Waves</td><td></td><td></td><td>17. Sound Wave Propagation</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Electrodes</td><td></td><td></td><td>7. Void Introduction
8. Volume Change</td><td>10. Corrosion of Monitoring System Components
11. Electrochemical Effects
12. Degradation
14. Chemical Interactions</td><td>16. Microbial Activity</td><td>13. Gas Generation</td><td></td></tr>
<tr><td>Electromagnetic Waves</td><td></td><td></td><td></td><td></td><td></td><td></td><td>18. Electromagnetic Wave Propagation</td></tr>
</table>

<table>
<tr><th>Monitoring System Component</th><th>Thermal</th><th>Hydraulic</th><th>Mechanical</th><th>Chemical</th><th>Biological</th><th>Gas</th><th>Electromagnetic</th></tr>
<tr><td>Data Transmission Cables</td><td></td><td></td><td rowspan="3">7. Void Introduction
8. Volume Change</td><td rowspan="4">10. Corrosion of Monitoring System Components
11. Electrochemical Effects
12. Degradation
14. Chemical Interactions</td><td></td><td></td><td></td></tr>
<tr><td>Wireless Nodes</td><td></td><td></td><td rowspan="8">16. Microbial Activity</td><td></td><td></td></tr>
<tr><td>Sampling Systems</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Borehole Sampling System</td><td></td><td>6. Pressure Reduction</td><td></td><td></td><td></td></tr>
<tr><td>Solid Chemical Batteries</td><td></td><td></td><td></td><td rowspan="2">10. Corrosion of Monitoring System Components
11. Electrochemical Effects
12. Degradation
14. Chemical Interactions
15. Contamination</td><td rowspan="3">13. Gas Generation</td><td></td></tr>
<tr><td>Thermoelectric Generators</td><td>2. Heat Generation</td><td></td><td></td><td></td></tr>
<tr><td>Electromagnetic Antennae</td><td></td><td></td><td></td><td rowspan="3">10. Corrosion of Monitoring System Components
11. Electrochemical Effects
12. Degradation
14. Chemical Interactions</td><td></td></tr>
<tr><td>Power Transmission Cables</td><td></td><td>3. Pathway Generation
4. Liquid Transport</td><td></td><td rowspan="2">5. Gas Transport
13. Gas Generation</td><td></td></tr>
<tr><td>Data Transmission Cables</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Data Loggers</td><td></td><td></td><td>9. Collapse</td><td></td><td></td><td>13. Gas Generation</td><td></td></tr>
</table>

4. Contribution of MODATS to Developing Confidence in Monitoring Data used to Strengthen System Understanding

This section describes how the results of MODATS contributes to the second purpose of monitoring in support of the post-closure safety case recognised in IAEA TECDOC 1208 [2]:

- 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.

First (Section 4.1), a discussion of what is required in order to have confidence in monitoring data so that it can be used to strengthen understanding of some aspects of system behaviour is presented. Second (Section 4.2), we describe the outcomes of MODATS that could provide confidence in monitoring data used for this purpose.

4.1 Building Confidence in Monitoring Data used to Strengthen System Understanding

The IAEA TECDOC recognised that decisions made during the early stages of a repository programme, for example, to select a site, to go ahead with construction, and to emplace waste in the repository, will have been based in part on the results of performance and safety assessments that will have evaluated the long-term, post-closure behaviour of the disposal system [2]. Much of the information used to underpin these assessments will have been derived from site characterisation work and supporting RD&D, often carried out over many years. In order to proceed with these early steps, sufficient confidence will need to have been accrued in the ability of the conceptual models used in the assessment studies to represent future system behaviour adequately.

Although endorsement of the early programme steps must be based on having sufficient confidence in post-closure safety, it is clear that the opportunity will exist to test and strengthen understanding of some aspects of system behaviour further during the long period, probably several decades, prior to repository closure.

Examples of the understanding of system behaviour that might be strengthened with the support of monitoring data provided in the TECDOC include [2]:

- The groundwater flow field.
- Groundwater chemistry.
- The hydraulic and mechanical behaviour of important structures in the rock.
- The thermal field around repository structures.
- The response of underground structures and the groundwater system to seismic events.
- The resaturation behaviour of regions of a repository that have been partially completed and isolated from operational areas.
- Chemical interactions between engineered barriers and the rock/groundwater system.

Not all programmes will conduct monitoring programmes to strengthen understanding of these aspects of system behaviour. Each repository monitoring programme will be tailored to the particular context of the programme. It is anticipated that monitoring parameters will be selected using a structured process, for example, the Modern Screening Methodology (Figure 1-2) [5], which considers the value of monitoring any parameter and the potential impacts of doing so.

The IAEA TECDOC uses the phrase "*system behaviour*" rather than "*system performance*". This is consistent with findings from MoDeRn and Modern2020, where it was noted that it is unlikely that repository monitoring programmes will monitor parameters with a direct relationship with safety (performance). Rather, repository monitoring is likely to feed into the development of further understanding of thermal, hydraulic, mechanical, chemical and gas transport (THMCG) processes and improvements in their modelling. This might be achieved, for example, by improving calibration parameters or identifying improved tools for modelling the full 3D volume of the repository system.

Amongst other requirements, in order for monitoring data to be used in support of strengthening system understanding, there will need to be:

- Confidence that the data has been acquired correctly.
- Having a broad range of technologies available could enhance the technical possibilities of monitoring, and improve the ability to understand processes occurring during the monitoring period. This would require development of technologies now, plus development of a plan for technology development going forward, so that long lead-time technology RD&D can be undertaken in time for application in the repository.
- Data anomalies will need to be understood and treated appropriately.
- Metadata will need to be stored and made accessible.
- Tools available for comparing monitoring data to models in an efficient and effective manner, and for forecasting some parameter values with increasing confidence as repository implementation proceeds so that we gain further confidence in the description of the initial state as we move towards repository closure.

4.2 Contribution of MODATS

The results from MODATS contribute to the development of confidence in monitoring data used to support management decisions in several ways. In this section, we highlight four specific activities:

- Development of enhanced monitoring technologies, and development of a roadmap for future technology developments (Section 4.2.1).
- Identification of the different anomalies that might be present in a monitoring dataset, and development of methods and tools for treating these anomalies (Section 4.2.2).
- Elaboration of the importance of metadata in interpretation of monitoring results (Section 4.2.3).
- Enhanced modelling approaches and development of prototype digital twins (Section 4.2.4).

In addition, MODATS has contributed to confidence that data have been acquired correctly by developing guidance on QAPPs, as discussed in Section 3.2.1.

4.2.1 Increasing the Toolbox of Monitoring Techniques to Extend Monitoring Capabilities

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 technologies. There is, therefore, a need to further develop the most promising novel technologies.

Four aspects of monitoring technologies that contribute to confidence are recognised in MODATS:

- To monitor with confidence, there would be benefits in enhancing non-intrusive monitoring technologies that operate in combination with *in situ* monitoring. This provides redundancy in measurements without interactions with the engineered barrier. Non-intrusive techniques can also increase the spatial and temporal coverage of key parameters (e.g., temperature and pressure).
- To monitor with confidence, there would be benefits from development of monitoring technologies that can determine parameters that are currently difficult to measure, for example, water saturation and pH. Providing an ability to monitor these parameters might strengthen the understanding of some processes.

- To monitor with confidence, there is a requirement to develop greater understanding of the interactions between monitoring sensors and the medium in which they are emplaced.
- To monitor with confidence, the RD&D on monitoring technology should be undertaken in a clearly planned manner.

Work in Task 3 of MODATS (and one activity in Task 2.1) focused on monitoring technologies, and was divided into four main themes (see [27] for a full description of this work):

- Develop innovative sensors and geophysical techniques to measure and infer parameters that are difficult to obtain for long-term monitoring.
- Develop and qualify optical sensors to get them ready to be used in the initial phase of the development of the geological disposal for temperature and strain measurement.
- Develop methods to investigate the impact of monitoring technology on the performance of a range of disposal systems.
- Develop a roadmap for technology development, to ensure that technologies can be used with confidence from the start of repository operations.

The activity associated with the impact of monitoring technology on the performance of a range of disposal systems focused on the development of the Monitoring FEPs Catalogue, which has been discussed in Section 3.2.3. The outcomes from the other activities are discussed below.

4.2.1.1 Innovative Sensors and Geophysical Techniques

The main advantage of geophysical technologies, compared to point information obtained with traditional sensors, is the volumetric information on relevant parameters. However, geophysical methods suffer from some deficiencies. They are often ambiguous, that is, several subsurface models explain the data equally well. Depending on the method(s) employed, they can offer only limited spatial and/or temporal resolution. Current geophysical methods yield physical material properties, such as elasticity parameters, density, or electrical conductivities, and it is not straightforward to translate these material properties to parameters of interest (e.g., temperature and pressure). These deficiencies have been investigated within MODATS.

The acquisition of some monitoring data is also subject to limitations owing to a lack of automation. This can make the methods time consuming and subject to error. Within MODATS, work has been undertaken to develop automatic methods for passive seismic monitoring and water leakage mapping.

Seismic Tomography

The objective of the work on seismic tomography was to develop methods for estimating parameter values from tomographic data. The work focused on the evolution of water content in the granulated bentonite mixture component of the FE experiment, and, in particular, the ability to estimate water content evolution based on cross-hole measurements (seismics and ground-penetrating radar). Direct measurement of water content close to the plane of the cross-hole measurements was limited to two sensors. Therefore, neutron logs, which are sensitive to the amount of hydrogen atoms in the surrounding environment, were used instead.

The work was undertaken in four steps:

- First, an attempt was made to develop high-quality seismic tomograms using full waveform inversion of the tomographic data. However, the seismic data from the FE experiment is subject to the presence of a low signal-to-noise ratio and pronounced 3D artefacts in the acquired data, such that reliable velocity models could not be obtained.
- Second, the reliability of the velocity models was investigated with the use of coda wave interferometry, and this demonstrated that the technique is robust for the FE experiment conditions.

- Third, the potential for joint inversions of the seismic data using seismic velocity, GPR velocity and GPR attenuation was investigated using synthetic data containing low-velocity and high-velocity artefacts. The results of the joint inversions suggested that such an approach allows the location, shape, and values of artefacts to be better imaged with joint inversions.
- Fourth, the capability of the geophysical data to replicate the neutron logs was investigated by training a machine learning algorithm based on the gradient-boosted tree model to predict the neutron log data. The data from both joint and individual inversions were used. Both models fit the data well (Figure 4-1), indicating that the neutron log values can indeed be predicted from the geophysical parameters.

This work has highlighted the potential for seismic tomography to be used for monitoring of parameter evolution and, when combined with local humidity measurements, to obtain tomographic images of humidity distribution in a granulated bentonite mixture.

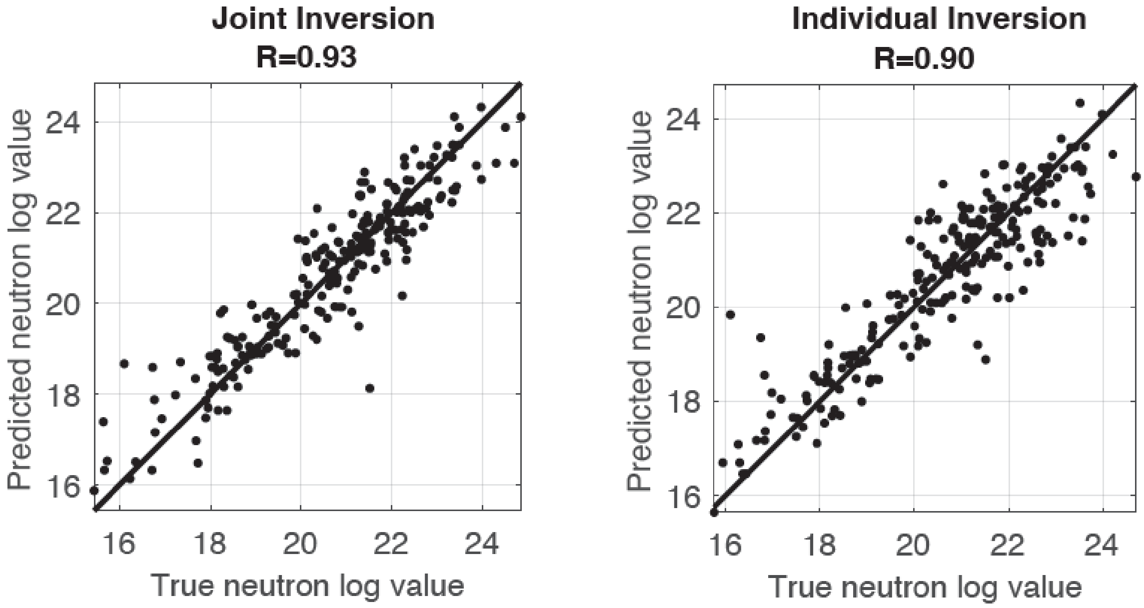

Figure 4-1 – Evaluation of the performance of the trained machine learning model for the geophysical prediction of neutron log values. Note that the model that is trained using the joint inversion results as input features appears to outperform the model that is trained on results from individual inversions.

Electrical Methods

Induced polarization (IP) is a geophysical imaging technique used to identify the electrical chargeability of subsurface materials, such as ore. The survey method is similar to electrical resistivity tomography, in that an electric current is transmitted into the subsurface through two electrodes, and voltage is monitored through two other electrodes.

SIP is an extension of the IP method, in which the frequency-dependent (i.e. spectral) complex impedance, equivalent to the amount of resistance and phase shift between electric current and voltage is measured. As such, SIP characterises the ability of a medium to store charges reversibly under a slowly alternating electrical field. The usual frequency range for alternating current applied during SIP surveys is tens of kHz to MHz. As with other geophysical methods, SIP aims to distinguish material properties of the subsurface, such as salinity and saturation.

In MODATS, the feasibility of using the SIP method to monitor saturation, water content, clay content, and dry density of bentonite and bentonite/sand mixtures was investigated. This was done using IP models that were built using a large database acquired at a centimetric scale on cylinder samples. These models were then used on decametric scale experiments to verify their robustness in determining key petrophysical parameters for different bentonite mixtures.

It was demonstrated that SIP is not only sensitive to variations in water content but also to the mineralogical and chemical variability of the water. Nonetheless, it is feasible to relate parameters acquired using the SIP technique to permeability. Therefore, SIP offers a new method to image in 4D the permeability of porous media.

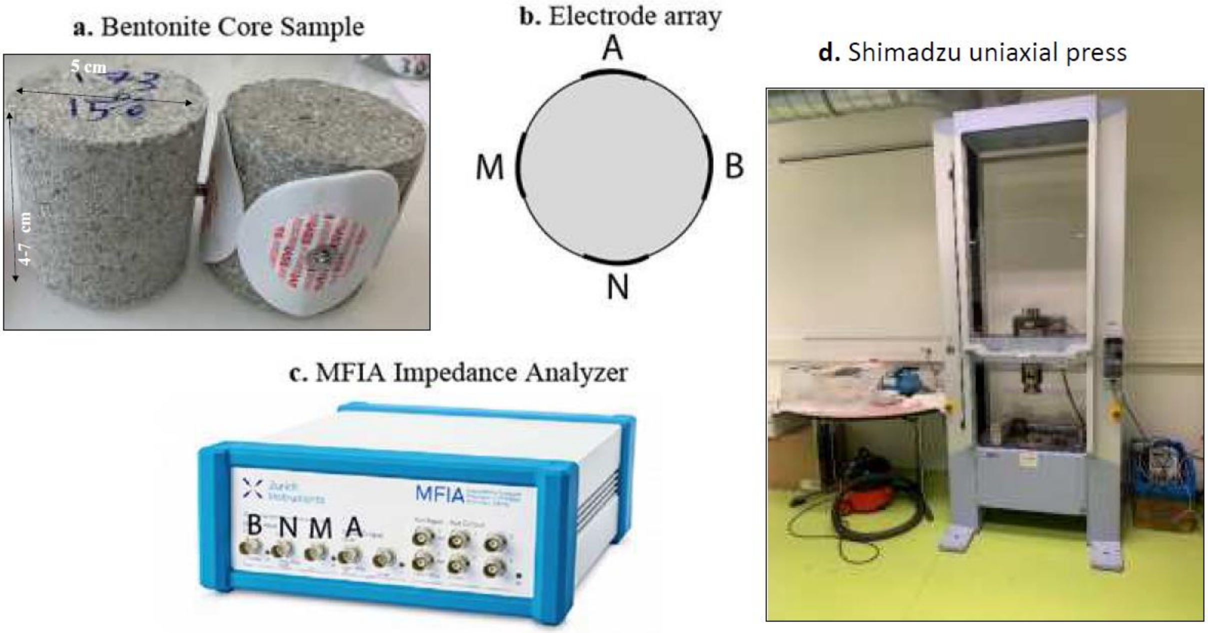

Figure 4-2 – Set-up at centimetric scale for measurement of IP on cylinder samples. a. Picture of a fabricated sample (the sample is 5 cm in diameter and 6 or 8 cm in length). b. Position of the electrodes (A and B are the current electrodes and M and N are the voltage electrodes). c. Zurich Instruments MFIA impedance analyser used to measure the complex conductivity spectra. d. The bentonite powder and sand grains were compressed using a Shimadzu uniaxial press.

Figure 4-3 – Mock-up scale experiments for verification of IP models. The matrix is made of pure sand. Six samples of bentonite-sand mixtures were buried in the matrix. The acquisition was conducted with 32 electrodes along 19 lines.

CHENILE

This research focused on understanding the thermal diffusion process in a fault zone, which, in a repository environment, can be influenced by fluid and thermal loading. The approach involves thermally controlled gas injection into one of the fault zones of the Tournemire URL to observe how heat propagates through the fractured rock. Heaters and fibre optic sensors were installed in boreholes that intersect the fault zone. Acoustic emission sensors were used to detect seismic activities that could be related to changes in the fault zone owing to heating (cracking).

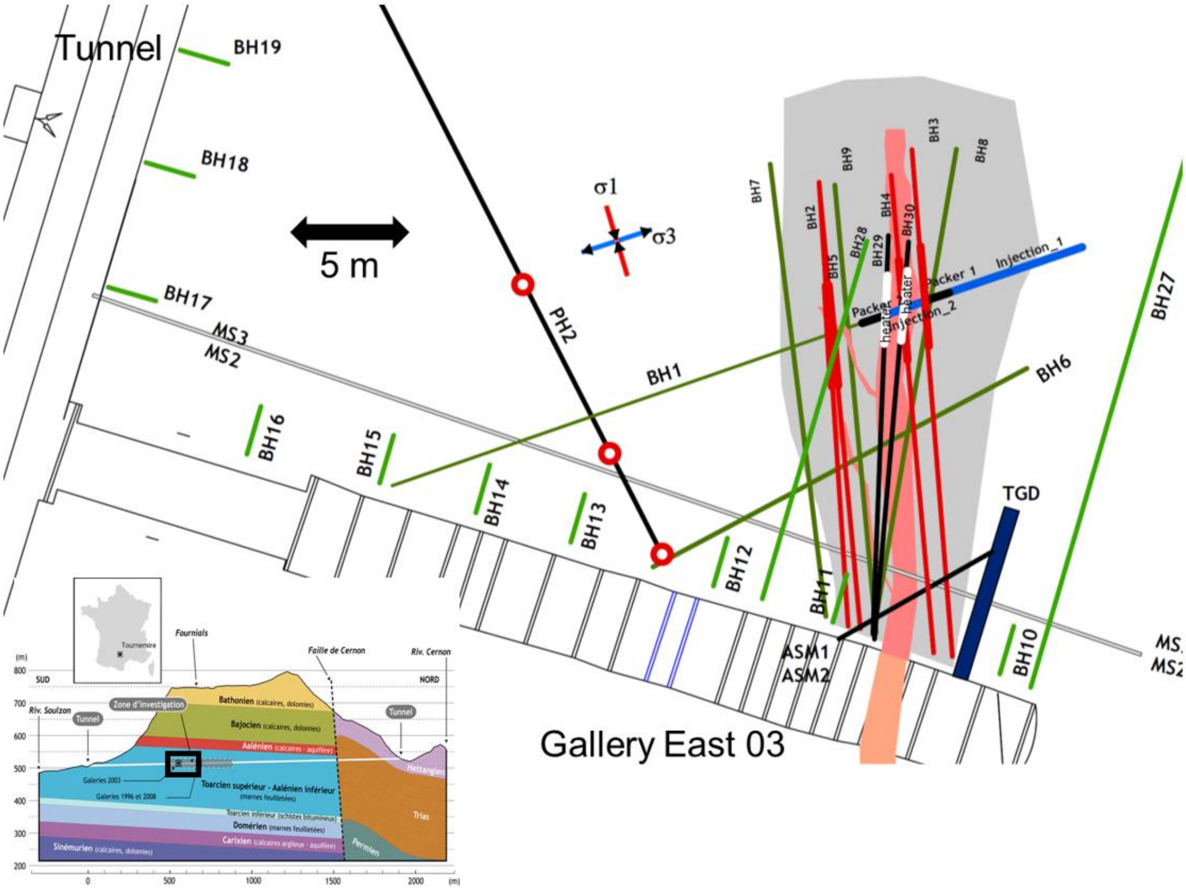

Figure 4-4 – Top view of the CHENILE experimental setup realised in boreholes (BH) at the Tournemire URL (inset). Grey shaded areas indicate the fault damage zone and light red the fault core zone.

Monitoring was conducted in BHs as follows: Temperature: BH1-injection well and BH2-5 (FO), Pressure: BH1-injection well, Acoustic emission: BH6-9 Seismic: BH10-28 Heating: BH29-30.

Drilling and installation of the monitoring system was undertaken between 2020 and 2023. The heating phase started on 20th November 2023. Ongoing operation of the experiment will include injection tests at temperatures in the range 50-90°C.

Initial results indicate that data acquisition is proceeding as expected, with heatmaps showing temperature variations over time and distance along the borehole. Acoustic emission records have captured seismic events that might be associated with crack opening. Future steps aim to use the generated datasets to calibrate and refine the THM model that could be used during repository operation.

Automatic Passive Seismic Monitoring

Posiva has performed seismic monitoring of ONKALO since 2004. Currently, the seismic monitoring network of ONKALO includes 19 stations and 24 sensors. Stations are installed both underground and on the ground surface. Analysis of daily seismic events includes locating and classifying seismic events of interest (i.e. those that are important for scientific and technical studies).

Events of interest, or “accepted” events include microearthquakes, blasts, rockfalls, and other signals that are not related to continuous mechanical work. Events that are not of interest are “rejected”. Annually, there are approximately 40,000 recorded seismic events in Olkiluoto, of which less than one thousand are accepted. Therefore, an automated system for event acceptance would ease the workload of human analysts.

In MODATS, the application of a machine learning algorithm owned by the Institute of Mine Seismology (IMS) to automatic classification of seismic events was tested alongside an improved velocity model of the underground. The algorithm is used as part of the IMS’s seismic analysis software “IMS Combined”. The algorithm was trained with two-and-a-half years of seismic event data from Olkiluoto’s seismic database (events in the period 2021-2023). Overall, the training set included over 67,000 events. A cluster of tens of thousands of rejected events (all of which occurred in August 2021) caused by mechanical noise was found to skew the learning process of the algorithm, and thus they were omitted from further training.

The automatic classifier was able to correctly accept 97% of manually accepted events from the database containing ONKALO’s seismic events from 2021 to 2023. The number of false positives, i.e. falsely accepted events, is still quite high with only 77% of manually rejected events being correctly rejected by the classifier. All surface blasts were correctly accepted. Most of the false rejections were related to regional seismic events, owing to a lack of relevant training data.

On the basis of these results, this algorithm shows good promise for use as an automated real-time tool. However, further testing is required to reduce the number of incorrectly classified events. There is a need to expand the training datasets, and to introduce new criteria or adapt the existing criteria used to classify the events (as well as the associated waveform characteristics). For example, increasing the period that is considered in classifying events.

Water Leakage Mapping

Mapping of water leakages into ONKALO is currently undertaken using visual observations. The process is time-consuming, and prone to human bias and error. As such, it is difficult to compare the resulting data over time.

The potential of automated and digital approaches to water leakage mapping was investigated in MODATS. For initial studies, the most promising and feasible technique for underground field testing was judged to be standard thermal imaging. The objective was to test the ability to detect different types of inflow in conditions where different structures such as shotcrete, steel mesh reinforcement and tunnel infrastructures may disturb the results. Previous studies, prior to MODATS, had shown that thermal imaging (with an infrared (IR) camera) can be used to locate and identify spots with even low water leakage rates in fractured crystalline rocks [35]. This previous study was not used for repeated flow mapping but was mainly focused on characterisation of leaking fractures. Leaks with flow rates less than 1 ml/min were identified with this method. IR imaging provides only qualitative information, and must be combined with 3D modelling of the fracture network to provide a better understanding of inflows [35].

In MODATS, testing of IR imaging has demonstrated that this approach can be used to identify the location of water leaks on uneven and heterogeneous rock surfaces, except where they are positioned behind infrastructure, such as pipes (Figure 4-5). Some leaks were challenging to detect. This is especially true for the tunnel roof since many pipes and other equipment are attached to it. In addition, roof anomalies are mostly point-like which make them even harder to detect. On shotcrete the anomalies were more pronounced and easier to detect. On exposed rock, the anomalies are more blurred.

Application of this technique is currently limited as it cannot be used as yet to accurately quantify the amount of leakage.

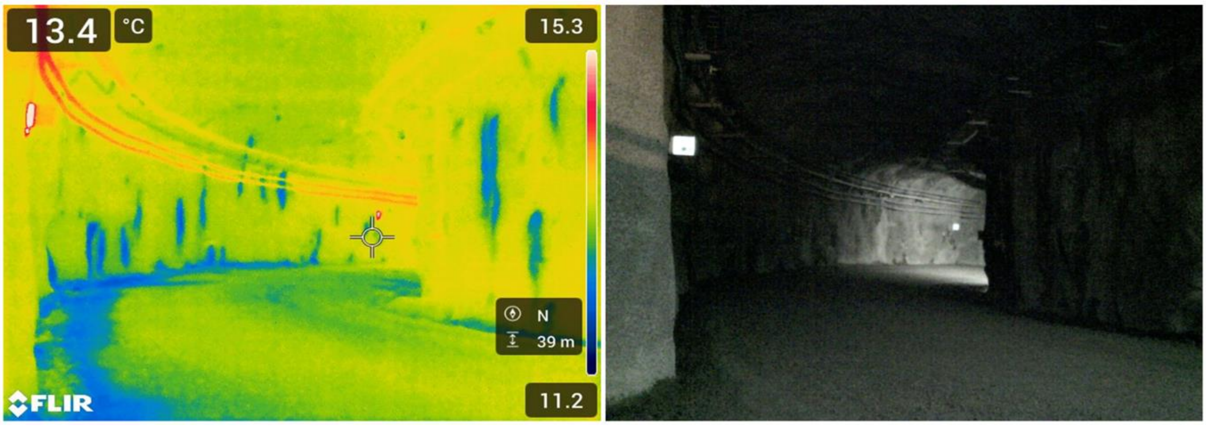

Figure 4-5 – IR image of a tunnel in Olkiluoto. The blue regions are the locations of water leakages. The orange and red locations are infrastructure. The roof and walls of the tunnels are covered with shotcrete.

There is a need to further develop the approach used to collect thermal images. Currently, photos are taken manually, which is likely to result in slight differences in the location at which subsequent photos are taken. As a result of these differences, it could be difficult to compare photos at the same locations through time (for the purposes of understanding the evolution of leaks). A drone or trolley system could be used to ensure consistency in photo location, and to automate the collection process.

Even though the thermal imaging has some challenges, it could be applied to assist human logging. IR-image/recording could be used to automatically identify the leaks and to digitise them. In practice, this would mean taking IR images and using photogrammetry [36] and pattern recognition to map the anomalies to the tunnel profile. This would provide significant help to the monitoring process. For ONKALO, water leaks are classified into five different classes. After anomalies are digitised, the logging personnel could then determine the class of leak in each anomaly by other means, for example by visual observation using the current procedure. If this method is feasible the next phase would be to conduct a machine learning exercise to distinguish the different types of inflow and to determine semiquantitative inflow rates.

Alternatively, light-emitting diode (LED) photogrammetry could be explored to quantify the inflow rates.

4.2.1.2 Qualification of Optical Fibre Sensors

Monitoring using optical fibre systems offers many advantages compared to the use of point sensors. It offers distributed and time-resolved monitoring with high spatial resolution, and, potentially, the ability to conduct monitoring in harsh environments [37]. Optical fibres can be implemented in a versatile manner, by tuning the composition and structure of the fibres to the requirements of the desired application. The spatial resolution of monitoring using optical fibres depends on the technique used to interrogate the transmitted light signals.

Qualification of Radiation Tolerant Sensors

Continuously distributed sensors based on Rayleigh, Brillouin and Raman backscattering are widely used to monitor the strain and temperature of various civil engineering structures. For application to repository monitoring (e.g., as envisaged in Andra's Cigéo programme), radiations (gamma-rays, X-rays or neutrons) are likely to influence the measurement performed by optical fibre sensors. The main irradiation influence on the fibre properties is an increase of optical losses; a phenomenon referred to as radiation-induced attenuation (RIA) [38]. The fibre composition (including the nature, concentration and location of dopants and impurities) and the manufacturing process have been shown to strongly influence RIA [39]. Based on data obtained from past irradiation campaigns, online and post-irradiation measurements were used in MODATS to evaluate the most suitable fibre optic cables for temperature and strain monitoring in the harsh environments of the Cigéo repository (both disposal of HLW and long-lived intermediate-level waste were considered).

This research involved laboratory testing of seven different germanium-doped optical fibre cables, to understand the impact of radiation on their performance. The assessment involved analysing RIA levels and radiation effects on both Brillouin and Rayleigh scattering-based sensing from online measurements of the seven cables during irradiation campaigns. Furthermore, pre- and post-mortem evaluations were conducted based on multiple criteria (e.g. radiation-induced frequency shifts (Brillouin/Rayleigh), RIA, temperature and strain sensitivities, robustness and longevity).

All fibres showed increasing RIA levels with time under radiation of the order of Ge-doped optical fibers (without cable coatings) ~200 dB/km. Two fibres experienced significantly increased RIA (after 100- and 300-hours exposure respectively, see Figure 4-6) related to hydrogen loading in the fibre, which is associated with ambient hydrogen in the atmosphere and hydrogen generated by radiolysis of gels and polymers present in the cable.

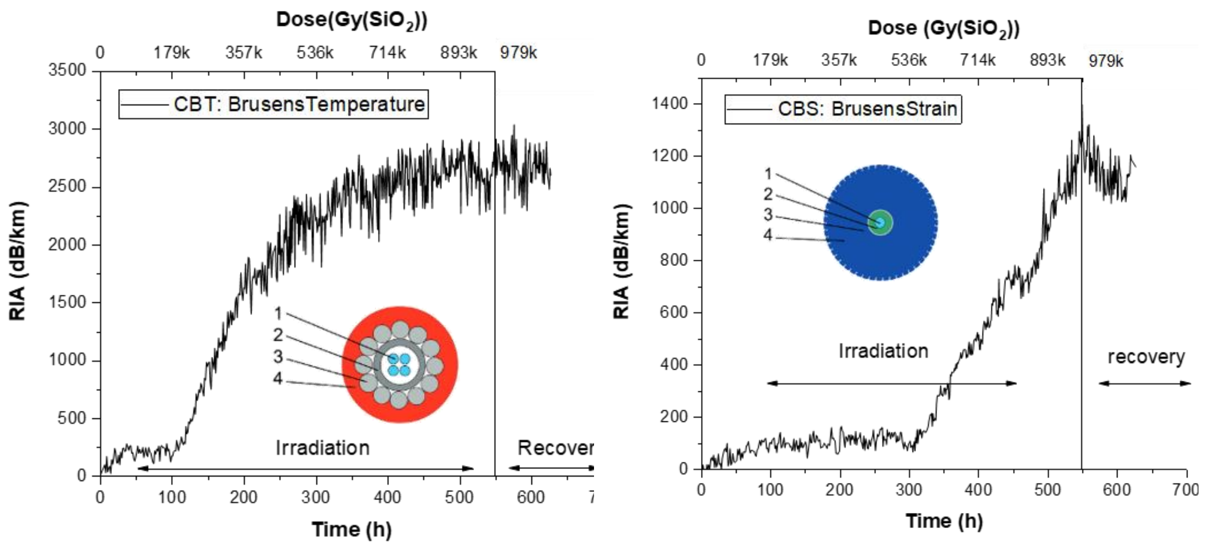

Figure 4-6 – RIA results from the optical cable γ-irradiation (^{60}Co) up to 1 MGy (SiO_2), exhibiting H_2-loading inside optical fibres drastically increasing optical losses.

The radiation levels (1 MGy) used in this experiment only related to gamma radiation (not neutron) at the levels expected by ^{60}Co for an intermediate-level waste repository. They represent the equivalent of 100 years of radiation exposure by a fibre. They do not represent higher radiation exposure to a fibre placed on a high-level waste container, which is expected to be 10 MGy over 100 years.

A second irradiation campaign tested radiation tolerance of six optical cables under a mixed neutron/gamma field at low doses (~1.7 Gy) was conducted at CVR in the Czech Republic. Six cables with different structures were investigated during and after irradiation.

Optical fibre cables were qualified for the gamma environment and a mixed gamma/neutron field but this work is still in the development phase. The development has progressed to include the consideration of neutron effects in addition to gamma effects, as well as the exploration of cable coatings. The next steps will require replacing Ge-doped fibres with radiation hardened optical fibers (these fibres will be fluorine-doped and polyimide-carbon-coated) in the most suitable optical cable candidates resulting from this previous work.

Advancement of Fibre Optic Strain Sensing Methods for Monitoring Tunnel Linings in Clay Rocks

This work focused on the testing of different fibre-optic strain sensing sensors and methods under repository-like conditions in the sandy facies of the Opalinus Clay at the Mont Terri URL. In this location, different tunnel support systems, including steel arches and shotcrete, have been installed and instrumented with different types of fibre-optic strain sensors. There are many options available for monitoring the convergence of the tunnels in response to the lithostatic stress. This work looked at monitoring of the shotcrete section, using three different distributed strain sensing methods: Brillouin optical time-domain analysis (BOTDA), which uses Brillouin scattering; Brillouin optical time-domain reflectometry (BOTDR), which also uses Brillouin scattering; and optical backscatter reflectometry (OBR), which uses Rayleigh Scattering; and two types of sensing cables: the V9 and V3 sensing cables manufactured by Solifos AG (Figure 4-7). Brillouin scattering using these cables has a spatial resolution of 0.5 m in BOTDA configuration, and can be deployed over 45 km, whereas Rayleigh scattering (OBR) has a spatial resolution of 0.01 cm, but can be deployed only over 70 m.

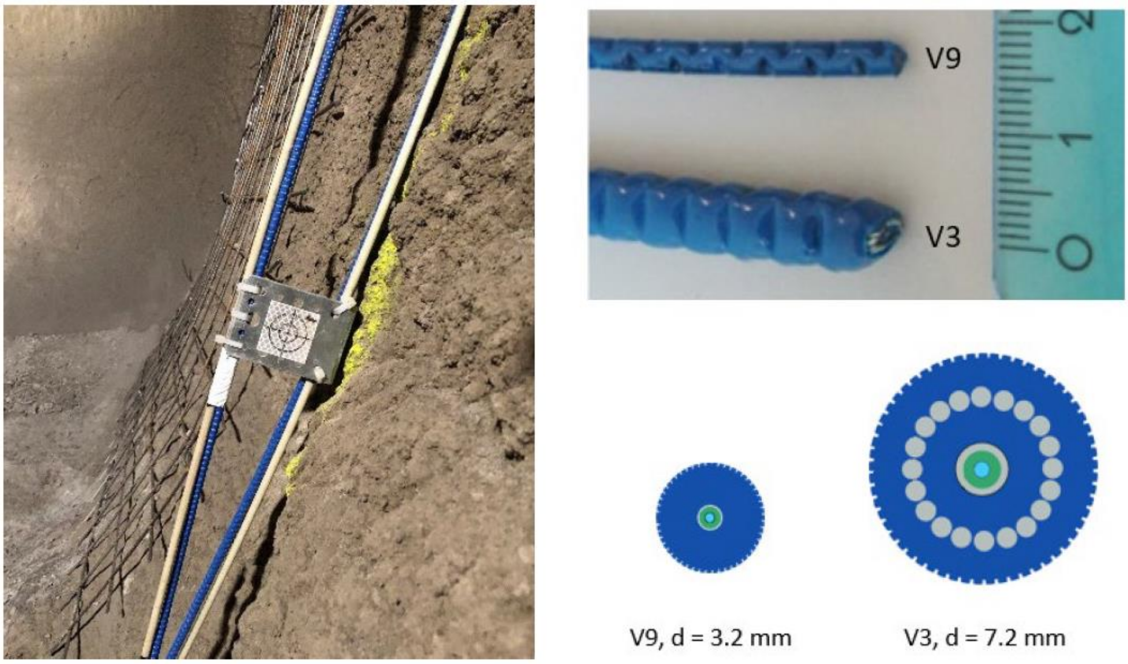

Figure 4-7 – The V9 and V3 fibre optic cables used for monitoring tunnel convergence in Mont Terri.

An example of the comparison of OBR-, BOTDA- and BOTDR-analysis for results from the V9 sensing cable is illustrated in Figure 4-8. Conclusions from this analysis were that:

- OBR data provided a detailed picture of the strain distribution owing to the high spatial resolution of this method.
- BOTDA data provided a relatively smoothed picture.
- BOTDR data were also smoothed; however, the data quality strongly depends on the measurement and sensor conditions.

A direct comparison of the measured strain between the different technologies, is difficult owing to the different spatial resolutions. However, spatial averaging of the OBR data shows that they correspond considerably well with BOTDA data.

The V3 and V9 cable were installed next to each other (Figure 4-7), but they show different strain distributions (Figure 4-9). The more sensitive design of the robust V9 sensor can capture the strain distribution in more detail and with higher spatial resolution compared to the robust V3 sensor design. The V3 cable in contrary has a lower sensitivity and produces a smeared strain distribution.

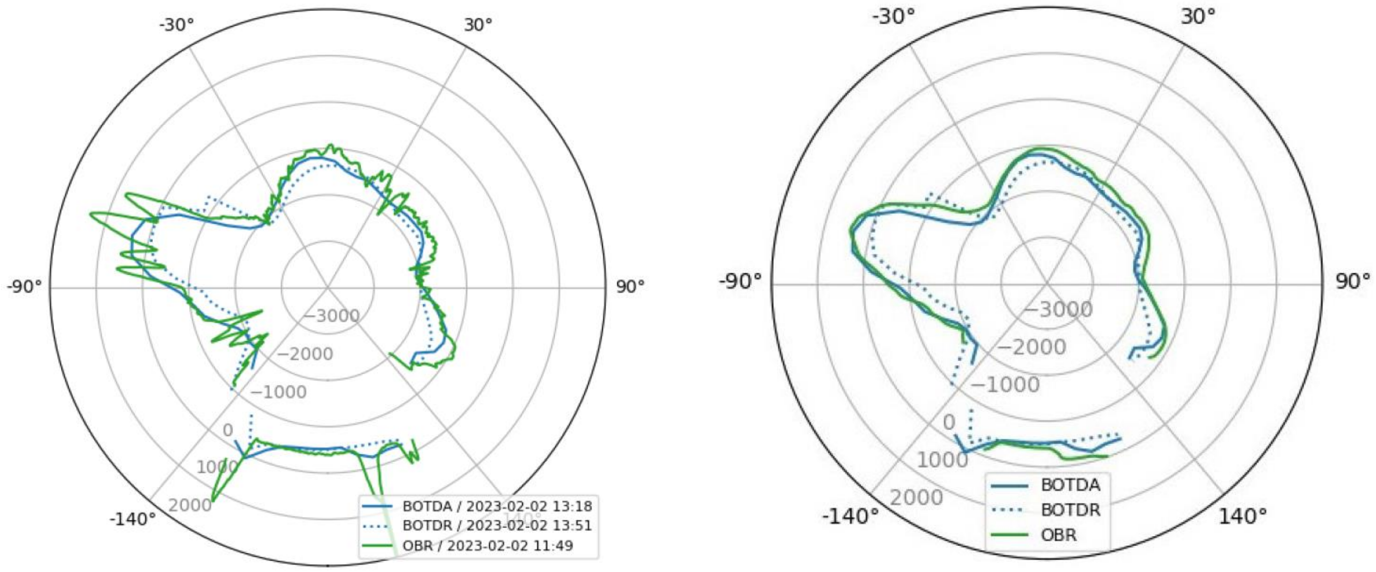

Figure 4-8 – Polar plots showing the tunnel cross section and strain distribution along sensors in microstrain (με). The raw data are shown on the left and averaged data on the right.

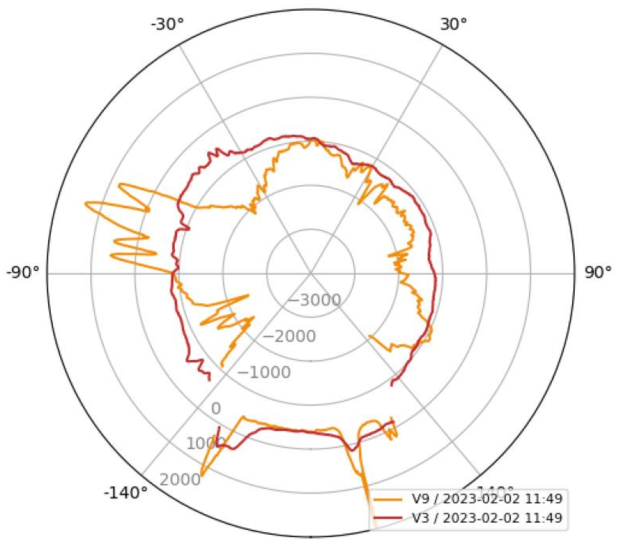

Figure 4-9 – Polar plots illustrating the results from the V9 and V3 fibre optic cables.

Overall, the selected sensing cables and the respective installation method, fixation and protection worked well, even in the harsh environment of shotcrete application in tunnelling construction.

In terms of measurement technologies, OBR sensing is to be favoured, if the relative short distance range is sufficient. It clearly offers the most spatially detailed strain distribution and is considered to best represent the actual deformations. OBR data could reveal high-resolution details of tunnel lining deformation that could remain undetected with the other monitoring techniques. However, a good strain transfer from the shotcrete to the cable and down to the bare fibre is required. Brillouin sensing, in particular stimulated BOTDA measurements, also offer a good picture of the averaged strain over a spatially longer distance (i.e. 1 m) and gives a good general overview, without showing local strain changes. Unstimulated Brillouin readings (BOTDR) have a lower quality than BOTDA and should only be used as a backup technology in case of sensor damages.

In terms of sensor selection, the robust V9 sensing cable offers enough durability for application in shotcrete while having a good sensitivity, and thus is recommended for future installations.

Optical pH Sensor

The development and use of analytical tools for on-site measurements are beneficial for environmental water quality monitoring in complex aqueous systems. Among measurable quantities, knowledge of pH is valuable because it governs many chemical reactions that can induce important modifications in a complex aqueous system. Electrochemical methods are ideal for measurements in research laboratories but are limited for on-site measurements. They are fragile, they require calibration with a reference electrode before measurement, and they can suffer from acid and alkaline errors. Optical methods offer advantages in terms of cost and simplicity of use, they do not require a reference electrode. They are not sensitive to electrical interferences and can address several measurement channels through multiplexing configuration. They can be used for remote, continuous, real-time, *in situ* measurements and can operate in harsh environments.

This activity focused on the development of a *proof-of-concept* optical sensor to measure porewater pH. In particular, the work focused on grafting of an acid base indicator on to an optical fibre, and testing of the resulting equipment. Grafting was facilitated through use of a diazonium salt to obtain a robust (covalent) grafting procedure, and the acid base indicator Neutral Red was used to monitor for neutral pH.

The development of these optical probes is based on a simple concept involving the immobilisation 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 analysed and the chemical recognition phase of the probe. The immobilisation 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 pH value of ~6 for pore water. These preliminary results are encouraging because they are independent of the localisation of the grafting (fibre or mirror) and are very close to the value pH ~7 measured by conventional on-site pH sensors.

4.2.1.3 Technology Development Roadmap

The challenges associated with repository monitoring, including the long timescales over which repository monitoring programmes are expected to operate, the harsh environment of repositories, and, for some monitoring strategies, the inability to access equipment for maintenance, recalibration or replacement, means that technology development must be planned carefully over a long period. The objectives of this work were to identify the monitoring technology issues that may need to be addressed before confident implementation of repository monitoring programmes commence, and to define the steps that are required to address these issues. The main output was a generic technology development roadmap (Figure 4-10).

To maximise value from the work, and fit in with pre-existing good practice, the methodology used and the resulting roadmap were linked to the Modern2020 Screening Methodology (Figure 1-2), and monitoring technologies were considered in the framework of process, parameter, and technology combinations.

Development of the roadmap was facilitated through a bottom-up approach involving the cross-comparison of current technology capabilities with generic monitoring requirements. Information on the capabilities of monitoring technologies was collated from a database [40], the survey of URL experiments [23], and the MODATS Reference Experiments [26]. The monitoring requirements were taken from work undertaken in the MoDeRn and Modern2020 projects [41].

Cross-comparing technical capabilities of, and requirements on, 36 technology and parameter combinations identified development issues that were then grouped into three broad categories and 14 sub-categories (Table 4-1). This understanding was then used to develop a roadmap that was iterated and revised using a series of test cases, which considered the RD&D steps required to make specific technologies ready for use in a repository monitoring programme. Further information is provided in the MODATS technology report [27]. In addition to development of the technical capabilities, the roadmap highlights the need for RD&D to include development of the ability to manufacture the technology and to develop QA documentation.

Table 4-1 – The issues requiring technology development identified in the development of the technology roadmap.

Development Issue Categories	Development Issue Sub-Categories
Unable to withstand harsh environmental conditions	Unable to withstand high relative humidity
	Unable to withstand high salinity
	Unable to withstand high pressure
	Unable to withstand high temperature
	Radiation induced attenuation
Unable to fulfil the data quality objectives	Insufficient lifetime
	Insufficient accuracy
	Require specific calibration, constitutive relationships
	Significant drift
Issues with operational suitability	Unsatisfactory measurement repeatability
	Cannot measure expected range
	Unsatisfactory sensor attachment
	Unsuitable sampling
	Unsuitable power supply

It is anticipated that use of the roadmap would be initiated through identification of an optional monitoring parameter for which there are technology development requirements. Following identification of a parameter, the roadmap can be used to guide the testing and development of the technology for monitoring the parameter in question. The roadmap splits into four columns influenced by similar roadmaps, starting from left to right: develop proof-of-concept, laboratory testing in relevant conditions, demonstration in repository-like conditions, and demonstration in site-specific repository environment (Figure 4-10). The fourth column is optional because it is not always practical/possible and depends on confidence.

Under the columns is a workflow designed around the output from the cross-comparison methodology used in the work, and which ultimately helps provide confidence that a monitoring technology can fulfil the data quality objectives, be installed and operated, and withstand the relevant expected conditions within the repository.

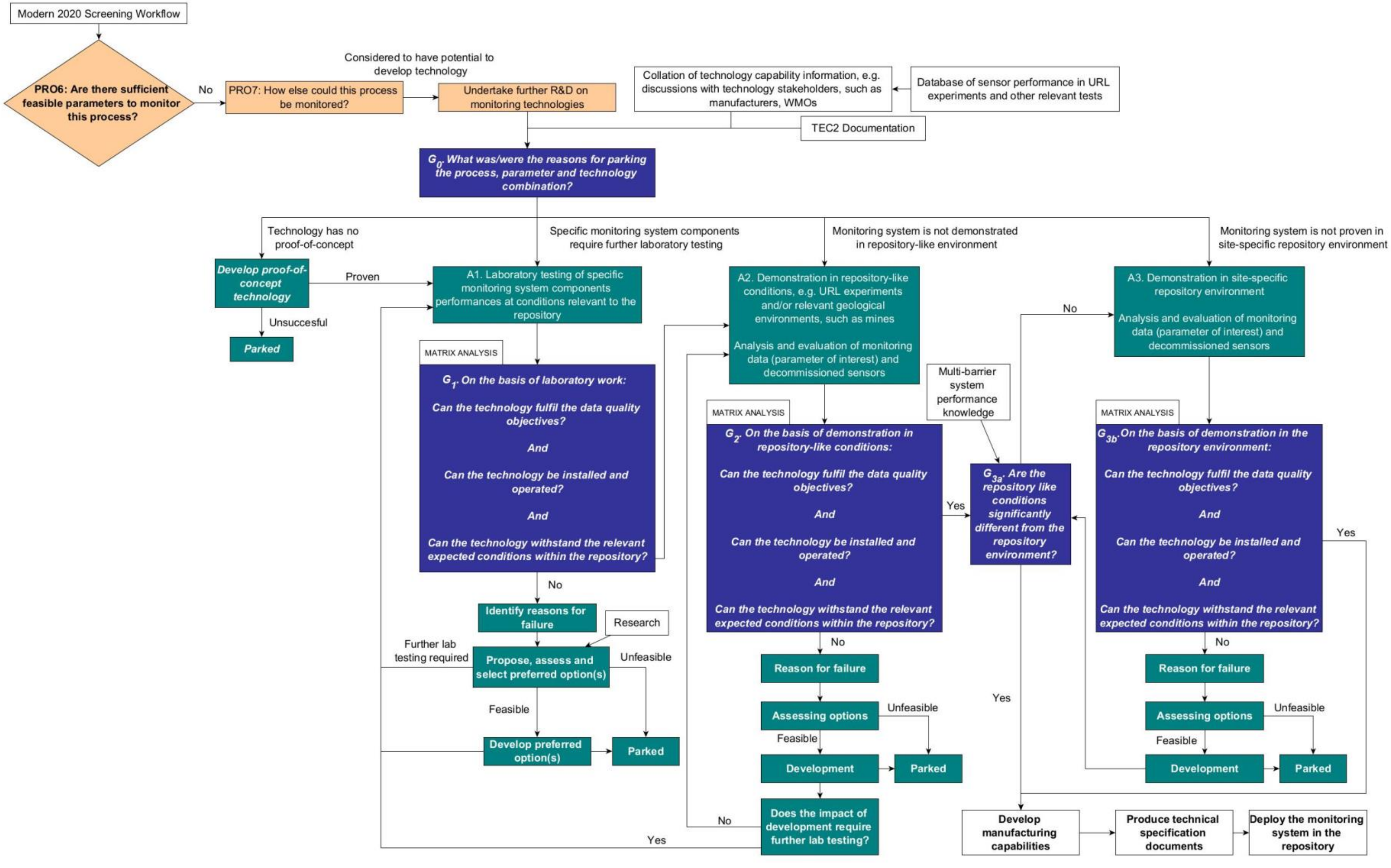

Figure 4-10 – Generic technology development roadmap for underground repository monitoring technologies. Orange coloured stages are from the Modern2020 screening methodology workflow. Blue stages are assessment gates. Green stages are activities to undertake according to the responses that follow the assessment gates.

4.2.2 Types of Anomalies

The test cases undertaken in Tasks 2.2 to 2.4 of MODATS provided an opportunity to identify different types of anomalies that can occur in monitoring data (Table 4.2). Characteristics of anomalies are defined in a qualitative sense in Table 4.2 because the data processing approach of (time series) measurement data needs to be customised according to the sensor type (e.g., characteristics of thermocouple data are different from those of porewater pressure transmitters), and the specific application(s) for which the data will be used. This comprehensive list of data anomalies allows those responsible for processing data and providing it for use in strengthening understanding to produce processing tools that are aligned with good practice, thereby developing confidence that the data is fit-for-purpose. The categories in Table 4.2 should be seen as examples of anomalies and are provided for guidance only. For any anomaly in a dataset, it is important to first identify the results as abnormal and then to explain the cause of the abnormality. It is not necessary to categorise abnormal data to process results appropriately.

Table 4.2 – Identification of the main types of monitoring data anomalies and options for their management.

Category	Characteristic (and example, if available)	Processing Options
NaN	No value is recorded for a particular timestep or for a specific period within the monitoring data set	Options include averaging of the adjacent values, or leaving the timestep as NaN and labelling the timestep so that the value can be left out from some uses
Null Value	Value recorded for a particular timestep is zero	Options include averaging of the adjacent values or leaving the timestep value as zero and labelling the timestep so that the value can be left out from some uses
Duplicate Values	The data file includes more than one value for a time step in a specific location or for a specific sensor	Options include averaging of the values, labelling of the values as uncertain to ensure they are not used in further analyses, or selection of a preferred value based on a pre-determined method
Non-Physical Value	Value recorded is not possible (e.g., negative relative humidity)	These data would be flagged and removed from data sets before use
Implausible Value	Value recorded is not reasonably expected (e.g., negative temperature)	These data would be flagged and removed from data sets before use based on a pre-defined approach for each parameter (this might include use of uncertainty ranges based on modelling, or definition of plausible parameter value ranges defined by expert judgement using formal elicitation methods)
Unexpected Constant Values	The values returned by a sensor do not change over time	These data would be flagged and removed from data sets before use
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.	These data would usually be flagged and removed from data sets before use, the value of the gap in data caused by removing the spike could be left as NaN or could be recreated by averaging adjacent values

Category	Characteristic (and example, if available)	Processing Options
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	This type of anomaly could be caused by temporary malfunction of the monitoring system such as an increase in electrical current over a short period. Data might be flagged and removed from data sets used in analysis, or an algorithm might be developed to correct the affected data
Permanent Step Change	Data records show a sharp change in values, before progressing at a similar rate of change as previously	It may be possible to correct for permanent step changes, or the flagged data might be removed from the data sets used for analysis
Noise	Noise is characterised by a scattering of values around a central trend	Noise that is not characterised by the features specified for other anomaly types is usually challenging to remove from data; therefore, noisy data need to be evaluated on a case-by-case basis and used in a manner suited to the end user needs
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	Clearly defined outliers would be removed from data sets, for example if one sensor in a group was shown to have behaviour inconsistent with other close-by sensors; however, removal could only be undertaken based on a pre-determined formal process
Unexpected Data Trends	Data trend is inconsistent with model prediction	Data that is inconsistent with modelling would have to be subject to root cause analysis to identify the reason for the discrepancy; this might involve testing of sensor performance (e.g., recalibration where possible) and revision to the modelling (e.g., consideration of the conceptual model implemented, and investigating the effect of changing parameter values); it would not be acceptable to remove data with unexpected data trends from analyses until the root cause of the trend was identified

4.2.3 Understanding of Metadata Requirements

Harmonised ontologies[3] and metadata conventions would benefit the efficient and transparent storage of monitoring data. Work in MODATS has highlighted the application of outcomes from the 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, for example, the recommendation that a metadata policy should be put in place by each WMO. In order to facilitate the implementation and use of shared digital infrastructure as well as to exploit the full capacities of automation, data standards and shared application programming interfaces should be agreed on. 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.

When interpreting monitoring data, it is necessary to distinguish between cause and effect. It is then paramount that the external influences (natural and anthropogenic) relative to the monitored system are

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

identified. During the operational phase of the repository there will be many activities on-going simultaneously that might generate responses in the monitoring system (e.g., construction activities or changes to the ventilation system). It is therefore necessary to have a system in place that will document all activities in support of data interpretation and root-cause analysis that might be warranted. This functionality, of booking and tracing activities/events, should be included as part of the monitoring database.

The MODATS test cases identified and listed the metadata that would be used to justify decisions to flag data as potentially “false” and thereby to remove such data from presentational plots to show parameter evolution (see [26] for a full description of this work). Examples of the metadata identified in these test cases are power outages and upgrades to data logging systems, where the events are known to have impacts on the data acquired.

4.2.4 Development of Advanced Modelling Methods and Digital Twins

Experience and expertise have been developed in coupled numerical modelling of THMCG processes over the last four decades of RD&D in geological disposal. For example, 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 [43].

Recently, machine learning has emerged as an alternative to the approaches adopted in coupled numerical modelling [44]. Machine learning involves using scientific methods, processes, algorithms and systems to extract or extrapolate information and knowledge from previously collected data (training data) to identify the characteristics of a data set and to predict the future trend. A sub-set of machine learning is data-driven modelling (DDM). Coupled numerical models, referred to as physics-based modelling (PBM) in data science, assume that a physical model describing the behaviour behind processes is available and sufficiently accurate to understand the operation of processes and (in some cases) to predict future behaviour. Originally, machine learning was suited to data-intensive applications such as image processing and pattern recognition. In recent years, physics-informed machine learning (PIML)[4] methods have been developed to an extent that they accelerate numerical simulations and have become directly usable for process-driven areas including, potentially, application to modelling of THMCG processes in repositories.

The spectrum of machine learning methods applicable to modelling of repository THMCG processes is extensive, presenting a diverse array of techniques, for example:

- Linear regression models constitute a fundamental approach for straightforward parameter prediction[5] tasks. These models establish a relationship between input features, such as historical data and geographical information, and predictions [45].
- Time series models, including autoregressive integrated moving average [46] and exponential smoothing [47] are particularly applicable to short-term predictions.
- Deep learning models are currently widely applied in machine learning applications, particularly recurrent neural networks (RNNs) and convolutional neural networks (CNNs). RNNs, which are proficient in capturing temporal dependencies within time series data, prove effective for short-term predictions [48]. Conversely, long short-term memory (LSTM) networks, a subset of RNNs,

[4] PIML allows scientists to use prior knowledge to help the training of the algorithm, making it more efficient. This means it will need fewer samples than a pure DDM to train it well or to make the training more accurate.

[5] Prediction is referred to as “forecasting” in machine learning.

excel in modelling prolonged dependencies within time series data [49, 50]. CNNs, which are adept at addressing spatial dependencies in predictions, find application in predicting parameter values across geographical regions [51, 52]. Additional approaches used for predictions include random forests [53], which amalgamate multiple decision trees to enhance accuracy.

- Support vector machines [54], which are applicable in the presence of non-linear and high-dimension data, present another noteworthy avenue for parameter predictions.
- Gaussian process models [55, 56] provide a means to encapsulate uncertainty and provide probabilistic predictions.
- Hybrid models [57] involve a fusion of machine learning models with physical models to bolster prediction accuracy.

The potential benefits offered by these approaches are more rapid modelling, which may benefit the continuous evaluation of monitoring data, and greater ability to model parameter evolution across 3D space. A particular opportunity is the use of the machine learning algorithms in digital twins; the emerging application of machine learning approaches allows for enhanced use of monitoring results by using the data acquired directly in the modelling approach.

In MODATS, the application of machine learning approaches to modelling of monitoring data was investigated in the ALC1605 test case and the FE test case (see [26] for a full description).

In the ALC1605 test case, it was 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 test case. The use of a hybrid twin, rather than a DDM 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 the results.

The PSI FE experiment test case came to a similar conclusion as the ALC1605 test case, i.e. that a hybrid modelling approach combining the PBM with a DDM provided the best modelling results. In the PSI test case, the preferred model was the use of a PIML model that combined the k-nearest neighbours' algorithm with data on the heater power or power density of the heat source.

Digital twins have the potential to support monitoring programmes in demonstration of compliance with requirements and conditions linked to post-closure safety. These requirements and conditions differ between each repository programme and 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 supporting 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 greater 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. An example would be the development of a 3D model of the temperature field over time, without the need for modelling of hydraulic and mechanical interactions.

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 machine learning approaches such as neural networks to train the model to deliver accurate results.

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.

5. Contribution of MODATS to Developing Confidence in Monitoring Data Provided to Society

This section describes how the results of MODATS contributes to the third purpose of monitoring in support of the post-closure safety case recognised in IAEA TECDOC 1208 [2]:

- 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.

First (Section 5.1), a discussion of what is required in order to have confidence in monitoring data provided to society is presented. Second (Section 5.2), we describe the outcomes of MODATS that could provide confidence in monitoring data used for this purpose.

5.1 Building Confidence in Monitoring Data Provided to Society

The IAEA TECDOC recognised that there are several critical points in a repository development programme that are likely to require input from a broader range of societal groups than the repository operators and regulators alone. These will vary from one programme to another, as will the nature and level of involvement of interested parties. It is conceivable, for example, that society, might want to be involved in making decisions on approving its eventual backfilling, sealing and closure. A decision to backfill, seal and close a repository is likely to require an evaluation of monitoring information collected over many decades of repository operation.

As noted in Section 3.1, there is an overlap between providing information to society and supporting management decisions. The purpose to be discussed in this section is more focused on the major decisions of repository programmes, such as a decision to move from a pilot phase to an industrial phase, a decision to close the repository, or perhaps a significant variation in the permission to emplace waste. It is envisaged that "major" decisions would involve greater discussion with a broad range of stakeholders than the detailed decisions that were the subject of Section 3.1. This does not imply that all stakeholders would not be consulted in more detailed decisions; the consultation on each decision for each programme would be dependent on the relevant engagement strategy.

As with other aspects of monitoring, it is envisaged that monitoring data will support engagement with society. Monitoring will not be undertaken in isolation. Instead, engagement on monitoring should be undertaken within the framework of a wider engagement programme that includes discussion of the safety case and decision-making processes. Nonetheless, monitoring can be a significant contributor to these engagement programmes. For example, work in the MoDeRn and Modern2020 projects concluded that citizen stakeholders appreciated involvement in the RD&D of the projects. Citizen stakeholders felt that their role in the project was to understand the context of the work, and welcomed the opportunity to ask critical questions in order to increase understanding and give feedback [5]. Engagement with the citizen stakeholders using monitoring data is anticipated to further enhance trust in WMOs and repository programmes.

Some examples of what might be/is required to develop confidence in monitoring data provided to society are:

- Understanding the views of members of the public / citizen stakeholders.
- Have confidence that good practice has been applied.
- Be provided with traceable and transparent data to ensure that the route from raw data to interpreted data is legitimate.
- Have good approaches to engagement focused on monitoring data.

5.2 Contribution of MODATS

The results from MODATS contribute to the development of confidence in monitoring data provided to society in several ways. In this section, we highlight four specific activities:

- Understanding the views of members of the public / citizen stakeholders (Section 5.2.1).
- Confidence the good practice has been followed (Section 5.2.2).
- Provision of traceable and transparent data (Section 5.2.3).
- Good processes for communication of monitoring data and associated monitoring programmes (Section 5.2.4).

In addition, MODATS has contributed to confidence that data have been acquired correctly by developing guidance on QAPPs, as discussed in Section 3.2.1.

5.2.1 Understanding the Views of Members of Citizen Stakeholders

Engagement of civil society in repository monitoring is expected to cover all aspects of the monitoring programme, i.e. both strategic aspects and details including acquisition, management and use of the data. Processing and storage of monitoring data, and use of the data to support decision making is a detailed technical activity. In Task 2.5 of MODATS, two multi-stakeholders' workshops were organised in Nancy in April 2023 and Paris in October 2023. 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).

Views collected in the Task 2.5 report include those related to:

- The diverse views on the 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 multi-party dialogue also recognised that the information provided to stakeholders during engagement on monitoring is important for collecting opinions that take into account an understanding (on behalf of citizen stakeholders) of the way monitoring is planned to be conducted by technical stakeholders. This responds to a conclusion from the MoDeRn project, which noted that transparency about the limits of monitoring is required for monitoring to contribute to repository governance [4]. As such, engagement on monitoring should be conducted through the perspective of the safety case rather than as an isolated activity, and this was addressed in the Task 2.5 workshops through presentations on the French approach to the post-closure safety case. The Task 2.5 work also recognised that discussion of the wider monitoring programme context needs to be introduced before discussing details regarding monitoring data.

The views and opinions collated within this work are consistent with other engagement activities on monitoring, and extended this 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. Further information is provided in the multi-party dialogue report [25].

5.2.2 Confidence that Good Practice has been Followed

5.2.2.1 Identifying Good Practice from Monitoring of URL Experiments

The technical and scientific basis for geological disposal has been developed over the last five decades. Information, understanding and knowledge from URL experiments has provided important inputs to this technical and scientific basis, and much of this information, understanding and knowledge has been derived from monitoring of the experiments.

It is important, therefore, that repository monitoring programmes identify, consider and use the lessons from monitoring of URL experiments. International collaborations such as EURAD provide an opportunity to learn the lessons from other programmes and to evaluate consistency of approaches and techniques used in monitoring.

Within MODATS, the URL survey [23, 58] provides a detailed analysis of the monitoring of 17 URL experiments. Some of these experiments are completed and have been dismantled, while others are ongoing. They are conducted in different EBS components and in different host rocks. Some of the experiments aim to understand the behaviour and test the performance of individual EBS components, while others aim to develop further understanding of one or more thermal, hydraulic, mechanical, chemical, gas and radionuclide transport processes in one component of the multi-barrier system or in full-scale repository concepts. Some of the experiments also test materials and emplacement technologies.

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

Numerous lessons were identified in the following areas [23]:

- Monitoring system design: parameter selection, technology selection, monitoring system layout, general design considerations, monitoring system performance.
- Data acquisition: QA/QC, installation, calibration and other testing.
- Data management: storage, treatment.
- Data analysis and use: data visualisation, use in coupled process modelling.
- Demonstration that these lessons have been applied in repository monitoring programmes could enhance societal confidence in monitoring data.

Application of the lessons learned from the URL survey can demonstrate that good practice has been applied in the design and operation of a repository monitoring system, i.e., that stakeholders can have confidence that the data has been acquired using knowledge from RD&D on monitoring technologies. It may be possible to build further societal confidence by demonstrating that monitoring data has been acquired, managed and used in a way that is consistent with good practice from monitoring of URL experiments.

5.2.2.2 Recording Good Practice for Future Generations

Application of good practice, requires that first, such practice is identified, then that it is accessible and available to future generations, and then that it is applied within a repository monitoring programme. MODATS has supported the identification and availability of good practice in monitoring through several knowledge management activities (see summary in [29]):

- A SOTA document on repository monitoring has been published [10]. This document collates the common understanding of repository monitoring that has been developed by the international community over the last two decades (commencing with the publication of the IAEA TECDOC [2]). It presents the SOTA on monitoring objectives, strategies, technologies and data, and identifies the most pertinent literature on repository monitoring. It is a reference document for EURAD actors, and includes the new understanding developed in MODATS.
- MODATS also contributed a domain insight document on monitoring to the knowledge base developed within EURAD [21]. The monitoring domain insight document provides an introduction to monitoring in repository programmes, focussing on activities and knowledge most critical for the implementation of monitoring through the different repository phases.
- A week-long, online training school was held towards the end of the project. The training school included a general introduction to monitoring, presentation of monitoring technologies, examples of monitoring programmes, and dissemination of new learning developed within MODATS. The agenda for the training school is provided in Table 5-1. Over 100 participants registered for the school, which was recorded and is available online via the EURAD website [https://euradschool.eu/]. The training school was successful in reaching a wide range of interested stakeholders. However, it was recognised that on-line training has some drawbacks compared to face-to-face training on monitoring, especially the inability to have practical sessions and the inability for participants to informally interact with each other and with the presenters.

Table 5-1 – Agenda of the MODATS training school.

Time	Subject	Presenter
Day One		
1000-1030	Introduction to MODATS and the Monitoring Training School	Johan Bertrand, Andra
1030-1200	General Aspects of Monitoring	Matt White, GSL
1300-1430	Monitoring Technologies, Part I	Johan Bertrand, Andra
Day Two		
1030-1200	Monitoring Screening Methodology	Tom Haines, GSL
1300-1430	Monitoring Technologies, Part II	Johan Bertrand, Andra
Day Three		
1030-1200	Example of Monitoring Approaches in Crystalline Rock	Johanna Hansen, Posiva
1300-1430	Example of Monitoring Approaches in Clay Rock	Johan Bertrand, Andra

Time	Subject	Presenter
Day Four		
1030-1200	Stakeholder Participation in R&D of Monitoring Systems for Geological Disposal	Julien Dewoghélaëre, NTW
1300-1430	Damage zone monitoring, Jan Cornet, ANDRA	Jan Cornet, Andra
Day Five		
1000-1100	Monitoring QAPPS	Matt White, GSL
1100-1200	Monitoring FEPS	Matt White, GSL
1300-1340	Data Treatment	Anoop Ebey Thomas, ESI
1340-1420	Artificial Intelligence	Nicolas Hascoët, ENSAM
1420-1500	Hybrid Twin	David Munoz Pellicer, ENSAM

5.2.3 Provision of Traceable and Transparent Data

Confidence in the information provided to society can be built by acquiring, managing and using data in traceable and transparent ways, and being able to demonstrate the use of traceable and transparent methods to data acquisition, management and use.

In this context, traceable refers to the ability to recreate the data set used for decision making from the raw data (which, as has been noted elsewhere, should remain accessible throughout the monitoring programme), and transparent refers to the ability to understand and communicate how the data have been acquired and managed.

Several activities undertaken in MODATS, all of which have been discussed elsewhere in this synthesis can contribute to building confidence in data through the use of traceable and transparent methods:

- The development of guidance on the structure and content of QAPPs, which, if applied would build confidence that data have been acquired, managed and used in a quality assured way. The guidance on QAPPs was developed with support from across the MODATS partners, including taking good practice from Äspö in Sweden, Bure in France, HADES in Belgium, and Mont Terri in Switzerland. The integration of good practice from these URLs adds to the confidence in the guidance provided in the document. The QAPP guidance is summarised in Section 3.2.1, and the work is reported in [24].
- The development of a generic workflow for data handling from acquisition to decision support (Figure 3-1). Application of the workflow could be used to demonstrate the approach taken to prepare data for use in decision making and to trace the management of the data through its lifecycle.
- Use of open-source tools for data analysis (Appendix B), which provides confidence that the tools are fit-for-purpose, by opening the tools for review, application and improvement across the data management community. The development of open-source tools also provides confidence that the tools will be available for application in the future.

5.2.4 Good Processes for Engagement on Monitoring Data and Associated Monitoring Programmes

5.2.4.1 Development of the Monitoring PEP

In Task 2.5 of MODATS, the process of engaging with multiple parties, including civil society, was enhanced through extension of the Pathway Evaluation Process (PEP), which 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.

The PEP methodology is based on a "serious game[6]" enabling a multi-party discussion. The objective is to facilitate discussions between different types of stakeholders to grasp the complexity of the 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 tools are 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 5-1). 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 5-2).

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 applied in small groups of 4-6 participants and facilitated by someone familiar with the methodology.

The PEP methodology was used in the two workshops undertaken as part of Task 2.5 of MODATS. The PEP methodology enabled discussion amongst different stakeholders on an equivalent footing and the specific version of PEP on monitoring and digitalisation is a promising tool that could be used in future research involving stakeholders from multiple parties. Members of the public 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 members of the public in face-to-face discussions trust can be built, and it may lead to technical experts improving the way that they explain their concepts.

[6] 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

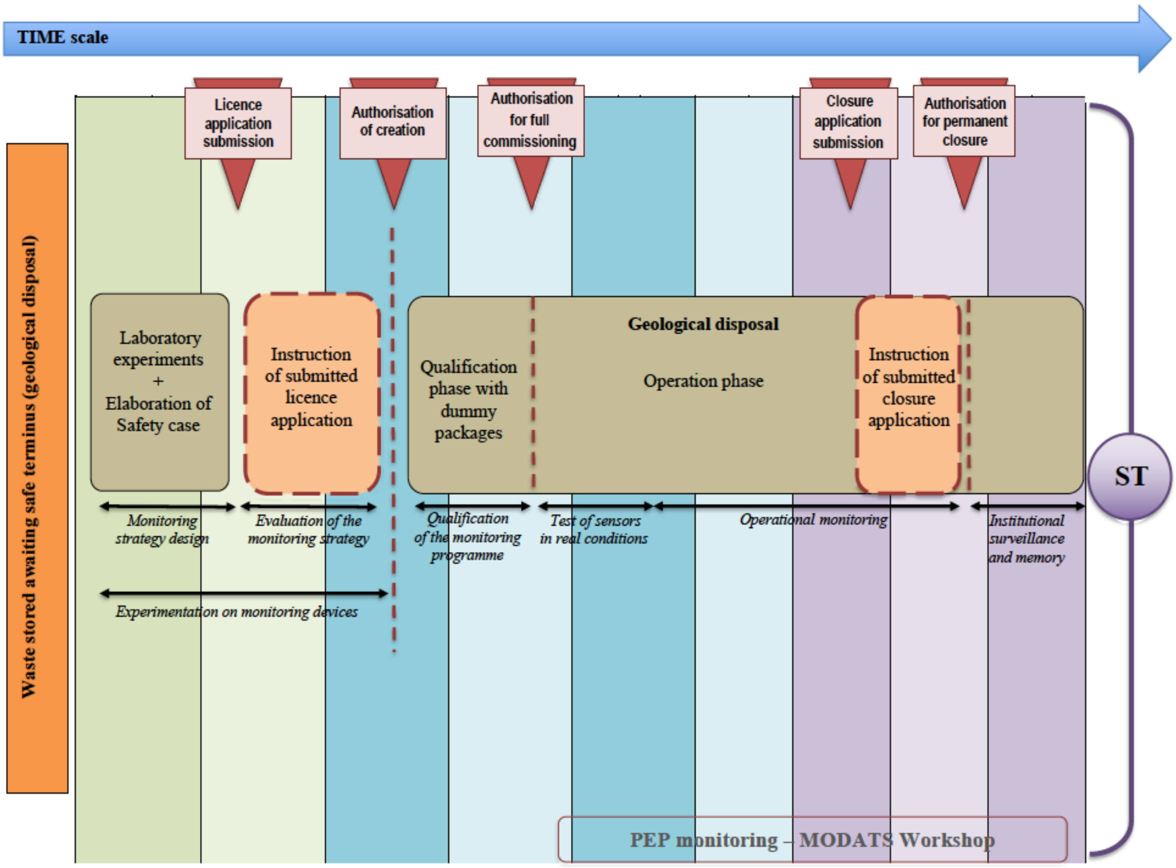

Figure 5-1 – The PEP Board - pathway on monitoring tested during the sub-task 2.5 workshop.

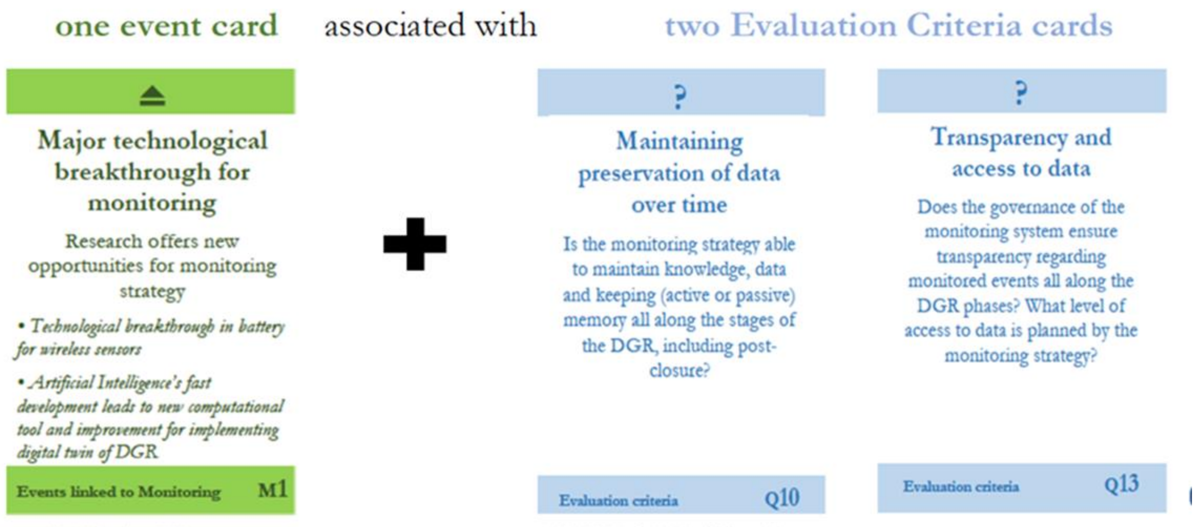

Figure 5-2 – Example of event (green cards) and evaluation criteria (blue cards) cards used for the PEP game developed in MODATS.

5.2.4.2 Development of Tools for Communication through Visualisation

In addition to using data in advanced modelling applications, monitoring data (and the models generated from the data) can be used to communicate the outcomes from repository monitoring and help with dissemination of understanding to society at large by providing content and formats tailored to the target groups. Visualisation tools can also be a good medium for facilitating wider discussions on monitoring. FE Test Case 3 demonstrated the power of visualisation tools to develop understanding and to facilitate discussions by integrating geological, infrastructure, monitoring and simulation data (see [26] for a full description of this work).

In this work, a virtual reality application referred to as the Virtual Experiment Information System (VEIS) was developed using information and data from the Mont Terri URL and its associated experiments (Figure 5-3). The VEIS virtual models of the URL and its geological context and measurements displayed in this virtual environment update automatically whenever sensors measure changes in the real URL. It can therefore be considered as a digital twin prototype with a focus on visualisation.

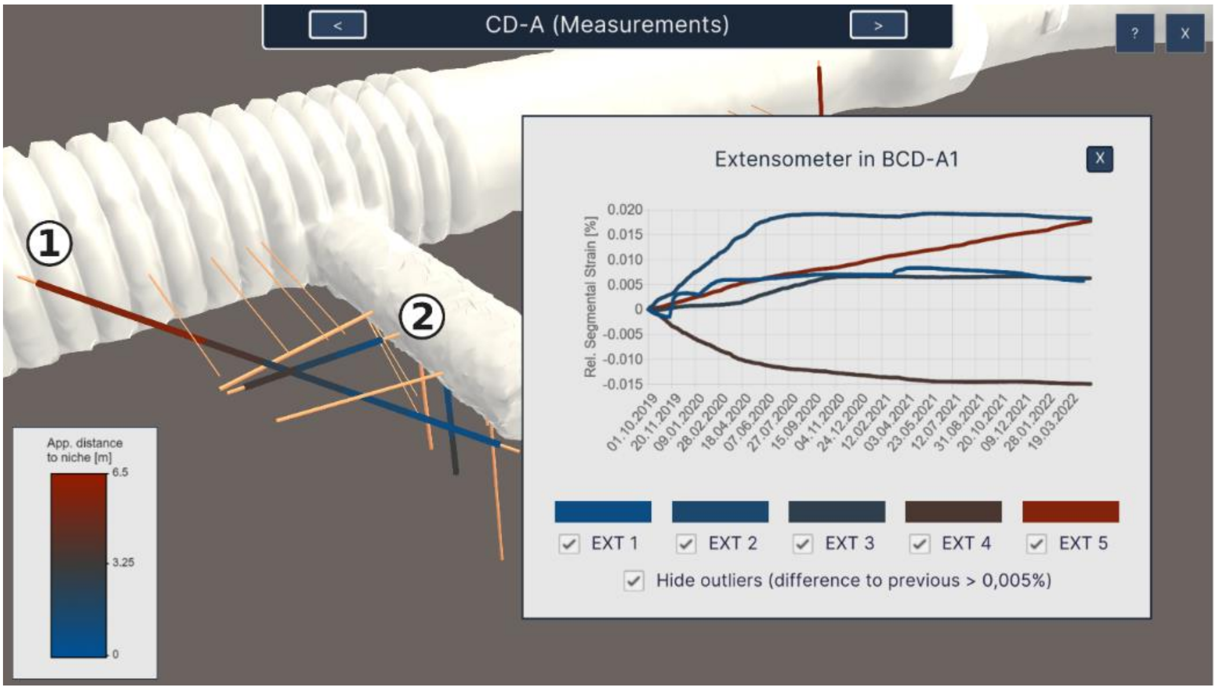

Figure 5-3 - Screenshot from the VEIS for the Mont Terri URL illustrating sensor measurements from the online databases, depicted with outlier removal.

The original application of the VEIS was focused on its use as an integrated information system for domain experts, allowing them to interactively visualise the data and associated models, in order to build further understanding. However, the application of the VEIS was extended for use by university students, with the objective of communicating scientific aspects of the Mont Terri URL and acting as a starting point for a multi-party-dialogue. The VEIS was extended in MODATS to allow 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 and an extrinsic motivation to explore the data, increasing their learning from the process. Evaluation of the use of the VEIS in this way demonstrated the effectiveness of the approach in communication and education. The learning outcomes were measured with multiple-choice tests and the results from additional questionnaires indicated a good perceived usability of the virtual tour prototype even for participants with low prior knowledge and little experience with 3D applications before using VEIS (Figure 5-4).

The communication work in FE Test Case 3 can be contrasted with the engagement work undertaken in Task 2.5 (Sections 5.2.1 and 5.2.4.1). In FE test Case 3, the objective was to use engagement tools to educate non-expert stakeholders. In the Task 2.5 work, the objective was to understand the views of a range of stakeholders to support the planning and conduct of repository monitoring.

The work in FE Test Case 3 also demonstrated that visualisation can be of significant benefit when comparing simulation results from different numerical models of THMCG 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.

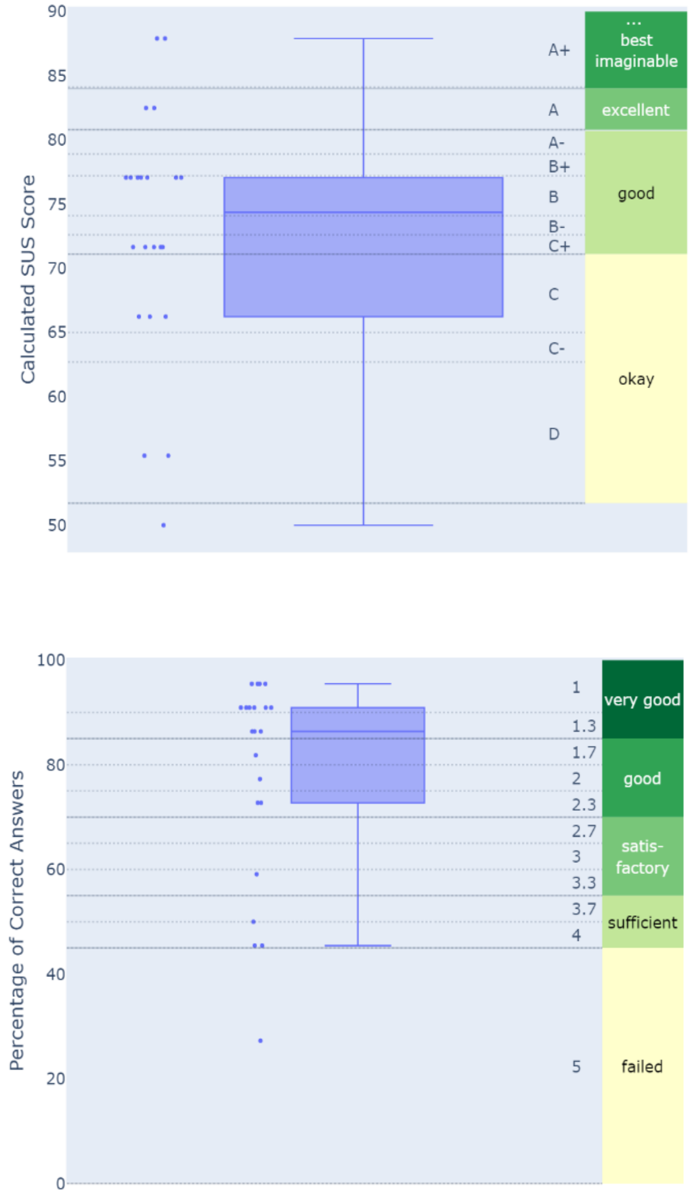

Figure 5-4 – Results of the virtual field trip evaluation concerning the perceived usability (top) and the knowledge transfer (bottom). The median System Usability Scale (SUS) score of approximately 74 indicates a good usability and the median score of ~86% correct answers shows that the group of participants reached good results in the knowledge test and demonstrates the virtual tour's ability to successfully teach relevant knowledge about the Mont Terri URL.

6. Discussion

6.1 How has MODATS Addressed 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, has been confidence in monitoring data. MODATS has undertaken a series of focused developments that improve the ability to acquire, manage and use monitoring data (including use of monitoring data in modelling and forecasting, and the use monitoring data as part of engagement activities). The issue of confidence has permeated all of these activities.

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 [59]. 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 has focused 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. In synthesising the outcomes from the work, MODATS has linked developments to building confidence in the three purposes of monitoring recognised in the IAEA TECDOC that relate to long-term safety [2]. Although the discussion of each activity in MODATS is linked to one specific purpose, it is recognised that most of the results could contribute to confidence more widely. For example, managing a repository monitoring programme over its full lifecycle using a comprehensive QAPP would contribute to all three purposes.

Within MODATS, there has been no attempt to quantify confidence, which would have required a standalone work package within EURAD. 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 [60]. Methods have been developed to measure confidence objectively [61]. 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.

6.2 Can the Results of MODATS be used to Build Confidence in Monitoring Data?

MODATS has undertaken a range of technical and sociological activities, with the aim of improving methods and approaches for acquiring, managing and using monitoring data. The following outcomes have been achieved:

- Lessons have been learned for repository monitoring from monitoring of URL experiments [23].
- Guidance has been produced on the structure and content of QAPPs [24].
- Six test cases have been undertaken to improve the methods and tools available for data processing and storage, for modelling the acquired data, and for visualising and communicating the data to various stakeholders [26].
- Methods for engagement using multi-party dialogue have been extended to include monitoring data issues, and members of civil society and technical experts have discussed their views on monitoring and monitoring data [25].
- A Monitoring FEPs catalogue has been developed and can be used to support the initial design and iterative development of the monitoring system to ensure there are no impacts on long-term safety caused by the use of the equipment or by leaving the equipment *in situ* after use [28].
- Technological developments have been undertaken in geophysical and thermal monitoring of repositories, including [27]:
    - Demonstration of the ability to derive monitoring parameters from geophysical data.
    - Development of new models for interpreting electrical data using SIP.
    - First steps in the development of automatic methods for classifying seismic events.
    - First steps in the use of IR thermal imaging for monitoring water leakage into tunnels.
- Technological developments have been undertaken in optical monitoring of repositories, including [27]:
    - Qualification of radiation tolerant optical fibre systems.
    - Identification of the most suitable optical fibre methods for monitoring tunnel convergence.
    - Extension of the capabilities of using Optodes for monitoring the full range of groundwater pH.
- A technology roadmap has been developed to support RD&D planning, and to ensure that monitoring technology is ready for use when required [27].
- SOTA [10] and Domain Insight [21] reports have been prepared, which can act as an entry point to the extensive literature that exists on repository monitoring.
- A training course on repository monitoring has been developed and has been published on the EURAD website [29].

As noted above (Section 6.1) it was not the role of MODATS to build confidence in actual monitoring data, but to provide the means for specific repository monitoring programmes to use selected outcomes from MODATS to ensure that monitoring work is reliable and of high-quality. The manner in which the guidance, tools and methods produced in MODATS can be used in repository programmes will reflect the different contexts of each programme, including: the relevant laws and regulations; the wastes to be disposed of and their characteristics, including packaging; the geological environment; the disposal facility design; decision-making practices used in the programme; and the socio-political environment.

As noted in the introduction (Section 1.3), when considering confidence, development of any plan to build confidence should define whose confidence is under discussion. For technical actors, confidence is likely to come from the scientific and technical approach to acquisition, management and use of the data. Confidence is an expression that an appropriate method has been used to undertake the monitoring programme. This includes identifying the need for the activity, agreeing the approach, designing an appropriate system including selection of the sensors and other monitoring equipment, and demonstrating that the programme has been implemented as envisaged. The guidance, methods and tools developed in MODATS can be used to help build this confidence (e.g., guidance on QAPPs [24] and the learning provided by the six reference experiment test cases [26]).

For members of civil society, confidence in specific monitoring data might not be as important as trust in the individuals and organisations undertaking the work (where trust can be defined as a choice or decision to place one’s confidence in others [62]). This requires wider engagement than just on monitoring data; especially for repository monitoring during the operational period in support of long-term safety. MODATS has demonstrated ways in which engagement on monitoring data can be facilitated, including the use of the Monitoring PEP and the use of visualisation tools tailored to engagement (i.e., with learning modules attached). Application of these methods could contribute to the trust of civil society stakeholders in WMOs. Although the multi-party dialogue work undertaken in MODATS has reemphasised that civil society is not focused on data alone but the use of the data in decision making, if scientists can communicate the basis for having confidence in monitoring data, this will help in the process of developing trust in the repository programme. Another element of confidence that should be considered is the national context of each member state and their culture. Confidence levels can vary significantly from one country to the other, and can evolve rapidly depending on the situation.

An additional aspect of trust is the ability for monitoring data to be consistent with the envisaged narrative for the repository during operations. For example, monitoring of the coupled process behaviour of the repository, and explanation of the results using physics-based conceptual models is one method through which confidence can be gained. In MODATS the use of PIML algorithms for improved modelling of coupled process behaviour has been illustrated using the test cases from Bure (ALC1605) and Mont Terri (FE).

6.3 Confidence in the Guidance Produced in MODATS

In addition to having guidance, tools and methods to develop confidence in monitoring data, there needs to be confidence that these products from MODATS are robust, can be implemented effectively, and reflect good practice. MODATS has ensured that products delivered through the work package are indeed robust, can be implemented effectively and reflect good practice by adopting an inclusive approach encompassing actors from different EURAD colleges and representing a broad range of repository programmes.

MODATS has involved the collaboration of five WMOs, four TSOs, thirteen REs and one CSO. In addition, members of the civil society larger group attended several of the Task 2 and WP meetings. This international perspective meant that MODATS took into account repository programmes across many Member States and Associated Countries, and the views of a broad range of actors.

In addition, the work within the project was able to engage with a broad range of actors to ensure that good practice was taken into account. For example, the development of the guidance on the structure and content of QAPPs was supported through visits to four URLs: Äspö in Sweden, Bure in France, Mol in Belgium and Mont Terri in Switzerland. During these visits, several experts, who were not otherwise engaged in MODATS, provided their experience and expertise through facilitated discussion sessions.

These included principal investigators for experiments and individuals responsible for instrumenting and monitoring of experiments over long periods. Similarly, the development of the Monitoring FEPs catalogue was supported by long-term safety experts from France, Sweden and the UK. A further example of good practice being taken into account was the URL survey, which engaged experts responsible for the design and operation of the systems used for monitoring a wide range of URL experiments.

The work in MODATS also took into account established industry standards as inputs and benchmarks. For example, the development of the QAPP was based on the ISO standard [31], plus guidance from the IAEA [32], the EC [33] and the US EPA [34]. The PEP methodology used for multi-party dialogue was built on the methodology developed and applied within the SITEX project.

The work within MODATS was also grounded in the extensive strategic, technological development and stakeholder engagement activities undertaken in the MoDeRn [4] and Modern2020 projects [5]. For example, the technology roadmap was designed to operate alongside the Modern2020 Screening Methodology (Figure 1-2) and the work on multi-party dialogue commenced with a review of the Stakeholder Handbook developed in Modern2020 [5]. Furthermore, the linking of the outcomes of MODATS to the guidance produced on monitoring by the IAEA provides consistency in approach. Continuity across other international collaborative projects on monitoring helps to demonstrate the fit-for-purpose nature of the work.

The outcomes from MODATS have been extensively reviewed, including internal reviews from the organisations leading each deliverable, internal review on behalf of MODATS by at least two members of the Steering Committee, and external review by mandated actors in EURAD with no direct involvement in MODATS.

7. Conclusions

MODATS has conducted RD&D on monitoring data, including:

- Data acquisition and management.
- The use of the data to enhance system understanding.
- Further development of specific monitoring technologies.
- Consideration of how interactions with civil society on repository monitoring can proceed.

MODATS results can be used to build confidence in monitoring data by contributing to the three purposes of monitoring data recognised by the IAEA [2]:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure:
    - Development of guidance on Quality Assurance Programme Plans (QAPPs).
    - Development of reliable and robust data management processes.
    - Development of the Monitoring Features, Events and Processes (FEPs) catalogue.
- 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:
    - Development of enhanced monitoring technologies, and development of a roadmap for future technology developments.
    - Identification and classification of data anomalies, and development of methods and tools for treating these anomalies.
    - Elaboration of the importance of metadata in interpretation of monitoring results.
    - Enhanced modelling approaches and development of prototype digital twins.
- 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:
    - Multi-party dialogue was undertaken to collect participants views on monitoring, including specific topics associated with monitoring data.
    - Good practice was established in data management:
        - Lessons for repository monitoring were developed in the URL survey, this can be used to demonstrate that good practice has been used in the design and operation of a repository monitoring system.
        - Knowledge management work has contributed to the description and availability of good practice in repository monitoring.
    - Development of open-source tools for data analysis contributes to the provision of traceable and transparent data.
    - The PEP used for multi-party dialogue provides a methodology for engaging with different actors on monitoring.
    - Visualisation can help members of society to develop an understanding of complex data and can support knowledge transfer; good practice in the use of visualisation for these purposes has been demonstrated through the development of digital twins of Mont Terri.

MODATS has provided developments that indicate how confidence in monitoring data can be achieved, and approaches that could be adopted within different programmes. Having an overall robust and reliable approach to the acquisition, management and use of monitoring data is the main way in which confidence can be built. The comprehensive approach adopted in MODATS contributes to this. Good management practices were identified for all aspects of the data lifecycle, including acquisition, management (processing and storage), use of the data (modelling) and communication of the data for decision making. The guidance provided from MODATS is generic and needs to be tailored to specific repository programmes, which respond to their specific boundary conditions. Tailoring the outcomes from MODATS to the specific context of each monitoring programme would provide a sound technical, scientific and sociological basis for developing and maintaining confidence in monitoring data.

Appendix A. MODATS Publications and Presentations

This appendix provides a list of the published and submitted papers and conference presentations on the MODATS work. Full references are provided in the reference list. PLACEHOLDER: This table is under development and a request has been sent to partners for additional information on published papers and conference presentations.

Title	Journal or Conference	Lead Organisation
MODATS – (Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure) [63]	The Role of Optimisation in Radioactive Waste Geological Disposal Programmes	Andra
CHENILLE: Coupled beHavior undErstaNdIng of fauLts: from the Laboratory to the fiEld [64]	EGU General Assembly 2022	GFZ
CHENILLE: Coupled Behavior Understanding of Faults: from the Laboratory to the Field [65]	Advances in Geosciences	GFZ
CHENILLE: the fault-heating experiment in the URL Tournemire (France) [66]	EGU General Assembly 2024	GFZ
Monitoring Lessons for Repositories from Underground Research Laboratory Experiments [58]	Waste Management 2023	GSL
Guidance on Quality Assurance Project Plans for Repository Monitoring [67]	Waste Management 2024	GSL
Confidence in Repository Monitoring Data - Key Results from the MODATS Work Package of EURAD [68]	Geological Disposal of Radioactive Waste	GSL
Combined Radiation and Temperature Effects on Brillouin-Based Optical Fiber Sensors [69]	MDPI Photonics	LHC
Radiation effects on Brillouin-based Sensors: Feasibility of Temperature and Strain Discrimination using LEAF Single-Mode Optical Fiber [70]	Optical Fiber Technology	LHC
Radiation Effects on Brillouin-Based Sensors: Temperature and Strain Discrimination Capability using Telecom-Grade Optical Fibers [71]	European Workshop on Optical Fiber Sensors (EWOFS 2023)	LHC
Geophysical Estimation of the Humidity Distribution in Bentonite by Joint Seismic and Radar Tomography [72]	Submitted to Geophysical Journal International	Nagra and ETH
Features, Events and Processes (FEPs) Analysis of the Interactions between Repository Monitoring Systems and Multi-Barrier Systems [73]	Second International Research Symposium on the Safety of Nuclear Waste Management (safeND)	NWS and GSL
Data-Driven Machine Learning for Disposal of High-Level Nuclear Waste: A Review [74]	Annals of Nuclear Energy	PSI
Machine Learning-Assisted Heat Transport Modelling for Full-Scale Emplacement Experiment at Mont Terri Underground Laboratory [75]	International Journal of Heat and Mass Transfer	PSI

Title	Journal or Conference	Lead Organisation
Performance Analysis of Data-Driven and Physics-Informed Machine Learning Methods for Thermal-Hydraulic Processes in Full-Scale Emplacement Experiment [76]	Applied Thermal Engineering	PSI
Comparison of Physical Informed Neural Network and other Machine Learning Methods for Simulating heat Transport in a Nuclear waste Disposal System [77]	Goldschmidt 2023 Conference	PSI
Machine Learning and Surrogate Models for Studies in Nuclear Waste Management [78]	Data Science for the Sciences	PSI
Prototype of a Virtual Experiment Information System for the Mont Terri Underground Research Laboratory [79]	Frontiers in Earth Science	UFZ
Feels like an Indie Game – Evaluation of a Virtual Field Trip Prototype on Radioactive Waste Management Research for University Education [80]	IEEE CG&A	UFZ
Design-of-Experiment (DoE) based History Matching for Probabilistic Integrity Analysis: A Case Study of the FE-Experiment at Mont Terri [81]	Reliability Engineering and System Safety	UFZ

Appendix B. Tools Developed in MODATS for Data Processing

Org.	Tool	Description	Availability
UFZ	OGS VisCoSiR	OGS VisCoSiR is a tool, that supports domain experts in combining and analysing multiple spatial simulation results, i.e. from different simulation software or conducted with different parameter setups. In contrast to other tools, OGS VisCoSiR focuses on the visual comparison in 3D. It consists of two modules: 1) A combiner, that allows to spatially and temporally combine (i.e., interpolate) the data sets and calculate metrics (like deviation), and 2) an analyser that presents the combination result and allows domain experts to explore the differences and similarities in an interactive, visual way.	The tool is available in a public git-repository: https://gitlab.opengeosys.org/vislab/non-unity-apps/viscosir-cxx
UFZ	Converter for Transforming Measurement Data to VTK Unstructured Grids	In order to make monitoring data available for visualisation, we implemented a python script, that accesses the FEIS database (provided by Nagra) and retrieves temperature measurements for a given list of sensors and dates. In this way, we provide infrastructure for making observation data compatible with OGS tools and scientific visualisation software such as ParaView.	The python script is available under the license GNU GPLv3, and can be accessed online: https://zenodo.org/records/10017852 Graebling (2023). Converter for Transforming Measurement Data to VTK Unstructured Grids. doi:10.5281/zenodo.10017851.
UFZ	Interactive Visualizations: Digital Twin Prototype & Virtual Field Trip	The visualisation applications are prototypes of digital replicas of the Mont Terri URL, that integrate heterogeneous data from several different sources. Both, simulation results and observation data are displayed within the same system.	Because these prototype applications include non-public data sets from external contributors as well as access to non-public external databases, they cannot be made publicly accessible. However, the visualisations are available in form of public videos online: Digital Twin Prototype: https://www.youtube.com/watch?v=X71DF7SG5uc Virtual Field Trip: https://www.youtube.com/watch?v=kH34J9cZ3aI

Org.	Tool	Description	Availability
PSI	# Step 1: Data collection	# Load the temperature data	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 2: Preprocessing and normalization	# 2.1 data prepocessing # define range for S_temperature and T_temperature	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 2: Preprocessing and normalization	# 2.2 Split the data into 70% for training and 30% for validation	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 2: Preprocessing and normalization	# 2.3 data normalization # Normalize the data using the mean and standard deviation of the training set	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 3: Build the Recurrent Neural Network (RNN) model	# Define the neural network architecture	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 4: Train the model	# 4.1 Instantiate the model	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 4: Train the model	# 4.2 Measure CPU and GPU usage after prediction	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 5: Evaluate the machine learning model on the validation set	# Evaluate the model on the validation set	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
PSI	# Step 6: Visualize the results	# Plot the predicted temperature T vs the true temperature T for the validation set # Plot the predicted relative humidity H vs the true relative humidity H for the validation set	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.

Org.	Tool	Description	Availability
PSI	# Step 7: calculate the indicators of MAE, MSE, r-squared	# Unnormalize the validation data sets # Compute the performance metrics for temperature T # Compute the performance metrics for relative humidity H # Print the performance metrics for temperature T # Print the performance metrics for relative humidity H	Currently in the access restricted PSI GitLab repository. Availability will be handled by request.
VTT	preprocessing.py	**Preprocessing and formatting data** Method: create_raw_dataset Creates a unified raw dataset of given csv or xlsx files and selected columns. Informs for each data element from what file it was taken. Drops duplicates.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	format_*.py	**Preprocessing and formatting data** Changes source file-formats to csv, adds column 'timestamp' for timestamps using UNIX epoch time format. In some cases, modifies column names to avoid confusion later. Data sources: Aitemin, Campbell, datataker, fuktlog, extensometer, rock.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	preprocess_*.py	**Preprocessing and formatting data** Uses create_raw_dataset in preprocessing.py to create a unified source-specific dataset from the formatted files.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: get_length_gaps Counts length of gaps in selected columns of data	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: resample_dataframe Changes the sampling rate of data to target sampling rate	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.

Org.	Tool	Description	Availability
VTT	cleaning.py	**Cleaning** Method: clean_analysis_data Creates a data frame without any gaps and resampled to preferred frequency.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: smooth_known_events Smooths out known (manmade) events from given data with interpolation.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: filter_resids Returns found trend and residuals in separate data frames.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: detect_outliers Detects outliers of selected columns individually.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: detect_outliers_group Detects outliers for selected columns as a group.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: identify_spikes Identifies the peaks in timeseries that are considered as spikes	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: peak_widths Detects start and end of identified spikes.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: remove_spikes Smooths the identified spikes. Uses peak_widths.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	cleaning.py	**Cleaning** Method: remove_baseline Removes baselines from given timeseries.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.

Org.	Tool	Description	Availability
VTT	cleaning.py	**Cleaning** Method: detect_correlation_change Tests whether two datasets with the same attributes have differences in correlation.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	Cleaning_pipeline.ipynb	**Jupyter notebooks** Purpose: Cleaning pipeline Example on a cleaning pipeline for a preprocessed dataset utilizing the functionality in cleaning.py.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	Anomaly_detection.ipynb	**Jupyter notebooks** Purpose: Anomalies Example on how anomalies can be detected using the functionality in cleaning.py.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	Drifting.ipynb	**Jupyter notebooks** Purpose: Drifting Example on how drifting can be detected using the functionality in cleaning.py.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	Spikes_detection_removal.ipynb	**Jupyter notebooks** Purpose: Spikes Example on how spikes can be detected and removed using the functionality in cleaning.py	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	RockData_BeforeVsAfterPOPLU_PCAMethod.ipynb	**Jupyter notebooks** Purpose: Rock data analysis Example on how to compare two time periods of high dimensional data: reduction of dimensions, time evolution in reduced space, detecting change visually, separating dominant behaviour and noise.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.
VTT	RockData_BeforeVsAfterPOPLU_StatTests.ipynb	**Jupyter notebooks** Purpose: Rock data analysis Example on basic statistical visualisations and testing for comparing two time periods of sensor data.	Currently in the access restricted VTT GitLab repository. If related WMOs allow the publication, can be released via e.g. GitLab.

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