Deliverable 17.4:
Guidance on Quality Assurance Programme Plans for Repository Monitoring Programmes

Work Package 17 MODATS

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Executive Summary

This document contributes to 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). The focus of the MODATS WP is monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. In particular, MODATS is focusing on confidence in monitoring data.

A Quality Assurance Programme Plan, or QAPP, is a written document outlining the procedures for planning, implementing and assessing a monitoring programme, as well as any specific quality assurance (QA) and quality control (QC) activities. This document contributes to the aims of MODATS by providing generic guidance on the structure and content of a QAPP for repository monitoring systems. It also provides guidance on the production of a QAPP.

The term “QAPP” has been adopted from the guidance on data quality in environmental monitoring provided by the United States Environment Protection Agency (US EPA) which we recognised as the most closely related good practice. However, as the US EPA focus is environmental monitoring, which differs from repository monitoring, other guidance documents with minor differences in the definitions of the terms were also used in this work such as the ISO 9001:2015, the European Statistical System handbook for quality and metadata reports, and the IAEA Technical document (TECDOC) on QA and QC in nuclear facilities.

It is envisaged that each repository programme would tailor the guidance based on this document to their needs and context related to national programme.

The guidance proposes that a QAPP is structured in five sections:

- Organisation of the Monitoring Programme: This section would outline:
  - The monitoring programme objectives, and the strategic approach to it.
  - The processes and parameters to be monitored and the technologies used to do so, as well as the method used to select the process, parameter and technology combinations.
  - The programme schedule.
  - The roles and responsibilities of the actors involved in the programme.
  - The documentation produced.
- Design of the Monitoring System: This section would detail the quality-relevant information on the design of the monitoring system. It would describe the knowledge on which the design of the system is based. It would present Data Quality Objectives (DQOs) for sensors and requirements for other components of the monitoring system, selection procedures for specific technologies (i.e., particular sensors), and procedures and protocols for describing the monitoring system layout.
- Implementation of the Monitoring System: This section would cover the practical implementation of the monitoring system from installation to decommissioning. It would include the procedures for equipment deployment, calibration, and maintenance.
- Checking Monitoring Data: This section would describe methods for verification and validation of monitoring data to ensure they meet the DQOs. It would encompass QA and QC aspects relating to data storage, treatment and management, and would outline processes and procedures that cover data QA measures including periodic data audits. Adherence to the procedures and protocols identified in this section would ensure the effective execution of the monitoring activities according to the established design and protocols.
- Feedback to the Monitoring Programme: This section would describe procedures and protocols related to the modification or change of the monitoring programme during its operation. It would describe the processes for proposing, agreeing, and implementing monitoring programme changes, including consultation with regulators and stakeholders during the decision-making process. The feedback section may also address continuous improvement strategies, lessons

learned, and adjustments to the monitoring programme based on the requirements of the safety case, stages in repository implementation and stakeholder input.

Examples of good practice quality processes from underground research laboratory experiments are also included to illustrate the guidance provided in this document.

The guidance in this document envisages that a QAPP would act as a gateway to a document management system that would be used to store and access the procedures and protocols to be followed during the design, installation, operation and decommissioning of the repository monitoring programme.

It is proposed that a QAPP is developed at the earliest stage in a repository programme to ensure that all work undertaken in designing and implementing the monitoring programme are undertaken in a quality-assured manner.

A repository monitoring programme is subject to specific QA issues owing to the long-time duration envisaged for the programme and the potential that some monitoring equipment may not be accessible for maintenance or replacement following installation. The guidance in this document addresses these challenges by:

- Covering the full life cycle of the repository monitoring programme and providing approaches whereby quality can be at the centre of all decisions throughout the life cycle of the programme.
- Placing an emphasis on using knowledge gained from successfully operating URL experiments and undertaking site investigations, and thereby ensuring that the design of the monitoring system will provide the necessary quality of data from the outset.
- Identifying the need for the repository monitoring programme to be appropriately defined at the outset.
- Recording decisions in a transparent and traceable manner.
- Identifying tools that can be used to check plans and ensure transparency and traceability.
- Proposing that the monitoring programme is actively managed.

Therefore, the guidance on QAPPs provided in this document offers a framework for addressing the challenges posed by repository monitoring. By structuring a QAPP into five main sections and offering flexibility in its implementation, waste management organisations and 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 monitoring programmes remain effective, credible, and beneficial over the entire duration of repository operations.

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Glossary of Quality Terminology

This glossary is based on the glossary of quality assurance (QA) and related terms developed by the United States (US) Environmental Protection Agency (EPA), which introduced and developed the concept of a QA programme[1] plan (QAPP) for controlling operations related to environmental monitoring data[2]. The definitions provided by the US EPA have been modified to be applicable to repository monitoring.

Quality	The totality of features and characteristics of a product or service that bear on its ability to meet the stated or implied needs and expectations of the user.
Quality Management	That aspect of the overall management system of the organisation that determines and implements the quality policy. Quality management includes strategic planning, allocation of resources, and other systematic activities (e.g., planning, implementation, documentation, and assessment) pertaining to the quality system.
Quality Management System	A structured and documented management system describing the policies, objectives, principles, organisational authority, responsibilities, accountability, and implementation plan of an organisation for ensuring quality in its work processes, products (items), and services. The quality system provides the framework for planning, implementing, documenting, and assessing work performed by the organisation and for carrying out required QA and QC activities.
Quality Management Plan	A document that describes a quality system in terms of the organisational structure, policy and procedures, functional responsibilities of management and staff, lines of authority, and required interfaces for those planning, implementing, documenting, and assessing all activities conducted.
Quality Assurance	An integrated system of management activities involving planning, implementation, documentation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the client.
Quality Control	The overall system of technical activities that measures the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer; operational techniques and activities that are used to fulfil requirements for quality.
Quality Assurance Programme Plan	A document describing in comprehensive detail the necessary QA, QC, and other technical activities that must be implemented to ensure that the results of the work performed will satisfy the stated performance criteria.

[1] The US EPA uses the term Quality Assurance Project Plans; in this document we have used “programme” in place of “project”, as explained within the discussion of the scope of the document.
[2] United States Environmental Protection Agency (2001). EPA Requirements for Quality Assurance Project Plans. EPA QA/R-5.

Acronyms

DAS:	Data acquisition system
DMP:	Data management plan
DQO:	Data quality objective
EPA:	Environmental Protection Agency
EURAD:	European Joint Programme on Radioactive Waste Management
FAIR:	Findable, Accessible, Interoperable and Reproducible
FE:	Full-Scale Emplacement
GSL:	Galson Sciences Limited
HADES:	High Activity Disposal Experimental Site
HLW:	High-level waste
HRL:	Hard Rock Laboratory
IAEA:	International Atomic Energy Agency
ISO:	International Organization for Standardization
IT:	Information technology
MODATS:	Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure
PDCA:	Plan-Do-Check-Act
PF:	Progressive Failure
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
RD&D:	Research, development, and demonstration
TECDOC:	IAEA Technical Document
TSO:	Technical support organisation
URL:	Underground research laboratory
US:	United States
WMO:	Waste management organisation
WP:	Work package

1. Introduction

1.1 Background

Repository monitoring will be used to support the development of safety cases by providing further understanding of system behaviour, will check that actual conditions are consistent with the assumptions made for safety after closure, and will be used to demonstrate compliance with regulatory requirements and conditions. Monitoring and management of the acquired data can also be used to support engagement with stakeholders. Monitoring will support decision making, help to build further confidence in geological disposal, and contribute to optimisation of the disposal system.

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) is conducting research, development and demonstration (RD&D) into: monitoring data acquisition, treatment and management; use of monitoring data to enhance system understanding, including development of digital twins; interactions with Civil Society and other stakeholders; development of monitoring technologies; and development of knowledge regarding repository monitoring. MODATS is building on previous international collaborative RD&D activities, including a European Thematic Network [1], and the MoDeRn [2] and Modern2020 [3] projects.

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

- AHA1605/ALC1605: A demonstration of the reference disposal concept for high-level waste (HLW) led by Andra in the Bure URL, France.
- The Full-Scale Emplacement (FE) experiment: The FE experiment investigates thermal-hydro-mechanical coupled processes at full scale, in repository-like conditions 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 (Äspö HRL).
- Preliminary Demonstration Test for CLAY Disposal (PRACLAY): 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 the MODATS WP is monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. In particular, MODATS is focusing on confidence in monitoring data.

A Quality Assurance Programme Plan (QAPP) documents the planning, implementation, and assessment procedures for a particular monitoring programme, as well as any specific quality assurance (QA) and quality control (QC) activities. It integrates all the technical and quality aspects of the programme in order to provide a "blueprint" for obtaining the type and quality of monitoring data and information needed for a specific decision or use.

The United States (US) Environmental Protection Agency (EPA) introduced and developed the concept of a QAPP for controlling operations related to environmental monitoring performed by, or for, the US

EPA [4]. This concept has been developed for all environmental programmes funded by the US EPA that acquire, generate, or compile environmental data. The term has been adopted by the MODATS WP of the EURAD programme, as the US EPA blueprint for a QAPP represents good practice in the management of monitoring programmes.

1.2 Objectives

The objectives of this report are to provide high-level guidance on the structure and content of a QAPP for repository monitoring systems, and to provide examples of good practice based on the MODATS Reference Experiments and other URL experience. It also provides guidance on the production of a QAPP. The guidance is generic in nature and defines a possible way in which the quality of a monitoring programme could be implemented and documented.

1.3 Scope and Audience

Each repository programme will follow an overarching quality management system, and related QA and QC procedures that will relate to all activities in the repository programme. However, repository monitoring will require additional specific processes and procedures, which will be developed within the monitoring programme. The primary audience of this document is the staff responsible for the monitoring programme as further discussed in Section 2, and the document has been prepared with this audience in mind.

The guidance in this document should also be of use for other audiences:

- Research Entities: Staff in research entities might wish to use the guidance in this document to plan monitoring work.
- Regulators and Technical Support Organisations (TSOs): Regulators and staff in TSOs might wish to use the guidance in this document as part of their activities in reviewing WMO programmes.
- Other Stakeholders: Other stakeholders, including members of Civil Society, may wish to use the guidance in this document to develop a greater understanding of the contribution of QA to developing confidence in monitoring data.

In most repository programmes, monitoring plans are under development (see for example [5]). Each monitoring programme will respond to a range of different programme-specific constraints and drivers, including the relevant regulations, the nature and quantities of the wastes to be disposed, the geological environment in which the repository will be located, the design of the facility, the expected inputs from monitoring to decision-making processes, and the role of stakeholder engagement within the repository programme. In this document, it is envisaged that these constraints and drivers will feed into the monitoring programme via the safety case, including the use of monitoring information to strengthen understanding of some aspects of system behaviour used in developing the safety case and to provide information for decision making (see guidance on the development of monitoring programmes provided by the International Atomic Energy Agency (IAEA) [6]).

Some repository programmes may develop an extensive monitoring programme, including monitoring of the near field using multiple technologies. Technologies for monitoring the near field might include point sensors, fibre optic systems and geophysical methods (e.g. seismic tomography). In contrast, other repository programmes might focus on monitoring of the geosphere and environment using borehole-based and surface-based methods, such as groundwater pressure monitoring and monitoring of seismicity (see for example [7]). Programmes that incorporate monitoring of different components of the multi-barrier system or different types of processes might break the programme into sub-programmes or specific monitoring projects.

In addition, it is recognised that the focus of a repository monitoring programme is likely to evolve during its operation. In the early stages of the programme the focus might be on establishing baseline

conditions and supporting repository design. In later stages the focus may be more on strengthening system behaviour, checking conditions and demonstrating compliance with licence conditions. This means that the monitoring programme might focus on different objectives and different stakeholders throughout its lifecycle.

The product of a monitoring programme is the monitoring data that is used to support other activities with the repository programme. However, the focus of the QAPP is not only the data that is acquired through the monitoring programme, but also the documentation that demonstrates the quality of the data. This document also describes some of the activities in managing data prior to its use in the wider repository programme, as these activities might be undertaken by the staff responsible for the monitoring programme, or involve monitoring experts. Each repository programme will decide on the boundaries of the repository monitoring programme (and this would be defined in the relevant QA documentation).

The guidance in this document is relevant to all monitoring programmes. Owing to the differences between programmes, the document does not provide a fixed recipe for developing QAPPs (for example suggestions regarding the types of documents that could be produced, and the roles and responsibilities of staff, are provided as examples and not as fixed solutions to be followed by each organisation). In addition, as any monitoring programme QAPP will fit into a wider quality management system (QMS) for the repository programme, and this may influence the manner in which the quality of the monitoring programme is assured.

As noted in the objectives, the aim is to provide high-level guidance. In particular, the guidance in this document is intended to address quality issues specific to repository monitoring, especially ones in which there are novel aspects compared to current standard monitoring activities. These are primarily associated with monitoring of the near field during the operation of the repository, but many novel issues for repository monitoring are also relevant to programmes focused on monitoring of the geosphere and the surface environment, and monitoring to establish baseline conditions or to support repository design. Novel issues include:

- Repository monitoring could be conducted for several decades following emplacement of the waste and the associated buffer/backfill. There will be, therefore, the potential for the monitoring system to fail, sometimes in unpredictable ways. The QAPP will need to identify procedures for checking for monitoring system failure.
- During the long timeframes over which a monitoring programme will be conducted, there will be changes in staff and a need to manage knowledge effectively, e.g., to document decision making during monitoring programme design.
- The long timeframes also mean that there is likely to be developments in technology, both in terms of the monitoring equipment that is available to acquire data, and also the software that is available for data treatment, management and analysis. A QAPP needs to ensure that data acquired during the early stages of the monitoring programme are available in the later stages of the programme.
- Over the lifetime of the monitoring programme, future generations may focus on different objectives, and a QAPP will need to provide flexibility in managing the requirements on the monitoring programme.
- The monitoring programme may use a combination of *in situ* and remote monitoring technology, where *in situ* technology refers to monitoring where the sensor is in contact with the medium being monitored, and remote refers to monitoring where the sensor is positioned in a different location to the medium being monitored. In the majority of cases, it will not be possible to access and maintain *in situ* sensors. Therefore, repository monitoring programmes should implement QA procedures that account for the inaccessibility of some monitoring technologies.

1.4 Methodology to Develop the Guidance

In this document, guidance on QA during repository monitoring has been developed through review of lessons learned from monitoring of URL experiments, review of literature on QA during monitoring, and by collective discussion amongst the partners in the MODATS WP. Initially, the high-level structure of this guidance was developed by reviewing the US EPA QAPP documentation [4] and consideration of its application in a repository monitoring programme context. More specific guidance was developed following visits to URLs. During these visits, discussions were held on overall approaches to quality management with relevant repository programmes and specific aspects of quality management related to individual experiments. Three URL visits were undertaken:

- Mont Terri: Thomas Haines and Matt White of Galson Sciences Limited (GSL) visited Mont Terri on 27-28 October 2022. Discussions were held with David Jaeggi (Swisstopo), manager of the Mont Terri URL; Klaus Wieczorek (GRS), Principal Investigator for the Sandwich Experiment [8]; Martin Ziegler (ETH Zurich), Principal Investigator for the Progressive Failure (PF) Experiment [9]; and Senecio Schefer (Swisstopo), a geologist working on the PF Experiment.
- Äspö HRL: Thomas Haines and Matt White visited Äspö on 23-24 May 2023. Discussions were held with Lars Andersson, Thomas Andolfsson, Pär Grahm and Mansueto Morosini (SKB), and Reza Goudarzi (Clay Technology), covering the QMS developed for experiments at Äspö, and the QA procedures applied during the Prototype Repository [10], the Dome Plug (DOMPLU) [11,12, 13] and the POPLU [14, 13] experiments in the framework of the Full-Scale Demonstration of Plugs and Seals (DOPAS) [15] project.
- Bure: Yannick Caniven, Thomas Haines, Chris Harbord and Matt White visited Bure on 12-14 June 2023. Discussions were held with Johan Bertrand, François Leveau and Phillipe Tabani (Andra) covering the QMS used by Andra for experiments at Bure, the QA procedures applied during the AHA1636 demonstrator and observing the application of QA procedures during monitoring equipment installation in the AHA1635 demonstrator.

In addition, the guidance presented in this document was discussed and further developed by MODATS partners at meetings held at Baden in Switzerland (1-2 February 2023), Espoo in Finland (31 May - 2 June 2023), and Leuven in Belgium (19-20 September 2023).

1.5 Report Structure

The next section of this report (Section 2) discusses the framework in which a repository monitoring programme QAPP is likely to sit and develops a generic structure for a repository monitoring QAPP. The subsequent sections of the report provide guidance on quality issues for each aspect of the generic structure in turn:

- Section 3 provides guidance on the content of a QAPP on organisation of the monitoring programme.
- Section 4 provides guidance on the content of a QAPP on designing the monitoring system.
- Section 5 provides guidance on the content of a QAPP on implementing the monitoring system.
- Section 6 provides guidance on the content of a QAPP on checking the monitoring data.
- Section 7 provides guidance on the content of a QAPP on feedback to the monitoring programme.
- Section 8 provides guidance on the production of QAPPs for repository monitoring.
- Section 9 provides a summary of the guidance in the document, including a discussion of how the guidance addresses quality issues specific to repository monitoring.

It is recognised that the level of detail in the guidance provided in these sections may vary because of the relative immaturity of some aspects of repository monitoring (e.g., procedures for the use of monitoring results in stepwise decision-making during implementation).

2. Quality Management and Quality Systems

This section provides the context on the development and maintenance of a QAPP for a repository monitoring programme:

- Section 2.1 provides a high-level overview of quality management.
- Section 2.2 describes other documentation that might be produced in a repository monitoring programme.
- Section 2.3 develops a generic structure for a repository monitoring programme QAPP, which is then used in the remainder of this document to provide guidance on the content and production of a QAPP.

2.1 Quality with a Repository Programme

International Organization for Standardization (ISO) 9001:2015 [16] is the most widely used quality management system (QMS) standard and defines the requirements for a QMS that would enable an organisation to manage their processes and systems whilst ensuring that customer and other stakeholder requirements can be achieved. It applies to any organisation, regardless of size or industry. More than one million organisations from more than 160 countries have applied the ISO 9001 standard requirements to their QMS. More specific QA and QC guidance for nuclear facilities has been provided by the IAEA, who published technical document (TECDOC) 1910 on QA and QC in nuclear facilities in 2020 [17]. IAEA TECDOC 1910 notes that definitions of the terms such as quality, quality management, QA and QC are evolving and that there are several definitions in use. The definitions and concepts provided in the European Statistical System (ESS) Handbook for Quality and Metadata Reports [18] are also considered. The definitions provided by ISO 9001:2015 and the IAEA, and in the ESS handbook, are consistent with the definitions provided by the US EPA in their guidance on QAPPs.

This section considers all three sets of guidance to provide a description of the quality framework within which a QAPP might sit in a specific repository programme. Figure 2-1 illustrates how different components of a quality framework could interact. These components are described below.

Quality is defined by the US EPA as “the totality of features and characteristics of a product or service that bear on its ability to meet the stated or implied needs and expectations of the user” [4]. Quality is, therefore, closely linked to the requirements that are placed on the product or service.

Quality management is “that aspect of the overall management system of the organisation that determines and implements the quality policy. Quality management includes strategic planning, allocation of resources, and other systematic activities (e.g., planning, implementation, and assessment) pertaining to the quality system” [4].

A QMS is a “structured and documented management system describing the policies, objectives, principles, organisational authority, responsibilities, accountability, and implementation plan of an organisation for ensuring quality in its work processes, products (items), and services. The quality system provides the framework for planning, implementing, documenting, and assessing work performed by the organisation and for carrying out required QA and QC activities”. The QMS will include a quality management plan, which is an overarching organisational quality document that describes a quality system in terms of the organisational structure, policy and procedures, functional responsibilities of management and staff, lines of authority, and required interfaces for those planning, implementing, documenting, and assessing all activities conducted.

ISO 9001:2015 [16] recognises the benefits of implementing a QMS based on ISO 9001:2015 as being:

- The ability to consistently provide products and services that meet customer, and applicable statutory and regulatory requirements.
- Facilitating opportunities to enhance customer satisfaction.
- Addressing risks and opportunities associated with its context and objectives.

- The ability to demonstrate conformity to specified quality management system requirements.

Figure 2-1 – Schematic diagram illustrating the relationship between the key quality terminology used in this report. Blue rectangles: Quality concepts; Green rectangles: Produced documents. Black arrows indicate how the quality concepts contribute to each other and feed into the documents.

ISO 9001:2015 employs a process approach, which incorporates the Plan-Do-Check-Act (PDCA) cycle and risk-based thinking (Figure 2-2). The process approach enables an organisation to plan its processes and their interactions. The PDCA cycle enables an organisation to ensure that its processes are adequately resourced and managed, and that opportunities for improvement are determined and acted on.

It is assumed herein that a WMO will have a QMS that will define the general approach to QA and QC for the repository monitoring programme, and also the requirements managements system [19] that will be used to define the specific needs of the monitoring programme. These specific needs will be reflected in the requirements placed on the monitoring system, such as Data Quality Objectives (DQOs). DQOs provide statements about the expectations and requirements of the data user. DQOs need to be translated into measurement performance specifications to satisfy data user's needs.

QA is defined by the US EPA as “an integrated system of management activities involving planning, implementation, documentation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the client” [4].

QC is defined by the US EPA as “the overall system of technical activities that measures the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer; operational techniques and activities that are used to fulfil requirements for quality” [4].

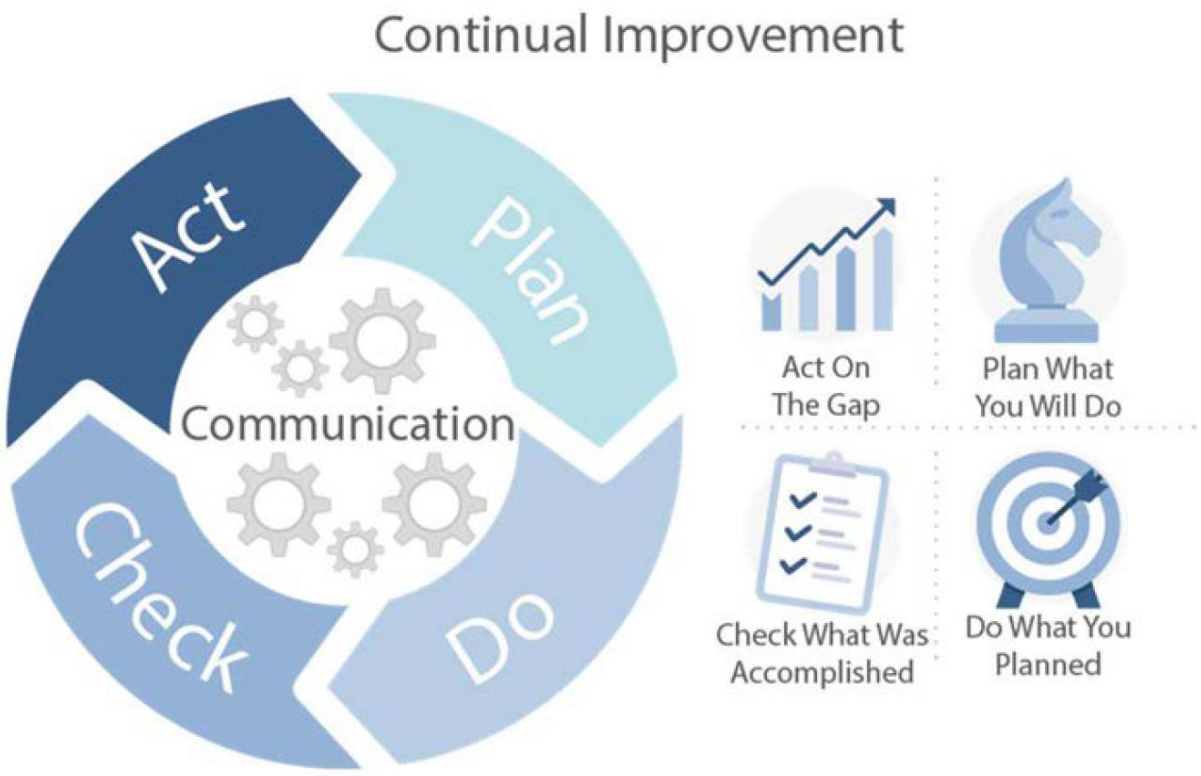


Figure 2-2 – The PDCA cycle. From [17].

The US EPA considers that a QAPP is the critical planning document for any environmental data collection operation because it documents how QA and QC activities will be implemented during the life cycle of a programme (e.g., a repository monitoring programme) [4]. A QAPP is the blueprint for identifying how the quality system of the organisation performing the work is reflected in a particular programme and in associated technical goals. US EPA guidance states that, in order to obtain environmental data for decision making, a programme should be conducted in three phases: planning, implementation, and assessment [4, 20] (Figure 2-3). The first phase involves the development of DQOs using a systematic planning process. In the second phase, a QAPP translates these requirements into measurement performance specifications and QA/QC procedures for the *data suppliers* to provide the information needed to satisfy the data user's needs. Once the data have been collected and validated in accordance with the elements of the QAPP, the data should be evaluated to determine whether the DQOs have been satisfied. In the assessment phase, statistical tools are used to determine whether the data meet the assumptions made during planning and whether the total error in the data is small enough to support a decision within tolerable decision error rates expressed by the decision maker. This requires that plans for data validation are included in the QAPP. Thus, the activities addressed and documented in a QAPP cover the entire programme life cycle, integrating elements of the planning, implementation, and assessment phases.

The process approach advocated in ISO 9001:2015 and by the US EPA in their guidance on QAPPs, is adopted in this guidance document for repository monitoring programmes, with specific adaptations or increased emphasis to address the unique aspects of repository monitoring. Many of the approaches are also relevant to the wider repository programme and hence the approach here is both overarching and specific to monitoring programmes. The proposed structure of a repository monitoring QAPP is defined in Section 2.3. First, the relationship of the repository monitoring QAPP to other documentation describing the monitoring programme is discussed in Section 2.2.

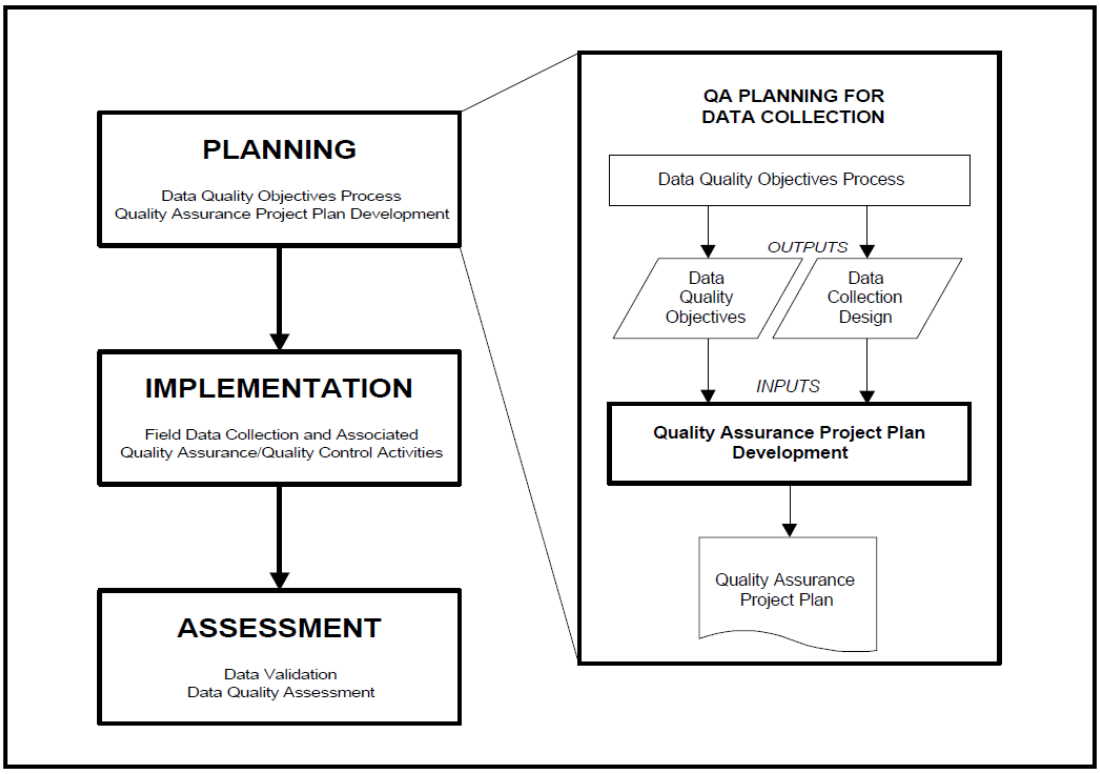


Figure 2-3 – QA planning and the data life cycle. From [20].

2.2 High-Level Monitoring Programme Documentation Hierarchy

It is envisaged herein that a repository monitoring QAPP would form part of a hierarchy of documentation describing the monitoring programme (Figure 2-4). This hierarchy of documentation would link to other documents within the repository programme, including the safety case (a repository monitoring programme will be driven by the needs of the safety case), the wider QMS of the organisation and for some cases (e.g. France) by a requirement for reversibility. The hierarchy of documentation proposed herein (Figure 2-4) is generic, and would have to be tailored to the needs of the specific programme. The proposed hierarchy, which is described in detail below, consists of:

- A Monitoring Programme Strategy document, which would define the general locations where monitoring might be undertaken (e.g., in a pilot repository); the processes to be monitored, and the parameters and technologies used to do so; and the use of the monitoring data in decision making.
- A Monitoring System Design document, which would define the sensors, their specific locations, and the DQOs.
- A Monitoring System As-Built document that would describe the actual implementation of the monitoring system, which may vary from the Monitoring System Design owing to, for example, operational challenges.
- A QAPP, which would identify the QA and QC procedures and protocols to be followed throughout the monitoring programme life cycle, and would provide links to the procedures and protocols.
- Monitoring Data Flow and Information Technology (IT) Architecture Plan[3] (one of the documents identified and referenced in the QAPP), which would describe the procedures and protocols for all data extraction, handling, processing and importing activities, as well as description of the IT architecture used (including both hardware and software).

[3] Also referred to as Data Management Plans, see discussion in Section 6.

- Monitoring Programme Audits, which would document checks of the performance of the monitoring programme against the QAPP.
- Monitoring Programme Operation and Results, which would document the integrated outcomes from the monitoring programme.
- Monitoring System Maintenance Plan, which would describe the activities required to keep the monitoring system functioning.
- Monitoring Data Report(s), which document the data acquired through the monitoring programme.

US EPA guidance on QAPPs envisages that a QAPP "should be detailed enough to provide a clear description of every aspect of the project" [20]. There will, therefore, be overlaps within the proposed documentation, and it is likely that a QAPP will need to summarise information from other documents. Further information on these overlaps, and guidance on how much information needs to be summarised, is provided in Sections 3-7.

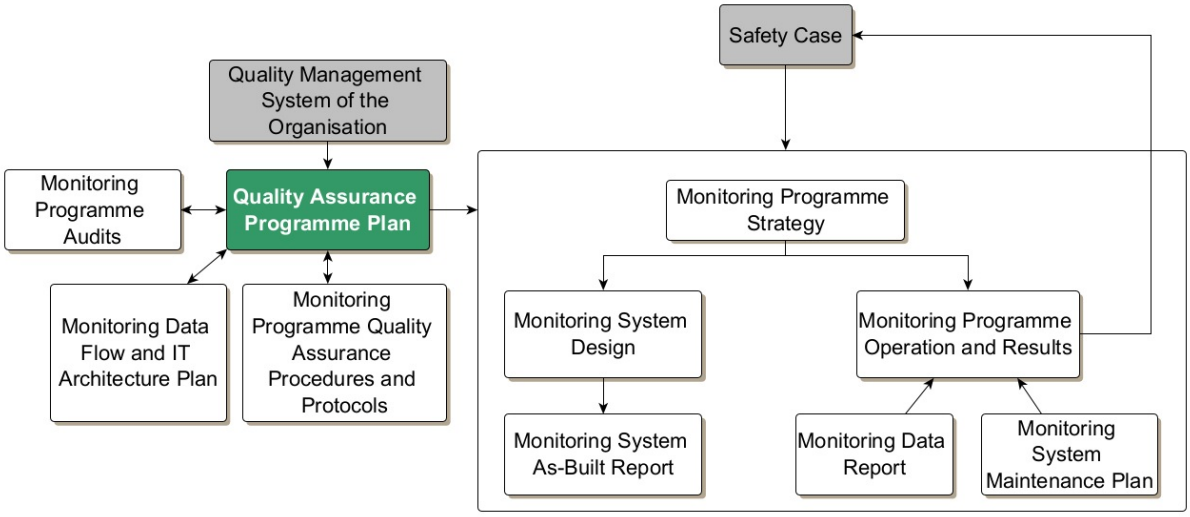


Figure 2-4 – Proposed structure of monitoring programme documentation for a repository monitoring programme. The QAPP is highlighted in green. Grey-coloured documents (or suites of documents), including the Safety Case and the QMS, provide overall requirements on the monitoring programme regarding the repository programme quality management.

The document hierarchy illustrated in Figure 2-4 is not a workflow or a representation of the evolution of the monitoring programme. However, it is consistent with the PDCA cycle discussed in Section 2.1, whilst reflecting the iterative nature of a repository monitoring programme. This iterative nature has been recognised by the IAEA; plans for monitoring, especially during the operational period, "have to remain flexible and, if necessary, they will have to be revised and updated during the development and operation of the facility" [21]. At the start of the repository monitoring programme, planning aspects are captured in the strategy and design documents, and the QAPP. The "doing" of the programme is reflected in the As Built and Data Reports documents, whilst "checking" is captured in the Operation and Results document. This guidance recognises the Safety Case as the primary driver for the monitoring programme during the operational period (see the scope in Section 1.3), and, therefore, "acting" on the outcomes from the programme is captured through use of the outcomes in updates to the safety case, which could feed into revisions to the documents within the hierarchy leading to a further cycle in the iterative repository monitoring programme.

The contents of each document in the proposed structure of monitoring programme documentation are described below.

A *Monitoring Programme Strategy document*, which would provide a high-level overview of the monitoring programme and how it responds to the requirements on it. This document would provide the strategic considerations and decisions made regarding the overall monitoring strategy, such as the

locations in which monitoring would be undertaken, the processes to be monitored and the parameters used to do so, and the types of technology to be used. This is consistent with guidance developed in the MoDeRn [2] and Modern2020 [3] projects, which identified structured methodologies for the identification of processes, parameters and technologies for monitoring that were dependent on the strategic approach to monitoring adopted by a WMO and the national context of the programme. A Monitoring Programme Strategy document would link to the safety case, which would describe uncertainties and the approach to managing these uncertainties, which might include monitoring. As relicensing or regulatory milestones approach, a Monitoring Programme Strategy document could undergo revisions to reflect updated requirements, advancements in monitoring technologies, or insights gained from previous monitoring activities.

A *Monitoring System Design* document would specify the DQOs and the type of sensors to be used and their locations. Sensor selection would respond to the DQOs, considering factors such as data accuracy, precision, and reliability. A Monitoring System Design document would serve as a blueprint for the planned implementation and operation of the monitoring programme.

A *Monitoring System As-Built* document would provide a description of the actual implementation of the monitoring system, which may vary from the design (for example, owing to operational challenges). However, as it depends on the programme needs, the as-built document is not prescriptive and does not provide a unique solution. An alternative to producing a Monitoring System As-Built document would be to issue a revised Monitoring System Design document following the installation of the monitoring system. Over time, the Monitoring System Design document or Monitoring System As-Built document would be periodically updated as changes or modifications are made to the monitoring system (for example, to incorporate advancements in monitoring technologies, lessons learned from previous monitoring activities, or to reflect evolving safety case requirements). These updates would ensure that the report accurately reflects the current configuration and operational status of the monitoring system.

A QAPP would describe the QA and QC procedures to be followed throughout the monitoring programme life cycle. As the monitoring programme evolves, a QAPP would be periodically reviewed and updated to ensure that it remains relevant and aligned with the changing needs and objectives of the programme. These updates may be driven by regulatory requirements, advancements in monitoring technologies, or lessons learned from previous monitoring activities. By updating a QAPP, the monitoring programme could incorporate the latest good practices, methodologies, and quality management approaches, thereby maintaining the highest standards of data quality and integrity.

A QAPP would include explicit links to the organisational QMS, which would provide the overall requirements on the monitoring programme, and procedures and protocols regarding the repository programme quality management. The organisational QMS could also link to other monitoring programme documents where these documents describe aspects linked to quality.

There will be many procedures and protocols that will be followed to ensure quality in the repository monitoring programme. It is not envisaged that all of these procedures and protocols would be included in a QAPP. Instead, it is envisaged that a QAPP would act as a portal to a document management system containing the protocols and procedures. This concept is elaborated further throughout this document.

A Monitoring Data Flow and IT Architecture Plan would be one of the documents referenced by the QAPP and would describe the data handling processes, including references to specific guides describing each data handling action required in order to establish a functioning monitoring data flow. The plan would also describe the IT architecture, on which the monitoring data flow and handling/processing systems are based on, including both hardware and software.

A *Monitoring Programme Audit* document would report the results from periodic evaluations of the performance of the monitoring programme, including audits of the data and database, against the established QAPP. As the monitoring programme progresses and associated technologies evolve, the audit report would be updated to reflect the current state of the programme and ensure ongoing

compliance with the QAPP and regulatory requirements. These updates may include incorporating new audit methodologies, expanding the scope of audits, or refining the criteria for evaluating the programme's effectiveness. The relationship between the audits and the safety case would lie in their role in providing independent assessments of the monitoring programme's performance, reliability, and adherence to quality standards.

A *Monitoring Programme Operation and Results* document would summarise the operation of the monitoring programme and the results obtained from it. This would cover the experience of conducting monitoring and implementing the Maintenance Plan, as well as the results of the monitoring. The document would be published according to a regular schedule (e.g., yearly).

A *Monitoring System Maintenance Plan*, which would feed into the Monitoring Programme Operation and Results document, would describe the activities to be undertaken in the next period of the monitoring programme to ensure its successful functioning. These could include, for example, recalibration of sensors, changes to power consumption, or computer software and hardware upgrades. The outcome of these activities would be reported in the Monitoring Programme Operation and Results document during each periodic update.

Monitoring Data Report(s) would provide the detailed results from the programme. Depending on the programme, separate reports might be provided for specific monitoring disciplines (e.g., rock mechanics, hydrogeology and hydrochemistry). These reports would feed into the Monitoring Programme Operation and Results document.

Updates to all of these documents are likely to align with periodic updates to the safety case (including the safety assessment and their underpinning models), ensuring that the monitoring system remains consistent with the safety case arguments, helping to meet relicensing and regulatory milestones. Together, these documents support decision making, stakeholder engagement, and the long-term safety of the disposal system.

2.3 The Contents of a Repository Monitoring Programme QAPP

As indicated above, a repository monitoring programme QAPP is a tool to ensure the quality of monitoring data, and thereby to help build confidence in monitoring data. It utilises the PDCA principle. It covers the entire monitoring programme life cycle in the repository. It will consider quality relating to:

- Planning, designing, installing, and testing the monitoring system.
- Checking the monitoring data adheres to Findable, Accessible, Interoperable and Reproducible (FAIR) principles for scientific data [22], if considered appropriate to the WMO programme.
- Evaluating monitoring data to ensure it fulfils monitoring data objectives.
- Responding to the monitoring data evaluation.

A QAPP should be considered a document that is periodically updated and revised according to installation, testing, and operations of the monitoring system.

Building on the structure of monitoring programme documentation proposed in Section 2.2, a repository monitoring programme QAPP could be structured into five parts:

- Organisation of the monitoring programme (see Section 3).
- Design of the monitoring system (see Section 4).
- Implementation of the monitoring programme (see Section 5).
- Checking monitoring data (see Section 6).
- Feedback to the monitoring programme (see Section 7).

Table 2-1 provides some information on the contents of each of these sections of a repository monitoring QAPP. Guidance on the content of each section is provided in Sections 3-7.

Table 2-1 – Key contents of the sections of a repository monitoring QAPP.

Sections	Key Contents	Benefits
Organisation of the Monitoring Programme	This section would summarise the monitoring programme objectives, the processes to monitor, their associated parameters and the monitoring techniques envisaged, the roles, responsibilities, and coordination protocols among the stakeholders involved, the monitoring programme schedule and the processes used to generate documents.	This section would provide a common understanding of the repository monitoring programme and describe expectations on all actors within the programme.
Designing the Monitoring System	This section would summarise the quality-relevant information on the design of the monitoring system, including the knowledge used in design, the requirements on monitoring system equipment, the procedures used to select monitoring equipment, and instructions for describing the monitoring system layout.	This section would identify the procedures and protocols used to ensure that the monitoring system is set up to generate data of the required quality.
Implementing the Monitoring Programme	This section would identify the procedures and protocols used for data collection, equipment deployment, calibration, and maintenance. It may also encompass data storage, management, and QC measures. It ensures the effective execution of the monitoring activities according to the established design and protocols.	This section would ensure the effective execution of the monitoring activities according to the established design and procedures and protocols.
Checking the Monitoring Data	This section would include a periodic evaluation of the monitoring system. It would identify procedures and protocols used for verification and validation of monitoring data to ensure their quality, accuracy, and completeness. The procedures and protocols would be applied during data treatment and data management, and implementation of QA measures such as periodic data audits.	This section would help to ensure that the collected data are accurate, complete, and reliable.
Feedback to the Monitoring Programme	This section would identify procedures and protocols used for modification or change of the monitoring programme during repository operation. The section would describe the processes for proposing, agreeing, and implementing monitoring programme changes, including consultation with regulators and stakeholders during the decision-making process. The feedback section may also address continuous improvement strategies, lessons learned, and adjustments to the monitoring programme based on operational experience and stakeholder input.	This section would provide the basis for decisions to be made to change the repository monitoring programme over time, ensuring it remains effective and relevant, and promoting transparency and compliance with any necessary changes.

3. QAPP Content on Monitoring Programme Organisation

This section summarises guidance on the organisation of the monitoring programme. It is envisaged that this chapter of a QAPP will include relevant contextual information from the Monitoring Strategy document and provide information on roles and responsibilities, and on documentation. The purpose of summarising the information from the strategy document would be to provide the appropriate context to the quality information presented elsewhere in the QAPP. Five sub-sections are envisaged:

- Monitoring objectives (Section 3.1).
- Monitoring processes, parameters, and technologies (Section 3.2).
- Monitoring schedule (Section 3.3).
- Monitoring roles and responsibilities (Section 3.4).
- Monitoring Documents Supporting the High-Level Hierarchy (Section 3.5).

3.1 Monitoring Objectives

This section of a QAPP would describe the overall purpose of the monitoring programme. This would include: the role of the monitoring programme in periodic updates to the safety case and in stages in the licensing of the repository; how the programme responds to regulatory requirements; and how the programme satisfies other stakeholder requirements if identified. It would not be necessary for a QAPP to document the development of the objectives and their associated sub-objectives in detail, as this would be done in the Monitoring Strategy. Instead, it is envisaged that a QAPP would reference the Monitoring Strategy and state the objectives and sub-objectives succinctly.

Guidance on the development of monitoring programmes provided by the IAEA [6] and the European Commission [1] includes discussion of general requirements on monitoring and how monitoring can support the implementation of geological disposal in a broad sense. Further guidance on how monitoring might be integrated within a repository programme was developed in the MoDeRn project, which proposed a *Monitoring Reference Framework* [23]. The reference framework identifies and discusses relevant issues that need to be considered during the development of a comprehensive monitoring programme, and describes feasible monitoring activities, highlights technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders. The advice is illustrated by the MoDeRn Monitoring Workflow (Figure 3-1), which is a structured approach to developing, implementing and operating a monitoring programme.

The MoDeRn project recognised four fundamental Main Objectives [2] (Figure 3-2):

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

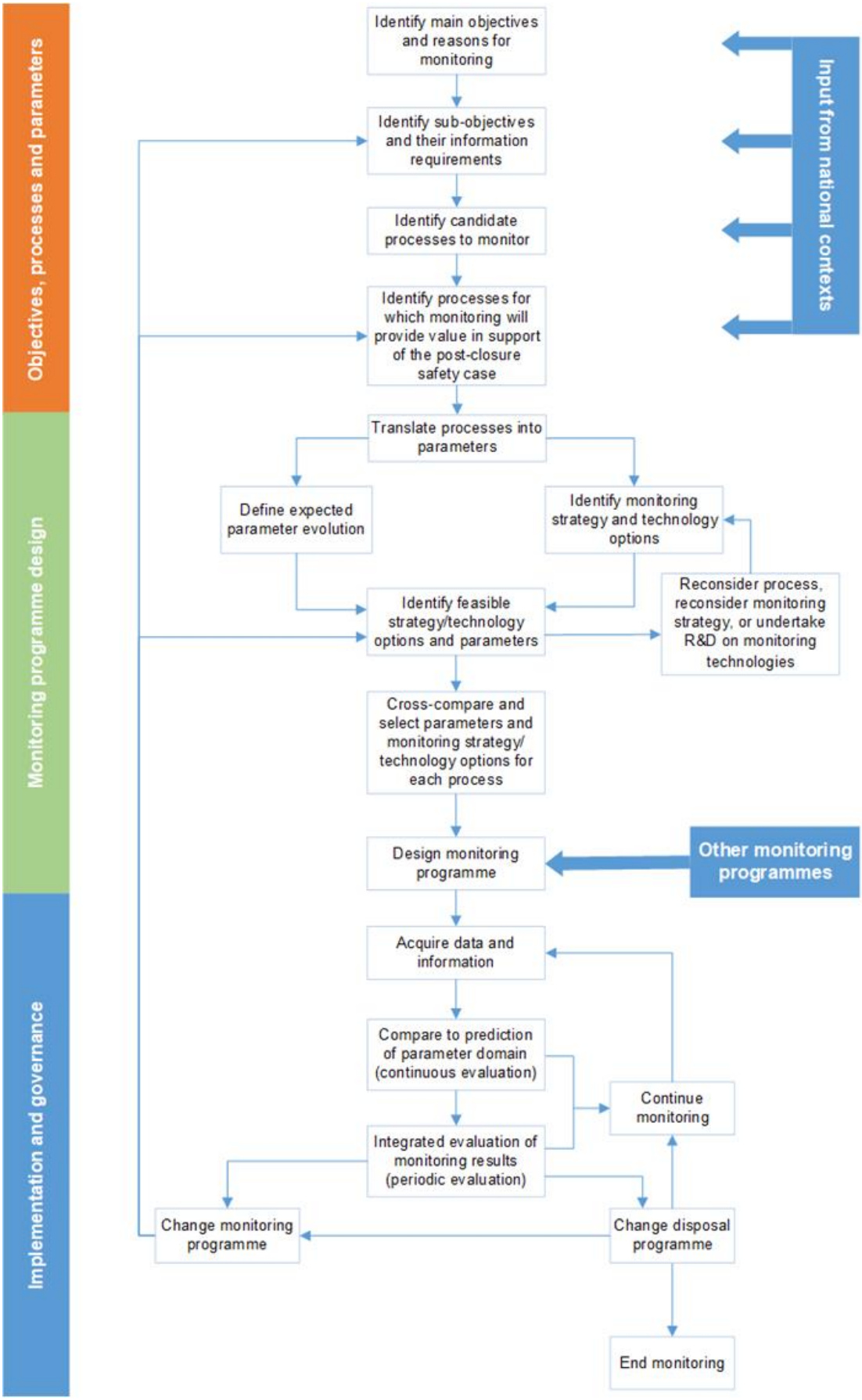


Figure 3-1 – The Modern Monitoring Workflow. From [3].

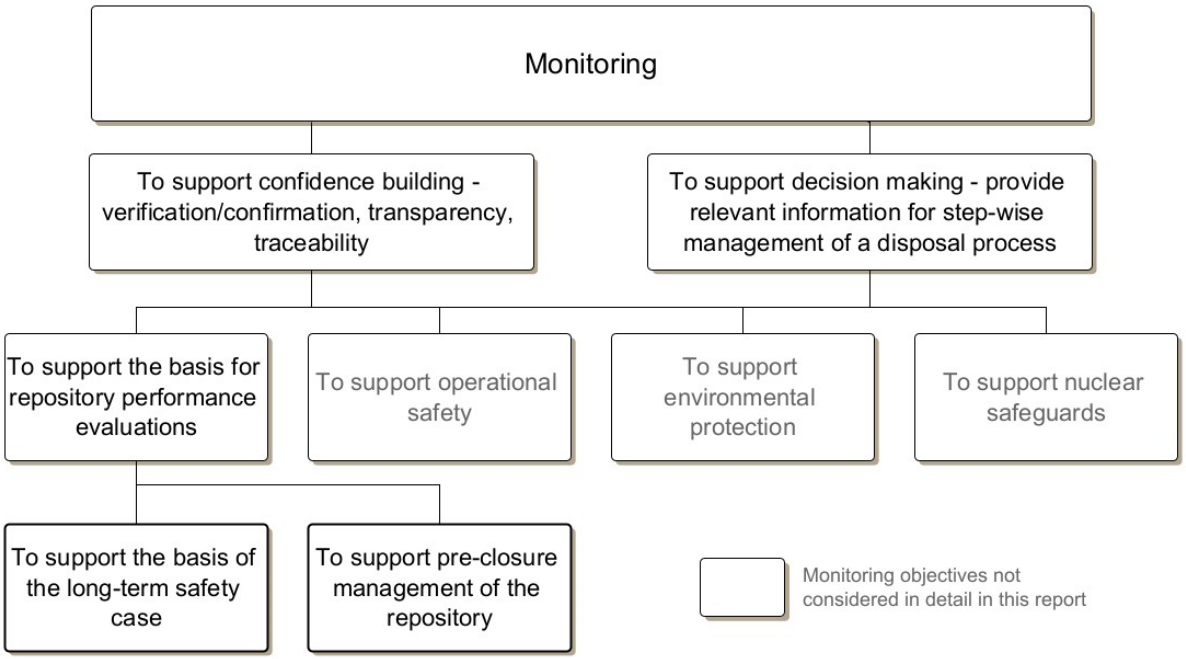


Figure 3-2 – Overarching goals and main objectives for monitoring. From [2].

For monitoring to support the basis for repository performance evaluations, generic objectives recognised in the MoDeRn project were [2]:

- To support the basis of the long-term safety case.
- To support pre-closure management of the repository.

Sub-objectives are precise statements of the purposes of monitoring that allow the identification of processes and parameters to be monitored. Sub-objectives are derived from other work in the disposal programme, including development and analysis of the safety case, repository design, regulations and stakeholder concerns. Sub-objectives take account of the national context; this could include specific legal and regulatory requirements, and stakeholder views, and will also be specific to the particular waste type, geological environment, disposal concept and overall implementation strategy. The national context may also define an overall strategic approach to the monitoring programme, including the general locations in which monitoring should be undertaken, e.g., in the actual repository or in a pilot facility. Sub-objectives can support the identification of potential monitoring processes and parameters, alongside the technologies that could be used to monitor them, but in order to adopt these process, parameter and technology combinations their value to the repository programme needs to determined using a structured approach. The analysis provided in the MoDeRn [2] and Modern2020 [3] projects, remains relevant, offering guidance for the development of effective monitoring programmes.

3.2 Monitoring Processes, Parameters and Technologies

This section would identify the procedure followed in the screening of monitoring parameters, and would list the monitoring processes and their associated parameters that would be the subject of the monitoring programme, and the technologies that would be used to acquire data on these processes and parameters.

Given the need for the repository monitoring programme to be transparent and traceable, it is envisaged that a structured process similar to the Modern2020 Parameter Screening Methodology (Figure 3-3) [3] will be used to identify the process, parameter and technology combinations to be used in the monitoring programme. However, it would not be necessary for a QAPP to document the use of the methodology, as this would be done in the Monitoring Strategy. Instead, it is envisaged that a QAPP would reference the relevant procedure, the discussion of the application of the procedure in the Monitoring Strategy, and present the list of process, parameter and technology combinations included in the repository monitoring programme. Any context necessary for presentation of the list would also be included.

The Modern2020 Parameter Screening Methodology describes the considerations to be taken into account in parameter selection [3], for example the possibility of observing parameter evolution within the monitoring timeframe or the availability of a technology to monitor a parameter reliably.

For each parameter, the expected magnitude of change, and hence the measurement range, will be established (see Section 4.2). Other relevant specifications are the resolution (smallest change that should be noticed or measured) and accuracy. In addition to sensors, the benefits of (planned and non-planned) human visual observations should be acknowledged as it might capture changes or nuances that sensors cannot, and they can complement sensor data by providing context or identifying unexpected issues.

In long-term experimental set-ups, several phases can be distinguished (e.g., saturation phase), which might also require dedicated monitoring. Similarly, in the repository, some parameters may only need to be monitored during a specific phase – this should also be specified in the parameter list.

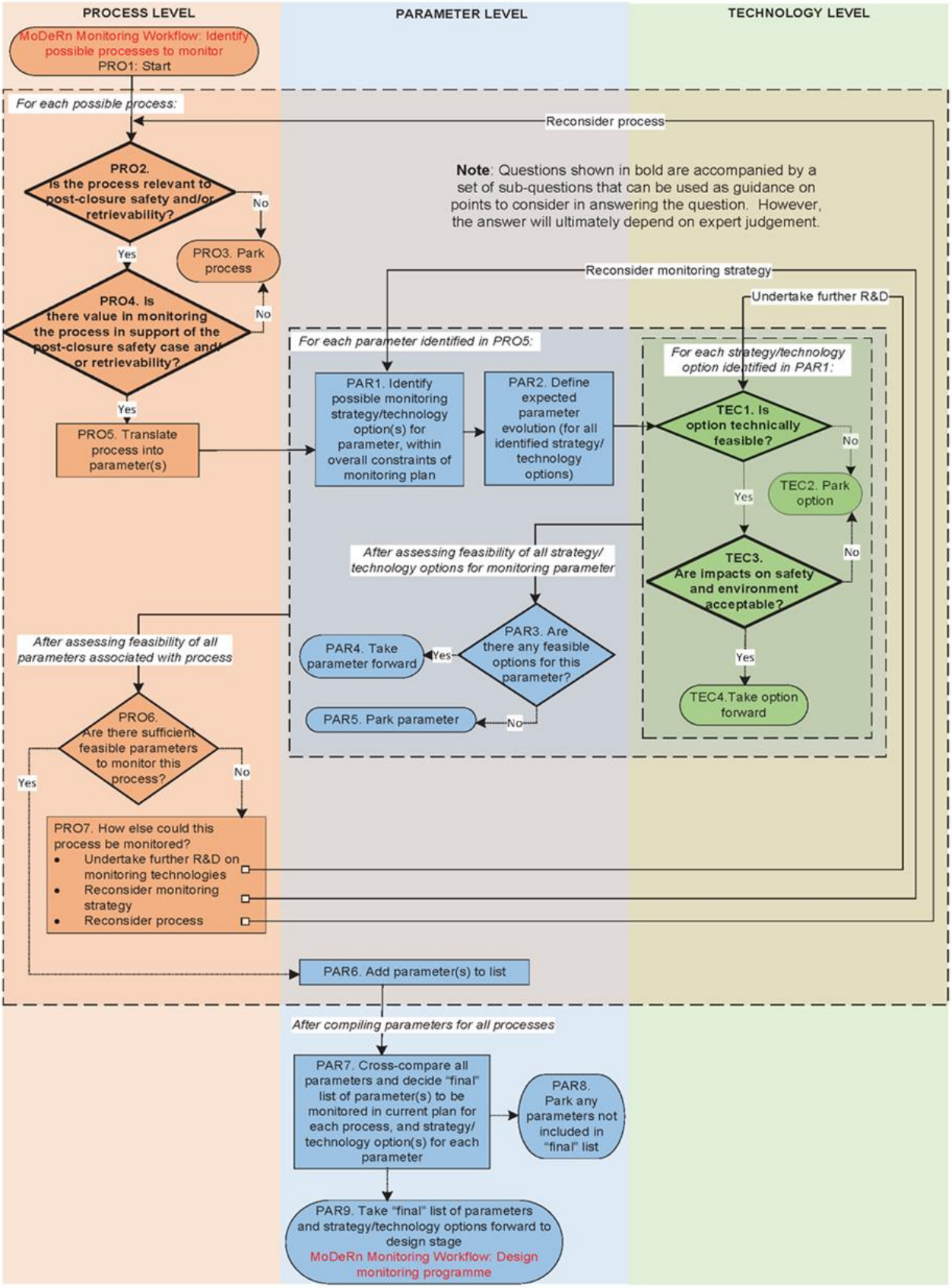


Figure 3-3 – The Modern2020 Screening Methodology for selection of monitoring process, parameter, and technology combinations. From [3].

3.3 Monitoring Schedule

This section of a QAPP would describe the expected schedule for the repository monitoring programme at the time of publication of the QAPP, and the relationship of this duration to periodic updates to the safety case. This schedule would serve as an input for the planning of the programme, for example, planning updates to software and hardware. By outlining the expected duration of the monitoring programme, the QAPP would provide a basis for evaluating the feasibility of the proposed monitoring system components to operate seamlessly throughout the entire programme duration.

Information to be included here would be key milestones that cover various aspects of the system's life cycle and operational processes, including:

- Period for monitoring system installation and testing: This refers to the timeframe dedicated to setting up the monitoring system, including the installation of hardware and software components. It also includes comprehensive testing conducted to ensure that the system functions properly and meets the required specifications.
- Expected dates for data freezes: Monitoring data freezes are predetermined points in time when a dataset is provided for particular analysis and/or decision.
- Operating period for component of the monitoring system: This is the period that the monitoring system is expected to be operational and provide data.
- Planned dates for periodic maintenance activities: These dates relate to scheduled tasks undertaken to preserve the system's functionality and performance, for example, equipment inspections, software updates, calibration checks and cleaning.
- Report delivery dates: These dates indicate when various reports generated from the monitoring system are expected to be delivered. Reports may include performance reports, status updates, compliance reports, annual reports or any other relevant documentation presenting the collected data, analysis, and insights about the monitoring system. Timely delivery of reports ensures that stakeholders, decision-makers, or other designated recipients receive the necessary information when needed.
- Audit dates: These dates are significant milestones to ensure the monitoring system's compliance and accuracy. Audits are systematic examinations or assessments conducted to evaluate the system's adherence to standards, regulations, or performance criteria. By establishing specific dates for audits, WMOs can maintain compliance, identify areas for improvement, and uphold the accuracy and reliability of the monitoring system programme.

3.4 Monitoring Roles and Responsibilities

This section of a QAPP would describe the roles of WMO and contractor staff that are responsible for delivery of the repository monitoring programme (should contractor staff be used in planning, design and/or delivery of the repository monitoring programme), and their organisation with respect to each other. It is anticipated that the information would be provided in the QAPP by presentation of an organogram identifying the roles and their interdependencies, and a complementary table defining each role. Naming individuals alongside their roles in the repository monitoring programme is good practice as it promotes accountability, clarity, transparency and effective communication within a programme or organisation. This practice also helps stakeholders identify the appropriate contact person for specific inquiries, updates, or discussions, facilitating efficient coordination and collaboration.

A generic example of a monitoring programme organogram is provided in Figure 3-4 and related roles and responsibilities that could be stated in a QAPP are listed in Table 3-1. A QAPP should define the responsibility for each activity described within the document by cross-reference to the organogram.

The scale of the monitoring programme will dictate the number of individuals that are named in the organogram; the named roles could be fulfilled by the same person. For example, an individual within the WMO could be a monitoring technologist, as well as a discipline lead.

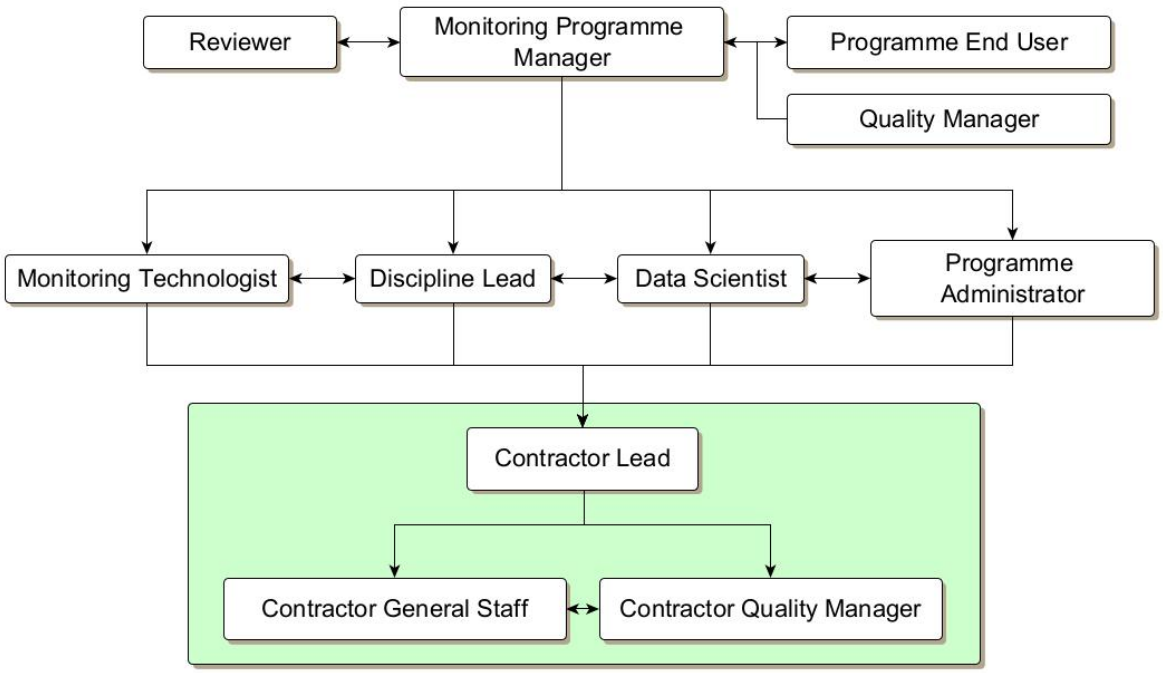


Figure 3-4 – An example of a repository monitoring programme organogram. Green box indicates roles fulfilled by contractors (if contractor staff are used during the planning, design and/or delivery of the repository monitoring programme; which might be undertaken by WMO staff only). It is reminded that the guidance provided here is generic and therefore only identifies examples such as this organogram.

Table 3-1 – Examples of roles and responsibilities undertaken in a repository programme, using the example roles in Figure 3-4. Note role names and definitions will vary between programmes, for example there may be limited or no use of contractor staff.

Roles	Responsibilities
Monitoring Programme Manager	To oversee the overall coordination, budget, and planning of the monitoring programme, ensuring the successful execution of each task.
Programme End User[4]	To provide feedback to the monitoring programme on the requirements on the monitoring data. The End User plays a role in leveraging the monitoring data for decision-making, safety assessments, research endeavours, or public awareness initiatives.
Quality Manager	To ensure adherence to quality standards and processes throughout the monitoring programme.
Monitoring Technologist	To lead the acquisition of monitoring data, deliver, implement and maintain the monitoring system, including data collection, instrumentation, calibration, and design decisions.
Discipline Lead	To lead the analyse of the monitoring data through technical expertise and guidance in specific technical disciplines, ensuring that appropriate interpretation methodologies are used, and necessary information is delivered to the required quality and time constraints.
Data Scientist	To lead the data treatment and management, curation, developing and maintaining databases.

[4] An End User in the context of the repository monitoring programme refers to individuals, organisations, regulatory bodies, or any other relevant stakeholders who rely on, access, or use the data, information, and insights generated by the monitoring system.

Roles	Responsibilities
Reviewer	To review and provide feedback on monitoring plans and reports.
Programme Administrator	To manage administrative tasks, documentation, and communication within the monitoring programme.
Contractor Lead	To coordinate and oversee the activities of contractors involved in the monitoring programme.
Contractor General Staff	To execute assigned monitoring tasks as per programme requirements (outlined in the QAPP) and guidelines. The contractor staff would be used in planning, design and/or delivery of the repository monitoring programme but the monitoring programme might be undertaken solely by a WMO depending on the programme.
Contractor Quality Manager	To ensure QC and compliance of contractor activities within the monitoring programme.

Definition of the roles and responsibilities within a repository monitoring programme should include description of the competencies required for its fulfilment (i.e., the required qualifications of the responsible person). Furthermore, a QAPP should describe lines of authority and communication, to facilitate managers ensuring that the required information is delivered to the necessary quality and time constraints. The QAPP will identify the process through which human resources will be assigned to the monitoring programme.

The responsibility for programme-related tasks should be defined in a QAPP, which could include:

- Consultation from end users to ensure that they are consulted during the planning, design and implementation of the monitoring programme. The end users of the monitoring data should be consulted throughout the various stages in the monitoring programme, as this will give the best guarantee to a successful implementation.
- Procurement of monitoring equipment and testing the equipment upon delivery.
- Installation of monitoring equipment (including cabling and data acquisition equipment).
- Maintenance and calibration where relevant; including maintaining a logbook or diary of the work undertaken.
- Data collection, treatment and management (review, validation and verification of data):
- Presentation of monitoring data.
- Reporting and conclusions.

During the operational period, the programme managers oversee the overall coordination, budget, and planning of each monitoring task. They are responsible for managing resources, timelines, and deliverables to ensure the smooth execution of the monitoring programme. For the scientific part, a discipline lead might be assigned to lead the scientific direction of the monitoring activities, ensuring the use of appropriate methodologies, data analysis techniques, and interpretation of results. Their involvement contributes to the scientific rigor and credibility of the monitoring programme, supporting decision-making processes and the ongoing optimisation of the repository's operational phase.

A QAPP would also describe the organisational approach to managing the required skill competencies, specifically the approach to ensuring the required skill competencies will remain within the organisation. A key aspect of this would be to demonstrate that an approach has been identified for succession planning to ensure that the understanding underpinning the monitoring programme is not lost over the decades that it is expected to be undertaken. This could include, for example, a structured induction programme, to ensure that all staff that work on the repository monitoring programme are familiar with how the programme has developed over time.

3.5 Monitoring Documents Supporting the High-Level Hierarchy

This section of a QAPP would define the documentation and datasets to be generated by the repository monitoring programme. This would include all documents and datasets to be produced, including, if necessary, documents and datasets produced for different stakeholders. The programme documentation is considered as important as the data, as it provides, amongst other information, the justification for the design and the record of monitoring system operation. It is envisaged that the focus of this section would be the production and approval of each document (see below). Quality-related aspects regarding the content of each document or dataset would be provided in relevant sections later in a QAPP (for example, discussion of the quality-related content of a daily log would be included in Section 5.2, which focuses on installation of the monitoring system).

For each document and/or dataset, the following is expected to be defined:

- Schedule, including the schedule for draft and final versions of the document/dataset.
- The authors of the document or generators of the dataset and reviewers, with a link to the organogram defining the monitoring programme roles and responsibilities.
- An outline of the contents of the document/dataset.
- The format of the document/dataset – for datasets, the formats will be as defined in the discussion of data management (see Section 6.4).
- The distribution of the document/dataset (level of accessibility and the nature of expected dissemination).

A full list of the documents to be produced during the repository monitoring programme would be provided here. In addition to the monitoring programme documentation list detailed in Section 2.2, a list of examples of documents to be produced during a repository monitoring programme is provided in Table 3-2.

Table 3-2 – Generic list of document examples to be produced during a repository monitoring programme and provided in this section.

Document Class	Document	Location of Definitions in this Document
Monitoring knowledge	Sensor data sheets	Section 4.1
Monitoring System Design	Topographic surveys	Section 4.4
	Sensor implementation plan	Section 5.2
Monitoring System Implementation	Sensor calibration sheets	Section 5.1
	Daily logs	Section 5.2.3
	Change record sheets	Section 5.2.3
	QC sheets	Section 5.2.1
	Equipment control sheets	Section 5.1
Programme Management	Audit documentation	Section 6.5.1
	Event logs	Section 3.5 (this section)
	Meeting records	Section 3.5 (this section)
	Activity plans	Section 3.4

This list of document examples is generic (Table 3-2), and the definition of documents can be found in referenced related sections. Some documents related to more general programme management are defined hereafter:

- **Event logs** detail significant events that could impact the monitoring programme results, such as drilling of a new tunnel close to the monitoring sensors, power outages, etc. These documents outline occurrences such as environmental changes, maintenance activities, sensor adjustments, and other noteworthy incidents. By maintaining event logs, the monitoring programme demonstrates its ability to account for external events that might affect the acquired data and its interpretation. These logs aid in assessing the context of data variations and contribute to trend analysis. The type of events that should be recorded in the event log, and their classification (if used) should be defined in a QAPP. In addition to being available for continuous evaluation of monitoring data, the event data should be collated, reviewed, and reported alongside periodic evaluation of monitoring data (e.g., during major updates to the safety case).
- **Meeting records** document discussions, decisions, and actions assigned during various meetings related to the monitoring programme. The template used to complete these records should be identified in a QAPP. These records document the programme's evolution and decision-making processes, thereby ensuring transparency, traceability, and accountability throughout the monitoring programme's life cycle.

This section of a QAPP would also describe the management of repository programme documentation (see Figure 2-4 and Section 2.2), including a description of how the documentation will be kept accessible over the lifetime of the repository programme (e.g., by re-issue of main documents periodically). Information to be included would be the processes required for review, change control and archiving of documents with a link to the organisational quality management plan.

As noted in Section 2.2, there will be many protocols and procedures that will be followed to ensure quality in the repository monitoring programme, including templates for the documents identified above, and instructions on their completion and management. It is not envisaged that these templates and instructions would all be included in a QAPP. Instead, as noted in Section 2.2, it is envisaged that a QAPP would clarify the need for procedures, protocols, templates and instructions used in the monitoring programme, and would act as a portal to a document management system containing them (i.e., defining how they could be accessed).

4. QAPP Content on Monitoring System Design

As discussed in Section 2.2, it is envisaged herein that detailed information on the design of the monitoring system would be presented in a separate design document (see Figure 2-4). This section of a repository monitoring QAPP would summarise quality-relevant information on the design of the monitoring system. It is envisaged that there would be, therefore, overlap between the two documents, with detailed information being provided in the design document and summary information in the QAPP.

Four separate sections are envisaged in this section of a QAPP:

- Knowledge used in the Monitoring System Design (see Section 4.1): this section would provide evidence, information, and experience used to support the design of the monitoring system used in the repository monitoring programme.
- Requirements on the Monitoring System (see Section 4.2): this section would list the objectives and specifications for monitoring sensors and systems, including data quality, safety, power provision, and data use.
- Process used to Design the Monitoring System (see Section 4.3): this section would provide the justification of choosing the monitoring system components (sensors, power systems, data transfer systems, and data acquisition systems (DASs)).
- Description of the Monitoring System Design (Instrumentation Plan and As Built Report) (see Section 4.4): this section would present the layout of the monitoring system, including the type, number, and specific location of monitoring components, uncertainties in system operation and their management, procedures for review and acceptance of sensor layout, as well as drawings and 3D models of the system.

4.1 Knowledge used in the Monitoring System Design

This section of a QAPP would describe the knowledge that a WMO used to support the design of the monitoring system, and how the knowledge provides confidence in the performance of it.

The design knowledge would provide evidence that the technology employed will operate over the period envisaged, and under the environmental conditions anticipated in the repository. It is recommended that the repository programme records the available knowledge on monitoring equipment performance into a structured database describing the available information on monitoring technologies to support the design of the monitoring system. Such a database could build on published state-of-the-art reports on repository monitoring technologies (e.g., [24] and [25]), and would focus on information that would support the QA of the monitoring programme. Such databases would provide support to a demonstration of confidence in monitoring data through the operational phase of the repository. A QAPP would describe the knowledge, how it is structured in the database and how it provides confidence in the performance of the monitoring system, and would provide a link to the database.

Knowledge on sensor performance (and the performance of other components of a repository monitoring system) might come from various sources such as:

- Manufacturer specifications and data sheets.
- Technology sheets.
- Feedback from URL experiments.
- Specific tests, for example accelerated performance tests.
- Shared information between programmes.

Manufacturer specifications and data sheets describe the operation of the equipment (usually sensors), including measurement principles, measurement ranges, electrical specifications (such as operating voltage), general specifications (which provide physical constraints such as temperature ranges), accuracy and input/output signal.

Manufacturer data sheets are not prepared according to a defined standard, and, therefore, information can be inconsistent. Furthermore, deployment of the technology in a repository monitoring programme might use a novel approach. There is likely to be, therefore, a need to supplement the information provided by manufacturers. This could include information derived from URL experiments, such as failure rates, development of good practice and identification of lessons for equipment deployment (see, for example, [26]).

Some aspects of monitoring equipment performance can be addressed by specific tests. For example, high-radiation experiments used for accelerated testing of the potential for radiation damage to fibre optic cables, which can contribute to understanding of the expected performance of sensor and reduce the uncertainty linked to the timescale issue.

It would also be of value for WMOs to continue to share information on monitoring technology, for example, the performance of sensors and knowledge gained from the decommissioning of URL experiments, including understanding of the failure mechanisms for monitoring systems and how these can be mitigated.

Technology sheets offer comprehensive information about individual monitoring technologies. These documents include specifications, installation details, and maintenance schedules. By maintaining up-to-date technology sheets, the programme ensures proper technology management and consistent data quality. Development of monitoring technology databases is already underway in some repository programmes. For example, to support operations in the Bure URL, Andra is developing an interactive database that covers information about all sensors that have been installed in the URL experiments. The knowledge database proposed herein would be broader and include information to be used in the selection of all components of the monitoring system.

Such a database could be presented as a catalogue of information sheets; for each piece of equipment available for use in the monitoring system, these could include:

- Description of the equipment:
  - A photograph or diagram of the equipment.
  - The name of the equipment.
  - The category to which the equipment belongs (e.g., sensor or data transmission system).
  - The dimensions and mass of the equipment.
  - Materials from which the equipment is made.
  - The operational principle for the equipment, for example the measurement principle for sensors.
- Information on the performance of the equipment:
  - Range of operating conditions: The maximum operating temperature, pressure, salinity, saturation, radiation and any other parameters that could have an impact on equipment performance.
  - Accuracy: Degree to which the measurements align with the true value of the quantity being measured.
  - Resolution: The smallest distinguishable change the equipment can detect and display.
  - Drift: Any information on the potential for gradual, undesired change in the output or performance of equipment over time.
  - Equipment longevity: Any information available on the expected equipment lifetime including a description of the processes through which the equipment might degrade.
  - Sensor-specific information, such as hysteresis for relative humidity sensors.
- Commercial features**:**
  - Patents: in the case of monitoring equipment developed within the programme, the database should record whether a patent exists or has been applied for.
  - Datasheet from the supplier.

- State-of-the-art reports: These would provide information on the latest advancements, technologies, and research related to the equipment. It could explore recent innovations or breakthroughs, discusses potential challenges or limitations, and highlight emerging trends or future directions in development and use.

4.2 Requirements on the Monitoring System

This section would summarise the DQOs that the monitoring system would need to meet. It is envisaged that a QAPP would present a table with each parameter to be measured, and the requirements on that parameter. The requirements on each parameter may vary depending on location (e.g., requirements on accuracy may be different in the engineered barriers compared to the geological barrier). Therefore, the table structure should include definition of the multi-barrier system component (or interface between two components) in which the parameter will be monitored.

The monitoring techniques that are set will be dependent on the data requirements in question (for example, fibre optic cables will have different types of requirements to pore pressure sensors). Requirements are likely to be set on:

- The required measurement range of the sensors as a function of space and time.
- Frequency of measurements.
- Accuracy of measurements.
- Resolution of measurements.
- The environmental conditions in which the sensor has to operate.

An input to the definition of data requirements is likely to be modelling of processes to bound the expected behaviour and the possible ranges of parameter values.

Other requirements might be identified, for example, requirements derived from the safety case (to ensure that the monitoring equipment does not significantly impact the long-term performance of the repository), requirements on the materials that could be used and requirements on installation of the equipment.

In addition to requirements on monitoring sensors, requirements would also be identified for other elements of the monitoring system, i.e., power provision, data transmission and DASs, although these would be different to the requirements on sensors (i.e., they would not include requirements on measurement range).

Requirements need to consider how monitoring data will be used; the monitoring system being driven by the needs of the end users. Therefore, there is a need to develop a plan for the use of the monitoring data in numerical modelling during further iterations of the safety case.

To ensure effective knowledge management, traceability, and stakeholder transparency, it is recommended to maintain detailed records that clearly identify and justify the design requirements. In this context it is good practice to develop specific documents that would outline various parameters, including measurement frequencies, derived from expert discussions between monitoring and modelling teams. For example, SKB generates such a type of document named “Specification of Demands”. Information from such a document could be used to justify the design requirements stated in this section of a QAPP, and a QAPP would reference out to these underpinning documents.

An example of design requirements on sensors for use by contractors in planning the monitoring system for the FE experiment is provided in Box 1. The example was produced by Nagra based on scoping calculations of FE experiment evolution.

Box 1 – Example of design requirements on sensors.

This example of document was used by contractors in planning the monitoring system for the FE experiment. The example was produced by Nagra based on scoping calculations of FE experiment evolution. It shows the maximum expected temperatures, porewater pressures, gas pressures and total pressures in two locations in the experiment, as well as the capabilities of the selected technologies. It also lists references to reports that provide this information.

For the instrumentation design an experimental duration of min. 10-15 years should be assumed. This does not predefine the requirements with respect to interpretation and modelling.

Max. Total P is defined as the pressure the installed sensors should be able to with-stand.

Working conditions of the instrumentation at specific locations

	Expected max. value	Design value	Unit	Comments Considering exp. life-time of 10-15 years	Source
2.1. 0.525 m distance from the tunnel axis, which equals heater surface.					
2.1.1. Max. Temp.	150	165	°C		AN 13-055, NIB 13-02
2.1.2. Max. P-water	0	0	MPa		Garitte 2013, NIB 13-01; ppt of Senger 2012
2.1.3. Max. P-gas (air incl. water vapor)	+0.3	+0.5*)	MPa		ppt of Senger 2012
2.1.4. Max. Total P	0	4	MPa	Swelling pressure Bentonite for dry density 1450 kg/m3.	NAB 07-23
2.2. 0.725 m distance from the tunnel axis, which equals 0.20 m distance from heater surface					
2.2.1. Max. Temp.	110	125	°C		Garitte 2013, NIB 13-01; NIB 13-02
2.2.2. Max. P-water	0	0	MPa		Garitte 2013, NIB 13-01; Senger 2012, ppt
2.2.3. Max. P-gas (air)	+0.3	+0.5*)	MPa		Senger 2012, ppt
2.2.4. Max. Total P	0	4	MPa	Swelling pressure Bentonite for dry density 1450 kg/m3.	NAB 07-23

4.3 Process used to Design the Monitoring System

This section would present the process to be used, or the process that was used (for later versions of a QAPP), for designing the monitoring system. In particular, this section of a QAPP would describe the process through which the knowledge of monitoring system capability (Section 4.1) could be compared to the DQOs (Section 4.2) to select the monitoring system components (sensors, power systems, data transfer systems and DASs), and their position within the repository to demonstrate that the chosen design would meet the requirements on it. This section might reference underpinning process and protocol documents.

The following aspects of the monitoring system would be justified:

- Type of equipment: the reason for selecting a specific sensor, power system, data transfer system or DAS.
- Number of each: how many sensors are required for each sensor type, with particular consideration for redundancy in performance and spatial density to capture the process of interest.
- Text description of each location of each component of the monitoring system. The justification should include specific mitigations against equipment failure during operation, for example cable failure owing to placement in high-strain areas.

The manner of the justification is dependent on the QA approaches adopted by the WMO. Different criteria could be used to determine the final selection. Important considerations to ensure quality when selecting sensors include:

- Measurement range of sensor covers the range of expected conditions.
- Measurement principle is appropriate (e.g.: measurements requiring *in situ* sampling are not appropriate).
- Robust material to avoid corrosion or mechanical damage, mitigating impacts on the multi-barrier system.
- Reliability.
- Accuracy.
- Resolution.

The design of monitoring systems in URL experiments has been primarily reliant on expert judgement. The long timeframe of repository monitoring programmes requires greater justification to ensure the knowledge remains accessible later in the programme and that quality is assured. For example, Andra is planning to use an evidence-based approach to sensor selection for repository monitoring, e.g., based on monitoring performance information collected during URL experiments, or as part of their decommissioning.

An example of sensor justification in the FE Experiment, provided by Nagra, is shown in Box 2**.**

Good practice in monitoring system layout is to arrange sensors in cross-sections aligned parallel to expected process gradients (e.g., from high temperature to low temperature). These cross-sections might be regarded as primary instrumented sections. In addition, zones with large gradients could be monitored with a greater density of sensors (e.g., a redox front or at the boundary between two components of the multi-barrier system) although the impact on passive safety of increasing sensor density would have to be considered. Furthermore, to increase spatial coverage, secondary sections could be introduced, with a more restricted set of sensors.

When selecting locations, it should be recognised that some instruments may suffer failures. The design should, therefore, include mitigations against the potential for sensor failure, for example placing pressure sensors in accessible locations at a well head rather than downhole, if possible.

Box 2 – Example of justification of sensor selection by contractors prepared by Nagra.

This example describes the reasoning behind the selection of a relative humidity sensor intended for installation within the buffer adjacent to the heaters in the FE Experiment. It discusses the expected conditions at this location, and states the capabilities of the sensor. This information shows that the sensor is capable of operating in the expected conditions in the location it is intended to be installed in.

5 BASIC SPECIFICATIONS OF SELECTED SENSORS

5.1 Relative humidity (suction) and temperature in the buffer: "Low temperature"

These sensors will be installed on supports attached to heaters to place them 20 cm apart from the heater surface, being the operation temperature of 110 ºC with maximum values of 125 ºC. Besides, they will be installed in the buffer both in the bentonite pedestals and in the bentonite wall.

The selected one is the relative humidity sensor SHT75 V3 that provides both relative humidity and temperature readings. The device is specially designed and constructed to be emplaced buried in soils or compacted sealing materials (clays or sand/clay mixtures). The electronic circuit is located in a robust stainless steel body and sealed with epoxy resin, what guarantees a high water-tightness degree by the cable entry side. The sensing element is mechanically protected with a stainless steel filter. The main features are in Table 3.

Table 3: Characteristics of relative humidity sensors SHT75

Manufacturer/Model	Aitemin/SHT75 V3 (2012)
Measurement principle	Capacitive
Relative humidity range	0 % to 100% R.H. (not condensing)
Temperature range	-40 ºC to 124 ºC (Temperature sensor) -40 ºC to 175 ºC (Humidity sensor)
Output	Digital 12 bit/14 bit
Resolution	0.03% R.H. /0.01 ºC
Accuracy	±1.8% RH between 10 to 90%/ ±0.3ºC
Dimensions	Diameter: 12 mm; Length: 87 mm
Head casing material	Stainless steel with steel filter
Cable	RT47. Teflon jacketed. Screen threaded cable
Nº of wires	4 x 0.3 mm^2, Teflon insulated
Diameter of cable	2.2 mm Teflon jacketed (260 ºC)
Cable protection	SS316L or PEEK tubing ¼" OD if required
Cable output protection	Epoxy potted. Tight up to 35 barg[2] (up to 155 ºC)

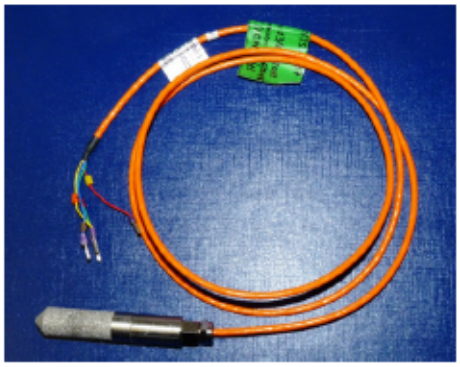


Figure 4: SHT75 V3 sensor

[2] Barg: bar gauge (relative).

Sensor lay-out will be influenced by the budget. When budgeting a monitoring programme, one should consider all costs, from procurement, over installation, data collection and maintenance to reporting. The cost of an individual sensor is usually not the decisive factor.

4.4 Description of the Monitoring System Design

This section of a QAPP would summarise the design of the monitoring system, highlighting the aspects of the design that contribute towards the QA of the monitoring system. Reference would be made to design documents in which the actual design would be presented (i.e. the Monitoring System Design and the Monitoring System As Built reports); the focus of this section of a QAPP would be to describe how the design contributes towards the QA of the monitoring system.

Examples of the types of information that could be included in this section are:

- A summary of how sensor layouts have been designed with respect to the evolution of parameters of interest, for example, using cross-sections oriented parallel to parameter gradients.
- A description of how naming conventions (the use of a structured title to describe the sensor, and other equipment) have been used to facilitate installation and analysis.
- A description of the use of redundancy in sensors and methods to mitigate against potential failure of the monitoring system, and why the amount of redundancy is considered sufficient.
- Presentation of wiring diagrams for power and data transmission cables, and for DASs to facilitate installation, maintenance and decommissioning activities. As an illustrative example, Nagra provided example of diagrams at data loggers after installation, location of dataloggers in the FE experiment niche outside the experimental tunnel, and tables with all sensor information (e.g., range, unit, offset, factor, output, serial number).
- Use of a 3D model of the monitoring system to check on the potential for spatial problems to arise during installation.

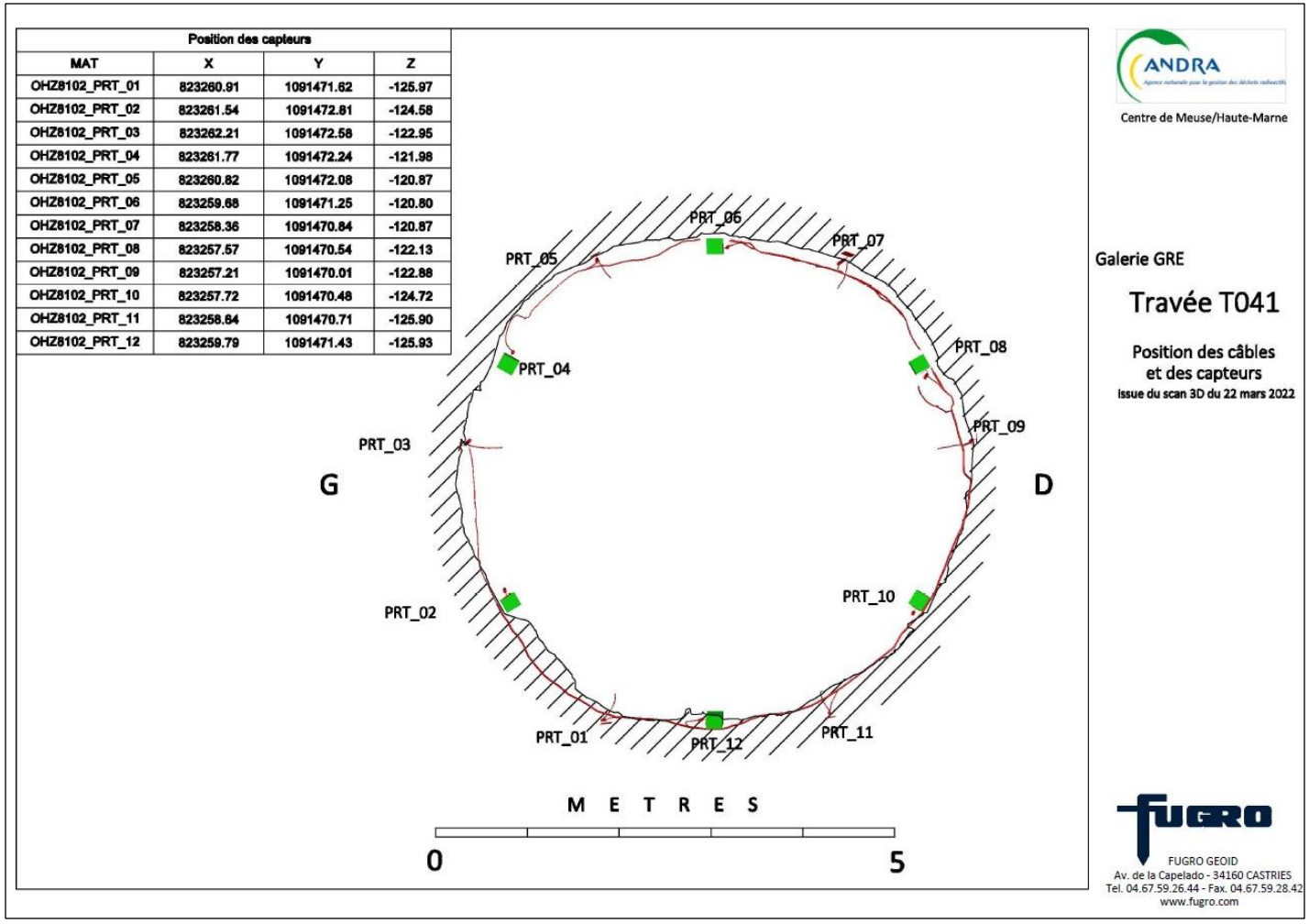
Naming convention could encompass galleries, wells, and associated structures like arches and concrete rings, as well as the monitoring system. The convention could employ three to two-letter acronyms to identify galleries and use numbers to identify gallery sections, starting from the gallery's entrance. Into each of the gallery sections, numbers could also be added to identify sensors located along the gallery walls using a clockwise convention. Being systematically oriented in sense of excavation, cross sections would aid positioning of sensors. In addition, topography surveys (e.g., Lidar and photogrammetry, see an example in Box 3) should be used to position sensors. Topographic surveys provide spatial data used in defining the location of monitoring equipment and any change in the position over time (e.g., owing to convergence of tunnel walls). Their positions would be represented in well-defined system coordinates. For example, Lambert projection system coordinates (X, Y, Z) are used by Andra and EURIDICE, the position being provided as metadata through sensor sheets but not included in the actual sensor name. An example of naming convention and 3D representation of URL main structures is provided by Andra in Box 4. Nagra follows a sensor naming convention implemented in the Grimsel Test Site for the High Temperature Effects on Bentonite Buffers experiment (HotBENT). This convention employs two letters denoting the measurement type (e.g., TP for Total Pressure) and numbers representing coordinates within a defined local reference frame. These coordinates include the distance from the tunnel entrance, the angle of orientation from the gallery direction, and the distance from the gallery centre. While this naming convention provides the exact position of the sensor within the gallery, it does not capture coordinates on the scale of the URL system.

In a repository, it would be beneficial to incorporate the advantages of these examples. Good practices would involve including location information from both local and global reference frames in the sensor name to provide accurate positioning within the system and knowledge of location in the future. However, it is important to ensure that the sensor name remains reasonably concise for ease of use.

Using geographic coordinate systems would ensure the ability to capture any unexpected global motion, including uplift and other geodetic events, unlike local reference frames. It is desirable to maintain consistency in the choice of geographic projection system across different repository programmes. The use of convenient Cartesian coordinate systems, such as Lambert or Mercator, would be preferred for this purpose.

Box 3 – Example of topographic surveys. Provided by Andra.

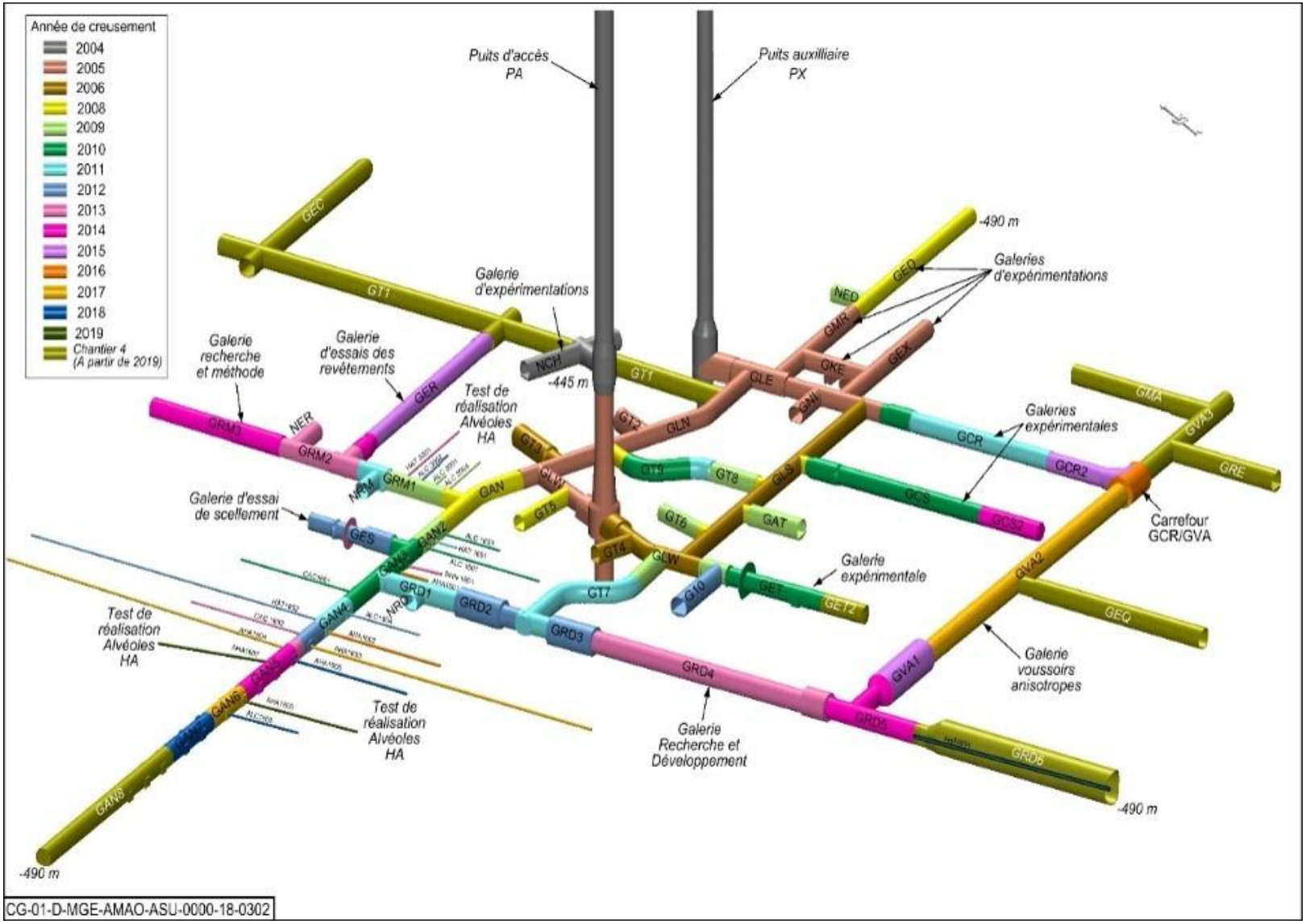
This topographic survey was conducted by Andra at Bure URL. It shows the position of 12 total pressure sensors (PRT) and cables in the GRE gallery cross-section (T041). The survey has been realised from a 3D scan.



Position des capteurs

MAT	X	Y	Z
OHZ8102_PRT_01	823260.91	1091471.62	-125.97
OHZ8102_PRT_02	823261.54	1091472.81	-124.58
OHZ8102_PRT_03	823262.21	1091472.58	-122.95
OHZ8102_PRT_04	823261.77	1091472.24	-121.98
OHZ8102_PRT_05	823260.82	1091472.08	-120.87
OHZ8102_PRT_06	823259.68	1091471.25	-120.80
OHZ8102_PRT_07	823258.36	1091470.84	-120.87
OHZ8102_PRT_08	823257.57	1091470.54	-122.13
OHZ8102_PRT_09	823257.21	1091470.01	-122.88
OHZ8102_PRT_10	823257.72	1091470.48	-124.72
OHZ8102_PRT_11	823258.64	1091470.71	-125.90
OHZ8102_PRT_12	823259.79	1091471.43	-125.93

Box 4 – Examples of naming conventions and design descriptions of the Bure URL with Andra's naming conventions of main structures. Provided by Andra.



5. QAPP Content on Monitoring Programme Implementation

This section of the repository monitoring QAPP would summarise quality-relevant information on the implementation of the monitoring programme.

Four separate sections are proposed:

- Monitoring Equipment Receipt and Testing (see Section 5.1).
- Installation (see Section 5.2).
- Operation (see Section 5.3)
- Decommissioning (see Section 5.3.3).

5.1 Monitoring Equipment Receipt and Testing

This section of a QAPP would describe the QA and QC activities that would be performed by the WMO staff on delivery of monitoring equipment to the repository, and identify the procedures and protocols under which these activities would be taken. Should any aspects of the implementation of the repository monitoring programme be delegated to contractors, this would include confirmation from the contractor that the right testing procedures have been conducted, and all equipment has been tested according to manufacturer specifications at all necessary stages of its manufacture. It would also include confirmation that the technology has been stored and transported according to manufacturer specifications. In particular, this would include checking of contractor's calibration of monitoring equipment in cases where calibration has been undertaken in laboratories remote from the repository.

Sensor calibration sheets provide a record of calibration procedures conducted on monitoring sensors. These documents outline the specific calibration standards used, measurement techniques, and results. Examples of contractor calibration sheets for displacement and tilt sensors in the FE Experiment are provided in Box 5. This confirmation could come, for example, in sharing of documentation demonstrating the testing of equipment.

Calibration is crucial to establish the accuracy and reliability of sensor measurements. All calibrated sensors or instruments have a calibration certificate that includes at least the date of calibration, equipment details, reference procedures with issue and revision status, a description of the environmental conditions under which the test was taken, calibration data, and signature of the responsible person for the test. Good practice for WMOs would be to develop and use a dedicated monitoring service facility, tailored for the testing and calibration of monitoring equipment. This specialised facility could allow experts to conduct comprehensive assessments, evaluating the precision and reliability of monitoring equipment.

The facility could include a purpose-built borehole, which could provide understanding of some aspects of the equipment's performance (this would be limited assuming a test borehole was not drilled to the same depths as investigation boreholes). SKB's uses such a facility in the field of borehole monitoring. This approach would effectively meet the testing and calibration needs while avoiding any potential additional impact in the repository's logistics. It is recognised that some calibration activities may be undertaken during/after sensor installation underground.

Should the monitoring system equipment be stored prior to installation in the repository, such storage would need to be undertaken consistent with manufacturer specifications such as minimum and maximum temperatures, and relative humidity. Confirmation of storage consistent with manufacturer specifications should also be recorded. In addition, equipment control sheets would provide a detailed record of monitoring equipment, components, and supplies. These documents would support efficient resource management and timely equipment maintenance. By ensuring accurate inventory tracking, the programme minimizes disruptions due to equipment shortages or failures. Equipment control sheets underscore the programme's commitment to operational readiness and reliable data collection. A QAPP would also include the procedure for identifying any non-conforming equipment and for dealing with the non-conformance.

Box 5 – Examples of sensor calibration sheets that was provided by Nagra.

These examples show two calibration sheets for displacement sensors. The information provided includes the date and temperature at which the calibration was performed, standard values, actual measurements, regression values and errors. Regression and measurement data are plotted for visual inspection. The regression formulas used and specific factors are also provided.

Wegaufnehmer Infos / Displacement Sensor info

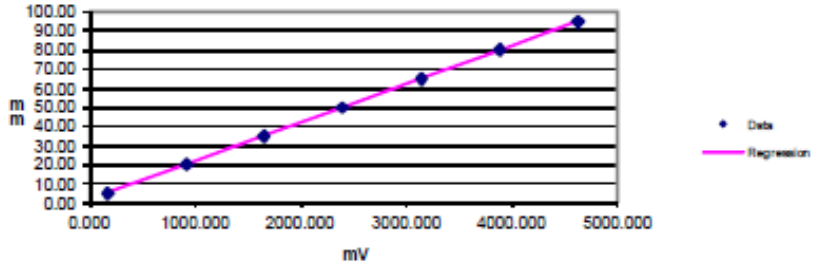
ID-Num.	401083 . 1366	System	MDX Modular Ext.	Datum / Date	04 . 10 . 2013
Weg / Range	100 mm			Bearbeiter/Operator	DDL
Kabel / Cable	- m	T-Sensor	Nein / No	Lufttem. / Air Temp	22 °C
Stecker / Plug	J / Y N	Sensorname:		Prüfgerät / Calibrator	1 02 030

Messungsprotokoll / Calibration conditions

Diese Messungen wurden mit einem Gerät durchgeführt, das eine stabile Spannung von 5V DC erfasst.
Der ganzen gestreckten Wegaufnehmer entspricht den Weg 0.00 mm auf dem Messschieber. Die Messungen wurden dann durch progressives Schliessen des Wegaufnehmers von 5 bis 95% des Messwegs durchgeführt.

These measurements have been done with a device which provides a stable voltage of 5V DC.
The full elongated displacement sensor corresponds to the displacement 0.00 mm on the caliper gauge. The measurements are carried out by a step-by-step sensor's closing up from 5% until 95% of the range.

Weg / Displacement [mm] Soll / goal	Ist / real	Messwert / Measurement [mV]	Regression / Regression [mm]	Fehler / Error [mm]
5.00	5.16	168.900	5.16	0.00
20.00	20.25	916.900	20.26	0.01
35.00	35.03	1648.600	35.03	0.00
50.00	50.03	2391.900	50.03	0.00
65.00	65.16	3141.300	65.16	0.00
80.00	80.15	3884.500	80.16	0.01
95.00	95.04	4621.700	95.04	0.00



Ergebnisse / Results

Faktor/Factor = 0.02 mm/mV
Konstant/Constant = 1.75 mV

Regression = Faktor * (Messwert mV) + Konstant
Regression = Factor * (Measurement mV) + Constant

Korrelationskoeffizient / Correlation coefficient	1.00000	Muss betragen / Must reach	1.0000
Linearität / Linearity [%] :	± 0.006	Muss nicht über / Must not exceed	0.2
Korrektur-Faktor / Adjustement factor	1.0092526		

Verkabelung / Wiring: braun = Versorgung (+) / brown = power supply (+); gelb und grün = Erde / yellow and green = ground; weiss = Signal (-) / white = signal (-)

Sonstiges / Others

PVC - Gewindehülse montiert / PVC - screw-bolt attached ☐ Ja/Yes ☑ Nein/No
Drucktest / Pressure test (6h, 15 bar) OK? ☐ Ja/Yes ☑ Nein/No

Datum : 04.10.2013 Visum : _ DDL

GEOKON 48 Spencer St. Lebanon, N.H. 03766 USA

MEMS Tilt Sensor Calibration

Model Number: MEMS Tilt Sensor

Calibration Date: February 15, 2012

Serial Number: Sensor A 1144056

Temperature: 22.7 °C

Technician: Elice

Inclination (degrees)	Inclination (sinθ)	* Reading 1st Cycle (Volts)	* Reading 2nd Cycle (Volts)	* Average Reading (Volts)	Error in Calculated θ (%FS)	Error in Calculated sinθ (%FS)
10.00	0.1736	2.728	2.728	2.7283	-0.08	-0.03
8.00	0.1392	2.179	2.179	2.1792	-0.02	-0.03
6.00	0.1045	1.627	1.627	1.6273	0.01	-0.03
5.00	0.0872	1.351	1.351	1.3510	0.02	-0.02
4.00	0.0698	1.074	1.074	1.0738	0.02	-0.02
3.00	0.0523	0.796	0.796	0.7958	0.01	-0.03
2.00	0.0349	0.518	0.519	0.5183	0.01	-0.02
1.00	0.0175	0.240	0.240	0.2403	0.00	-0.02
0.00	0.0000	-0.037	-0.036	-0.0365	0.00	0.00
-1.00	-0.0175	-0.314	-0.315	-0.3148	-0.01	0.00
-2.00	-0.0349	-0.593	-0.593	-0.5928	-0.02	-0.01
-3.00	-0.0523	-0.871	-0.871	-0.8713	-0.04	-0.02
-4.00	-0.0698	-1.149	-1.149	-1.1488	-0.04	-0.02
-5.00	-0.0872	-1.426	-1.426	-1.4257	-0.04	-0.01
-6.00	-0.1045	-1.704	-1.704	-1.7038	-0.05	-0.04
-8.00	-0.1392	-2.255	-2.255	-2.2550	-0.01	-0.02
-10.00	-0.1736	-2.805	-2.805	-2.8051	0.04	-0.04

6150, 6155 and 6170 In-Place Inclinometer Gage Factor (D): 0.0628 (sinθ/ Volt)

Deflection = DL(R_1-R_0) mm (inches)

6160 and 6165 Tiltmeter Gage Factor (G): 3.608 (degrees/ Volt) over + / - 10° range

Calculated Tilt = G(R_1 - R_0) degrees

Temperature Correction Factor -0.0003 (T_1-T_0) Volts / °C

Wiring Code: See manual for further information

The above instrument was found to be in tolerance in all operating ranges.

The above named instrument has been calibrated by comparison with standards traceable to the NIST, in compliance with ANSI Z540-1.

5.2 Installation

This section of a QAPP would focus on identification and description of the procedures and protocols used to install the monitoring equipment. Prior to installation of the monitoring system, a QAPP would act as an implementation plan, and would identify the procedures and protocols to be used in the installation of monitoring equipment, including protocols to follow in the case of non-conformances. Following installation, the QAPP would identify the documents that record how the installation was undertaken, thereby providing transparency and traceability for future generations.

The implementation plan (sensor/equipment) would include, on a component-by-component basis, a description of all quality affecting aspects of the placement and configuration of the monitoring equipment. This could include for example, procedures for fixing sensors and testing to be undertaken prior to emplacement of engineered barriers around the sensors. By outlining specific installation procedures and detailing factors like positioning, alignment, and environmental considerations, these documents contribute to the uniformity and reliability of monitoring data.

A QAPP could also include a description of the processes used to protect monitoring technologies during the emplacement of engineered barriers so that the monitoring technologies are not damaged.

A common feature of the installation of monitoring system components in URL experiments is that installation of monitoring equipment has been based on the experience of key individuals that have been involved in previous URL experiments. For repository installation, QA could be supported by following detailed procedures, with the development and maintenance of the procedures based on good practice in monitoring system installation from URL experiments and repository operation commissioning tests.

5.2.1 Responsibilities of WMO Staff

As it is possible that installation would be undertaken by a supplier/subcontractor, this section of a QAPP would also describe the QA activities undertaken by the WMO staff associated with the oversight of monitoring system installation. These activities could include:

- Checking that the installation of the monitoring system is consistent with the design and the implementation plan, and that any differences are recorded.
- Checking that the installation of the monitoring system is installed as defined by the contractor's and the WMO's QMSs.
- Evaluating the QMS of the subcontractor.

It is anticipated that a monitoring technologist (or staff member with similar responsibilities to those defined for a monitoring technologist in Table 3-1) would be on-site permanently whilst contractors are installing the system to ensure the QMSs are being implemented correctly and completely. It may be necessary to identify staff that can deputise for the monitoring technologist in case of their absence. Therefore, this section of a QAPP could also refer to the design process section (see Section 4.3) where procedures for review and acceptance of sensor layout proposed by contractors by waste management staff would be described.

Monitoring technologists (or other WMO staff members) should hold the primary responsibility for overseeing all aspects of the monitoring installation. While both the contracted parties and WMO personnel could participate in completing QC sheets, WMO staff would be the responsible person. QC sheets record results from QC checks performed on monitoring equipment and data. These checks validate the accuracy and reliability of the monitoring system over time. QC sheets demonstrate data integrity and consistency with established quality standards. They also facilitate the identification of deviations and prompt corrective actions. QC sheets filled out by contractors or third parties should therefore be reviewed and signed off by suitably qualified WMO staff.

It may be necessary for the monitoring technologist to take an independent view on the suitability of the manufacturer tests for the specific conditions in which the equipment is emplaced. Hence, during

installation, the WMO staff will undertake QC processes as referenced in the QAPP. These will include confirmation that the contractor has undertaken the correct procedures to demonstrate that:

- The correct sensors have been installed in the correct place. To facilitate this control, all monitoring equipment could have a unique identification number (see discussion in Section 4.4).
- The sensors have been connected to the correct port of the datalogger.
- Each sensor has been tested according to the manufacturer specifications (e.g., testing of pore pressure sensor water tightness), and is working correctly after installation.
- Any additional installations have been correctly executed (e.g., boreholes have been completely grouted, resin injection in borehole has been completed successfully and packer pressures are consistent with expectations).

Therefore, internal QC checks could be conducted upon receiving the sensors as a demonstration process to instil data user confidence. A contractor would be named as responsible for making the necessary sensor connections to the DAS and programming it to initiate data acquisition. Prior to making the connection, information about the sensor (e.g., calibration tests) should be required to ensure its proper functioning. In case the sensor behaves unexpectedly, efforts would be made to identify the underlying reasons, such as issues with the DAS or cabling.

Andra has well-developed procedures for checking the installation of sensors by contractors. In case of unexpected sensor behaviour, these procedures include tests to check cabling using specific protocols to verify the functionality and the integrity of sensor connections. The specific testing procedures vary depending on the technology used, such as conducting an optical budget test for optical fibre connections or measuring resistance for cabling. Diagnosing issues with novel sensors follows a unique procedure, while standard sensors are comparatively easier to diagnose. EURIDICE uses such procedures in particular for borehole installations, using a dedicated template for the drilling and installation, which covers more than 20 years of reporting in a consistent way.

An example of QC documentation completed by Nagra during the installation of sensors in the FE experiment is provided in Box 6.

5.2.2 Monitoring System Equipment Positioning

A QAPP should identify the procedures and protocols to be used to ensure that monitoring equipment is placed in the correct position and that the position of the equipment is suitably recorded and surveyed.

Prior to installation of the monitoring system, it is good practice for a surveying company to mark the planned location of monitoring sensors and key locations for other monitoring system equipment.

Owing to the number of cables that could form part of a monitoring system, it is important to ensure clear labelling of cables at both ends and, if possible, connect cables to the DAS at the time of sensor installation. It is poor practice to leave cables unconnected because it could become uncertain where the cables need to be connected.

After installation, every borehole orientation and sensor position should be surveyed. For sensor positioning, there needs to be one or multiple recognised points on the sensor where the relative position in the excavation is measured. For example, this could be the top and bottom of a point sensor. As recommended in Section 4.4, cross sections should be systematically oriented with respect to the excavation in which they reside, to aid in the positioning of sensors.

Absolute position measurements should be undertaken using standard surveying procedures, e.g., geodetic surveying. This will allow for convergence and axial strain in the monitoring location to be accounted for in positioning. For ease of use, Cartesian coordinate systems like Lambert or Mercator should be used for capturing geographic coordinates (see Section 4.4). The error associated with the positioning measurements should be reported as metadata.

Box 6 – Examples of QC documentation.

This example of QC documentation provided by Nagra was produced during installation of the FE experiment monitoring system. The table summarises internal QC from installation of sensors at tunnel wall. It includes documentation of heating tests, fixing of the sensors, installation dates, serial numbers, cable channels and pictures information.

	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	Sensor name 1	Sensor name 2	SAGD names 1	SAGD names 2	Holder name	Heating test	Sensor fixed yes / no - comments	Installation date	Serial number	Cable channel	Flotron 26.8.14	Photo no. (P1120xxx, 15.10.2014)	Photo doku 25.11.14
39	GM35_1350_00_P	GM35_1350_00_P_TEM	FE_PRE_062	FE_TEM_062		ok	y	17.06.2014			ok	564	ok
40	GM35_1350_04_P	GM35_1350_04_P_TEM	FE_PRE_063	FE_TEM_063		ok	y	17.06.2014			ok	566	ok
41	GM31_1350_01_TEM		FE_TEM_098			OK	y	02.06.2014			ok	568	ok
42	GM31_1350_06_TEM		FE_TEM_099			OK	y	02.06.2014			ok	-	covered, now ok
43	GM31_1350_11_TEM		FE_TEM_100			ok	y	03.06.2014			ok	569	ok
44	GM31_1200_01_TEM		FE_TEM_101		Holder032_1	OK	y	02.06.2014		R2	ok	568	ok
45	GM31_1200_06_TEM		FE_TEM_102		Holder032_6	OK	y	02.06.2014		R4	ok	-	covered, now ok
46	GM31_1200_11_TEM		FE_TEM_103		Holder032_11	ok	y	03.06.2014		L2	ok	569	ok
47	GM31_1350_01_HUM	GM31_1350_01_HUM_TEM	FE_HUM_012	FE_TEM_012		OK	y	02.06.2014			ok	568	ok
48	GM31_1350_06_HUM	GM31_1350_06_HUM_TEM	FE_HUM_013	FE_TEM_013		OK	y	02.06.2014			ok	-	covered, now ok
49	GM31_1350_11_HUM	GM31_1350_11_HUM_TEM	FE_HUM_014	FE_TEM_014		ok	y	03.06.2014			ok	569	ok
50	GM31_1200_01_HUM	GM31_1200_01_HUM_TEM	FE_HUM_015	FE_TEM_015	Holder032_1	OK	y	02.06.2014			ok	568	ok
51	GM31_1200_06_HUM	GM31_1200_06_HUM_TEM	FE_HUM_016	FE_TEM_016	Holder032_6	OK	y	02.06.2014			ok	-	covered, now ok
52	GM31_1200_11_HUM	GM31_1200_11_HUM_TEM	FE_HUM_017	FE_TEM_017	Holder032_11	ok	y	14.08.2014		L2	ok	569	ok
53	GM31_1350_00_P	GM31_1350_00_P_TEM	FE_PRE_064	FE_TEM_064		ok	y	17.06.2014			ok	570	ok
54	GM31_1350_04_P	GM31_1350_04_P_TEM	FE_PRE_065	FE_TEM_065		ok	y	17.06.2014			ok	571	ok
55	GM28_1350_01_TEM		FE_TEM_104			OK	y	02.06.2014			ok	572, 574	ok
56	GM28_1350_11_TEM		FE_TEM_105			ok	y	03.06.2014			ok	575	ok
57	GM28_1200_01_TEM		FE_TEM_106		Holder029_1	ok	y	02.06.2014		R2	ok	572, 574	ok
58	GM28_1200_11_TEM		FE_TEM_107		Holder029_11	ok	y	03.06.2014		L2	ok	575	(ok, not erected)
59	GM28_1200_01_HUM	GM28_1200_01_HUM_TEM	FE_HUM_018	FE_TEM_018	Holder029_1	ok	y	02.06.2014			ok	572, 574	ok
60	GM28_1200_11_HUM	GM28_1200_11_HUM_TEM	FE_HUM_019	FE_TEM_019	Holder029_11	ok	y	14.08.2014		L2	ok	575	(ok, not erected)
61	GM28_1200_01_TDR		FE_SEA_001		Holder029_1		y	02.06.2014		R4	ok	572, 574	ok
62	GM28_1200_11_TDR		FE_SEA_002		Holder029_11		y	02.06.2014		R4	ok	575	ok
63	GM27_1350_01_TEM		FE_TEM_108			ok	y	02.06.2014			ok	578	ok
64	GM27_1350_11_TEM		FE_TEM_109			ok	y	03.06.2014			ok	579	ok
65	GM27_1200_01_TEM		FE_TEM_110		Holder028_1	OK	y	02.06.2014		R2	ok	578	ok
66	GM27_1200_11_TEM		FE_TEM_111		Holder028_11	ok	y	03.06.2014		L1	ok	579	ok
67	GM27_1350_01_HUM	GM27_1350_01_HUM_TEM	FE_HUM_020	FE_TEM_020		ok	y	14.08.2014		R1	ok	578	ok
68	GM27_1350_11_HUM	GM27_1350_11_HUM_TEM	FE_HUM_021	FE_TEM_021		ok	y	03.06.2014			ok	579	ok
69	GM27_1200_01_HUM	GM27_1200_01_HUM_TEM	FE_HUM_022	FE_TEM_022	Holder028_1	OK	y	02.06.2014			ok	578	ok
70	GM27_1200_11_HUM	GM27_1200_11_HUM_TEM	FE_HUM_023	FE_TEM_023	Holder028_11	ok	y	03.06.2014			ok	579	ok
71	GM27_1350_01_O		FE_O2_081	FE_TEM_081			y	17.06.2014			ok	578	ok

5.2.3 Changes

Installation procedures and sensor locations can change compared to the planned designs, and in such instances, the changes need to be undertaken with respect to specified procedures and protocols, and any changes made need to be documented. A QAPP should identify the procedures and protocols to be followed and explain the contribution to QA of the monitoring system performance.

An example of a change in installation procedures from the SW-A experiment in Mont Terri was a decision not to use silicone to seal relative humidity sensors as it was agreed that this was not necessary during installation. Other changes could involve, for example, changing a sensor position. Permission to change the sensor position would be obtained from the responsible authority. Depending on the magnitude of the change, specific modification sheets could be used. These sheets could include the justification for the requested change and would necessitate the agreement and signatures of all relevant parties involved (e.g., contractor, director and safety officer). Change record sheets document any modifications, updates, or adjustments made to the monitoring system or its components. These records ensure transparency in change management and highlight the programme's adaptability. By systematically recording changes and the associated justifications, the programme demonstrates a structured approach to maintaining and enhancing data quality over time. An example of change record sheet used by Andra is provided in Box 7.

Daily logs are useful tools to document progress in the installation as well as changes and relevant events (routine and non-routine) associated with installation of monitoring equipment. It is expected that templates and guidance on completion of daily logs would be provided. These logs serve as a chronological record of the progress on installing equipment. It includes what was done, by whom, who checked it, and what issues were identified. These daily logs could cross-reference to the event log (see description in Section 3.5). Contractors could be required to maintain a daily log, documenting activities and their respective timings. These logs would then be consolidated into larger spreadsheet providing a summary of all activities, which ultimately could contribute to the as-built report.

A QAPP should include a link to a daily log template contained within a document management system, as well as guidance on how to produce and use them. Guidance on use of daily logs could include who they should be sent to and when, and what their associated actions would likely to be. Potential actions could be:

- Confirming they have read the log, and no further action required.
- Confirming they have read the log, and questioning/discussing its content.

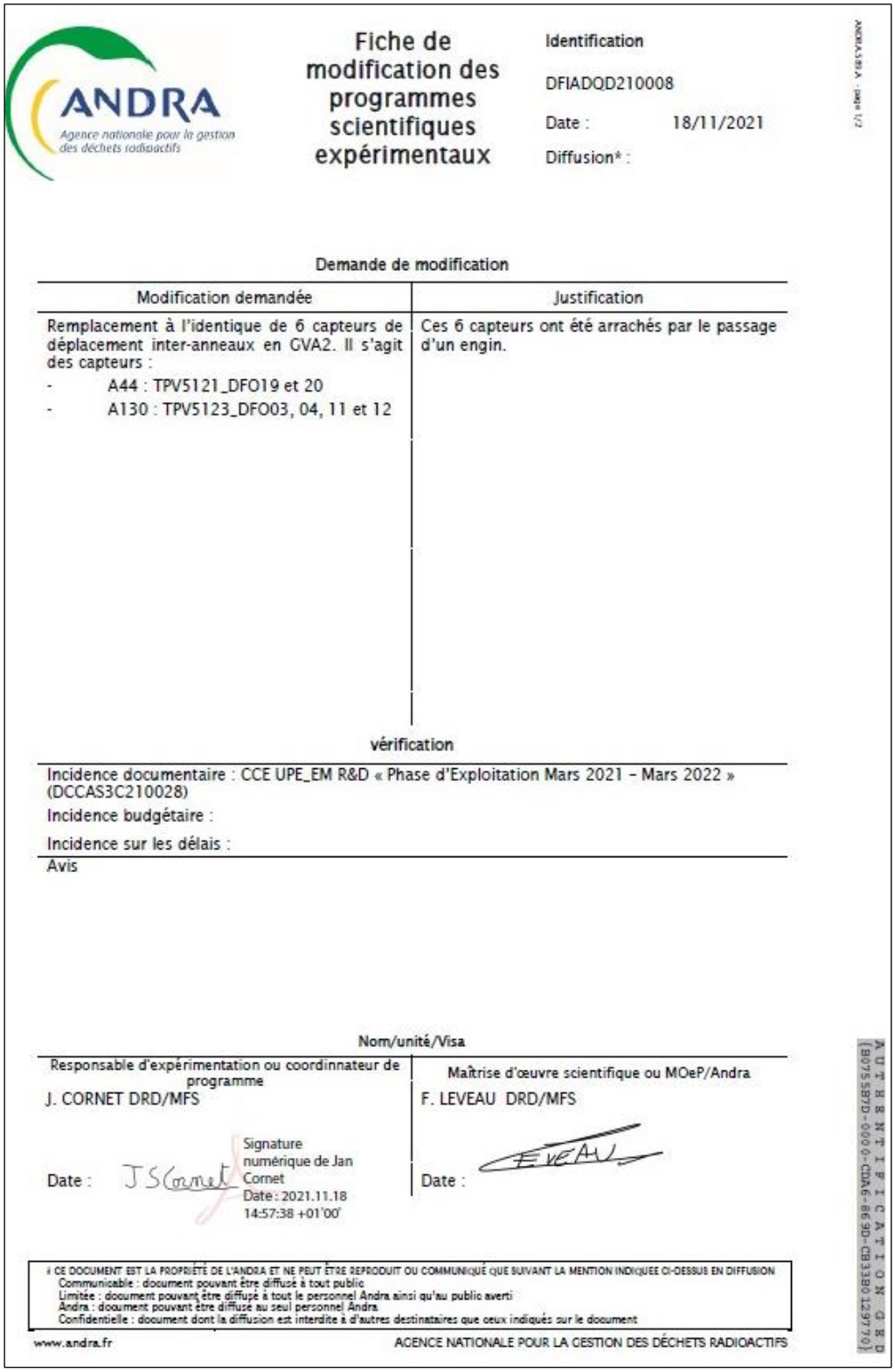
The daily log should include photographs of the installed sensors, along with their measured position; an example of an expected daily log photo is presented in Box 8. The template for the daily log would state how photographs are captured e.g., what to include in the photographs of installed sensors (e.g., sensor name) and what angles to take photographs from.

A log for maintenance actions and changes regarding each piece of monitoring equipment should be established and maintained throughout the lifetime of the monitoring programme. A register can be used and it can include equipment-specific action logs.

Andra provides information about changes to the monitoring system in an operations report. This report summarises all daily logs and modifications to the URL monitoring system. Major changes to the monitoring system must be made in accordance with the Monitoring System Change Policy. Minor changes require discussion with and authorisation by the Experimental Lead.

Box 7 – Example of change record sheet. Provided by Andra.

This example is a document produced by Andra to record modifications following a specific event in the Bure URL. Here, 6 displacement sensors were torn off the gallery wall (GVA2) and damaged by a truck. On the left, the text specifies the request by asking for the replacement of the sensors. On the right, the justification text explains what happened.



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Agence nationale pour la gestion des déchets radioactifs

Fiche de modification des programmes scientifiques expérimentaux

Identification
DFIADQD210008
Date : 18/11/2021
Diffusion* :

Demande de modification

Modification demandée	Justification
Remplacement à l'identique de 6 capteurs de déplacement inter-anneaux en GVA2. Il s'agit des capteurs : - A44 : TPV5121_DFO19 et 20 - A130 : TPV5123_DFO03, 04, 11 et 12	Ces 6 capteurs ont été arrachés par le passage d'un engin.

vérification

Incidence documentaire : CCE UPE_EM R&D « Phase d'Exploitation Mars 2021 – Mars 2022 » (DCCAS3C210028)
Incidence budgétaire :
Incidence sur les délais :
Avis

Nom/unité/Visa

Responsable d'expérimentation ou coordinnateur de programme	Maîtrise d'œuvre scientifique ou MOeP/Andra
J. CORNET DRD/MFS	F. LEVEAU DRD/MFS
Date : J S Cornet Signature numérique de Jan Cornet Date : 2021.11.18 14:57:38 +01'00'	Date : F. LEVEAU

i CE DOCUMENT EST LA PROPRIÉTÉ DE L'ANDRA ET NE PEUT ÊTRE REPRODUIT OU COMMUNIQUÉ QUE SUIVANT LA MENTION INDIQUÉE CI-DESSUS EN DIFFUSION
Communicable : document pouvant être diffusé à tout public
Limitée : document pouvant être diffusé à tout le personnel Andra ainsi qu'au public averti
Andra : document pouvant être diffusé au seul personnel Andra
Confidentielle : document dont la diffusion est interdite à d'autres destinataires que ceux indiqués sur le document

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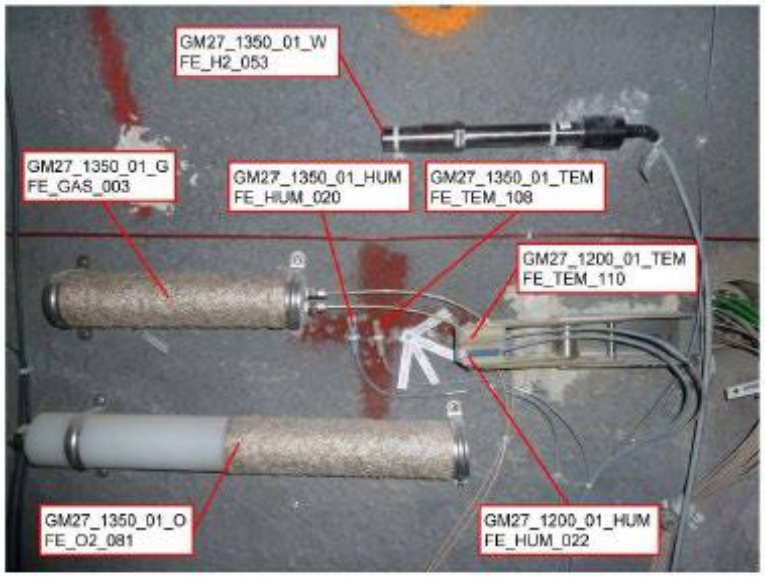
Box 8 – Example of sensors' location documentation.

This example illustrates part of the process used by Nagra to record the position of sensors during the installation of the FE experiment, including the use of photographs of the installed sensors, along with their measured position. The top photo shows a heater (top) on a bentonite pedestal with an oxygen concentration sensor *Hamilton Visiferm* (red rectangle). GM 25.6 indicates that the photo was taken at 25.6 meters from the gallery entrance. The bottom photo shows the position of a gas sampling port for *Neroxis MTCS 2204* hydrogen sensor, *SH25* humidity and temperature sensor and *MS5803-01BA* integrated digital pressure sensor. The sensor codes in the red rectangles indicate the sensor type such as for example GAS, HUM and TEM for gas, humidity, and temperature sensors, respectively.

GM 25.6

GM 28-29



5.3 Operation

This section of a QAPP would describe the QA-relevant aspects related to the operation, ongoing maintenance, and adaptation of the monitoring system to ensure reliable data acquisition.

5.3.1 Ongoing Maintenance and Uncertainty Management

As the monitoring system is expected to operate over an extended timeframe, ongoing maintenance is needed to uphold the integrity of data collection. Maintenance of the monitoring system should be governed by a dedicated maintenance plan (see Section 2.2 and Figure 2-4). In the context of this section, a QAPP would provide a summary of QA-relevant features of the maintenance plan. It would highlight how maintenance activities align with the overall QA objectives of the monitoring programme and how any QA challenges specific to maintenance would be addressed.

This includes routine maintenance activities such as software and hardware upgrades, recalibration of accessible sensors, and addressing uncertainties identified during the design phase (i.e., the timescale of the monitoring period, which is likely to extend beyond the timescale of operating experience and the potentially harsh environment of the repository). In addition, operation of the monitoring programme should include periodic evaluations of monitoring system performance. This evaluation would serve as a critical component in ensuring the reliability and effectiveness of the monitoring system.

A QAPP would provide a link to the maintenance plan and explain how the maintenance plan provides confidence in the future operation of the monitoring system. A QAPP could also outline how uncertainties related to the monitoring system's operation will be managed, ensuring that any deviations from expected performance are addressed promptly and transparently.

5.3.2 Updates and Adaptation

During operation, updates to a repository monitoring programme may become necessary, particularly in response to periodic updates to the safety case or license. These updates might stem from evaluations of the monitoring programme, potentially leading to changes in the programme. Changes could be relatively minor, for example, changing the frequency of measurements made by a particular sensor, or more significant, for example, conducting additional monitoring using new sensors. It will not be possible to plan for such changes, as they will depend on the results of the monitoring programme and any external influences such as changes in stakeholder requirements. A QAPP would clarify the process for making such updates, ensuring alignment with evolving programme needs while maintaining consistent QA practices and would describe how the quality-related activities of implementing any changes to the monitoring system would be undertaken and recorded. The identification of updates is discussed in Section 7.

5.3.3 Decommissioning

A QAPP would identify and summarise the expected procedures and protocols through which the monitoring system equipment would be decommissioned. This would include an assumption of whether the equipment would be removed or left *in situ*.

For some monitoring technologies, decommissioning provides an opportunity to gain additional QA insights. For example, should monitoring sensors be removed from inaccessible positions during their operations (e.g., by over-coring followed by sealing), the state of the sensor could be assessed. However, as indicated in Section 6, the emphasis here is on ongoing evaluation of monitoring system data as the primary means of assessing data quality and building confidence in results. Decommissioning-related QA information is viewed as complementary and secondary to the continuous evaluation of operational data.

6. QAPP Content on Monitoring Data

This section of the repository monitoring QAPP would outline the plan for managing the data (Section 6.1), processes for responding to acquisition of monitoring data that exceed action limits (Section 6.2), QA/QC procedures associated with monitoring data processing (Section 6.3), storage (Section 6.4) and auditing (Section 6.5). These procedures should be developed by WMOs to ensure that the data can meet the monitoring data objectives expressed in the DQOs (Section 4.2).

6.1 Monitoring Data Flow and IT Architecture Plan

A Monitoring Data Flow and IT Architecture Plan, also referred to as a Data Management Plan (DMP), would describe the management of the monitoring data. It is a key element of good data management. The plan would describe the data management life cycle for the data collected, processed and/or generated by a repository monitoring programme. As part of making the data acquired during a monitoring programme FAIR, the plan should include information on:

- The handling of data during and after repository operation.
- What data will be collected, processed and/or generated.
- Which methodology and standards will be applied for managing the data.
- Whether data will be shared/made open access.
- How data will be curated[5] and preserved (including after the end of the programme).

Monitoring data flow and IT architecture in general are topics of importance. A large proportion of the effort expended during a monitoring programme is spent on data-related tasks. These include importing data, data processing, ensuring the technical functioning of the hardware and software systems on which the data flow and processing is based, and visualising the data into the reports. These tasks can take the biggest proportion of the available work time of monitoring experts. It is extremely important that all data procedures for different datasets in different monitoring disciplines are defined in guides of the management system in the WMO. It is a good example of an area of work, where it is not practically possible for the experts to remember how things should be done as different data handling procedures and software need to be applied for different sets of data, and the amounts of data alone, can be significant.

This section of a QAPP would refer to the Monitoring Data Flow and IT Architecture Plan or DMP and outline the quality-aspects of the methods by which data will be transferred to the database, and document how the data will be organised, stored and backed-up in the database, including data formats. It will also outline the metadata that will be stored alongside other data in the database.

6.2 Responding to Data Exceeding Action Limits

This section of a QAPP would define the administrative process used to evaluate monitoring data that fall outside of action limits. Reacting promptly and systematically to situations where monitoring data deviate from the allowed range of variation is important to ensure that monitoring supports its main overarching goals and objectives (see Figure 3-2). A range of responses to data exceeding action limits can be envisaged (Table 6-1) [27. The Monitoring Data Flow and IT Architecture Plan would provide the procedure for implementing any or all of these actions.

[5] Data curation is the organization and integration of data collected from various sources. It involves annotation, publication and presentation of the data so that the value of the data is maintained over time, and the data remains available for reuse and preservation. Data curation includes "all the processes needed for principled and controlled data creation, maintenance, and management, together with the capacity to add value to data" (Wikipedia, 231129)

Table 6-1 – Generic responses to monitoring results. From [27].

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

6.3 Monitoring Data Processing

This section of a QAPP would describe QA-relevant aspects of monitoring data treatment and identify the procedures and protocols to be used for data treatment, including the following steps:

- Conversion of raw data to parameter of interest.
- Error detection.
- Anomaly detection.
- Data cleansing.
- Filling data gaps.
- Data classification.

A QAPP will identify the procedures and protocols that define the formulae used to convert the data into the parameters of interest. Some data loggers would automatically convert a measured parameter into a parameter of interest, e.g., time-domain reflectometer velocities into water content. However, confidence in this conversion would need to be demonstrated within the QAPP. A QAPP could also document the types of error that could occur in monitoring data, the criteria that could be used to identify and document the errors, and the actions that could be taken in response. In addition, a QAPP could define data cleansing procedures, including, if necessary, the conversion of the results into consistent timesteps, smoothing of data, and removal of null values. It would also include descriptions of the response to trigger values being exceeded in the alarm systems.

In URL experiments, principal investigators/experiment leads are responsible for data cleansing and treatment, prior to its use. Daily downloads of monitoring data to a central database would indicate if data have not been received from a particular sensor, which would act as a warning that the sensor may have failed. Daily reviews of data could also identify values outside of expected range. For repositories, a dedicated data scientist could be employed to check data and ensure they meet quality requirements, outlined in the QAPP and the underlying procedures and protocols. To support efficient data treatment, WMOs could classify data into four distinct types:

- Raw Data: This category would include the original electrical signals as well as signals that have been automatically converted into the parameter of interest. It would represent the unprocessed and unfiltered data captured from the measurements. All raw data should be retained.
- Cleansed Data[6]: Preliminary cleaning of the data should be automatically processed. It could consist of algorithms that would flag null values, noise, outliers, or any other data suspected to be incorrect.
- Structured Data: Once the cleansed, data could be organized and structured based on spatial and temporal information. This categorization would allow for efficient analysis and retrieval of data based on their location and time of measurement, enabling a better understanding of the overall data patterns.
- Integrated Data: Integrated data would refer to a subset of the cleansed data that would be specifically selected for a particular purpose or analysis. This selection process could involve carefully choosing relevant data points from the cleansed dataset to address specific research questions or achieve a specific objective. Integrated data could be used to gain insights or draw conclusions about particular needs or issues during the programme.

[6] Data cleansing or data cleaning is the process of detecting and correcting (or removing) corrupt or inaccurate records from a record set, table, or database and refers to identifying incomplete, incorrect, inaccurate or irrelevant parts of the data and then replacing, modifying, or deleting the dirty or coarse data.[1] (Wikipedia, 231129)

6.4 Monitoring Data Storage

6.4.1 Data Management System

To ensure effective data management, it is considered good practice to establish a dedicated data management system, such as a comprehensive database, which can cover the entire monitoring system. This system could be linked to other relevant databases, such as a geological database, providing a holistic view of the data. Raw data would be collected in each DAS, which, in URL experiments, are typically specific to each sensor manufacturer. Each DAS would transfer the raw data to the central database.

To facilitate analysis and understanding, each sensor should be associated with metadata containing essential information such as calibration details, location, events and related activities. It is important to ensure that these metadata are dynamically updated to reflect any changes made.

These metadata should be easily accessed and displayed through a graphical user interface, allowing for intuitive visualisation and analysis of the monitoring data.

6.4.2 Data-User Relationships

To accommodate user needs and requirements, it is advisable to establish a system that allows users to request changes to sensor data, for example removal of null values, delivery of data in specific timesteps or adjustment for drift (see Section 6.3). Implementing a helpdesk-style support system can effectively log and address these requests (which would then be subject to a formal approval process), ensuring a streamlined process.

As an example, Andra has an online maintenance management tool which uses a ticketing system to request changes, such as:

- Replacement of sensors.
- Changes to sensor calibrations.
- Replacement of software.
- Changes to the data.

6.4.3 Data Format

For storing sensor data, it is recommended to use a non-proprietary standardised ASCII format, with the capability to automatically convert proprietary formats if needed.

When recording timestamps, it is recommended to use the Coordinated Universal Time in a consistent string format such as YYYYMMDDHHMMSS that represents date and time values with:

- YYYY: Four-digit year.
- MM: Two-digit month (01-12).
- DD: Two-digit day of the month (01-31).
- HH: Two-digit hour (00-23).
- MM: Two-digit minute (00-59).
- SS: Two-digit second (00-59).

This format allows for easy interpretation and synchronisation of timestamps across different datasets. Note that seasonal changes to the clocks also need to be considered and factored into the DMP.

6.4.4 Save and Backup

To ensure data integrity and longevity, it is recommended to periodically replace database servers, (e.g., every three years for Andra), in line with manufacturer guarantees. During this process, all data and metadata should be seamlessly transferred to the new servers, preserving the entire historical record of the database.

Archiving and organising all of the maintenance notes and other notes regarding different monitoring devices and equipment is crucial in order to process the data so that peaks or erratic values resulting from the devices themselves or their maintenance etc. can be systematically ruled and filtered out of the actual processed monitoring data. In practice, this requires a dedicated register or registers, which can then be updated by the persons doing the maintenance etc. actions and accessed by the monitoring discipline specialist to distinguish “real” events in the data from artificial events caused by the devices or maintenance actions.

Potential challenges such as software compatibilities and power failures should be taken into consideration during server replacements. To mitigate the risk of data loss during power failures, uninterruptible power supplies can be employed as a backup power source.

6.5 Monitoring Data Audit

This section of a QAPP would establish the procedures for conducting audits to assess the monitoring data in relation to the defined data objectives. The audits serve as an essential step in ensuring the data meet the DQOs. By systematically reviewing and evaluating the data and monitoring system performance, the audit process could identify any potential issues, discrepancies, or deviations from the intended objectives. The supporting audit documentation would include audit plans, checklists, observation logs, and any other relevant forms or templates necessary for recording the audit activities.

6.5.1 Audit Procedures

A QAPP would include, or reference out to, audit procedures that would outline the specific steps and methodologies employed to carry out the data audits. These procedures should encompass the following aspects:

- Timing and Frequency: This sub-section of an audit procedure would specify the intervals at which audits will be conducted throughout the monitoring programme (see Section 3.3). It would consider factors such as the data collection schedule, programme timeline, and the significance of the data being monitored. Regular audits would be conducted to provide consistent oversight and control over the data quality.
- Responsibilities: Clearly defined roles and responsibilities will be assigned to individuals or teams responsible for conducting the audits. These individuals will possess the necessary expertise in data analysis and interpretation to ensure effective evaluation of the collected data. Their responsibilities will encompass organising, executing, and documenting the audit activities. Note that the audit responsibilities would be defined in Section 3.4.
- Documentation: Comprehensive documentation of the audit process should be prepared and maintained. This sub-section of an audit procedure would outline the specific records that need to be maintained during the audits. Documentation may include audit plans, checklists, observation logs, and any other relevant forms or templates necessary for recording the audit activities.
- Audit Results: Once any audits were completed, the results would be documented and analysed. This sub-section of an audit procedure could specify the format for recording the audit outcomes, including any identified data discrepancies, anomalies, or non-compliance with data objectives. Additionally, it could describe the protocols for communicating the audit results to the relevant stakeholders.

- Verification of DQOs: Depending on the programme, the audit may encompass an assessment of the DQOs to ensure their appropriateness.

6.5.2 Addressing Audit Results

This sub-section outlines the general approaches and procedures for addressing the findings and outcomes of the data audits. It may include the following elements:

- Data Verification and Validation: In cases where discrepancies or anomalies are identified during the audits, further verification and validation steps would be undertaken. These steps may involve additional data collection, cross-referencing with independent data sources, or statistical analysis to ensure the accuracy and reliability of the data.
- Corrective Actions: When significant issues are detected during the audits, corrective actions would be implemented to rectify the identified problems. This sub-section of an audit procedure could outline the procedures for developing and implementing these corrective actions, which may include revising data collection protocols, modifying monitoring procedures, or providing additional training to personnel involved in the data collection process.
- Continuous Improvement: The audit results would be used as valuable feedback to improve the overall monitoring process. This sub-section of an audit procedure would highlight the importance of using the audit results to identify areas for improvement and to implement measures that enhance data quality and reliability. It may include periodic reviews of the monitoring protocols and adjustments to ensure ongoing compliance with data objectives.
- Preventive action: This aspect involves instituting proactive measures to forestall potential issues before they arise in the data monitoring process. It may encompass a comprehensive evaluation of existing protocols and procedures to identify vulnerabilities. Subsequently, measures would be implemented to strengthen these processes, such as refining data collection methodologies, enhancing monitoring protocols, or conducting regular training sessions for personnel involved in data collection. The aim is to establish a robust preventive framework that minimizes the likelihood of errors or discrepancies occurring in future audits, thereby fostering sustained data quality and reliability.

Implementing such a rigorous audit procedure and addressing the outcomes effectively is expected to build confidence in the monitoring data, leading to informed decision-making.

7. QAPP Content on Monitoring Programme Feedback

This section of the repository monitoring QAPP would summarise quality-relevant information on the modification or change to the monitoring programme during repository operation. Monitoring programme responses were recognised as one of three generic group of responses to periodic evaluation of monitoring data in the Modern2020 project (the other two were desk-based responses and disposal programme responses) [3]. It is envisaged that changes to the monitoring programme would be made according to a pre-defined procedure that would be identified within a QAPP.

Two types of monitoring response are envisaged, either to continue monitoring in the same way as previously, or to change the monitoring programme.

Continuing the operation of the monitoring programme using the same method means that the monitoring programme would continue using the same number and type of sensors, in the same locations, and with acquisition of data at the same frequency. This could include some differences in the monitoring programme, for example, reduced number of sensors owing to sensor failure or differences to the methods through which monitoring data were treated, managed or audited.

Changes in the monitoring programme could relate to changes in the frequency of data acquisition using the current monitoring system, monitoring the same parameter(s) with additional sensors of the same type (additional redundancy), monitoring the same parameter(s) with different sensors (increased diversity), or monitoring of different parameters.

As recognised in the Modern2020 project, it will not be possible to *a priori* define the manner in which the monitoring programme will evolve during the period of repository operation [3]. Therefore, the procedure identified in a QAPP should describe the processes through which monitoring programme changes are proposed, agreed and implemented, including the need for consultation with the regulator and other stakeholders during the decision-making process.

Overall, this feedback section of a QAPP would serve as a component for maintaining a robust and adaptive monitoring programme. It establishes a framework for gathering and incorporating feedback from stakeholders, ensuring that the programme remains responsive to changing needs, technological advancements, and evolving regulatory standards.

8. Guidance on the Production of QAPPs

This section discusses the approach that could be used by WMOs to produce and maintain a QAPP:

- Section 8.1 discusses the roles and responsibilities for QAPP production and maintenance.
- Section 8.2 provides guidance on the production of QAPPs.

8.1 Roles and Responsibilities

As noted in Section 2.2, it is envisaged herein that the QAPP will be a signposting document that identifies the procedures and protocols to be followed during the monitoring programme. Therefore, it is envisaged that a QAPP would be produced by a team, each member of which would contribute in their own area of expertise.

The Monitoring Programme Manager, who is responsible for overseeing the overall monitoring programme, holds a comprehensive understanding of the monitoring objectives and requirements. It is envisaged that they would co-ordinate the production of the of a QAPP, for example, acting as lead author of the document and co-ordinating the preparation of underpinning procedures and protocols. For the underpinning documents, it is anticipated that each specialist working on the monitoring programme would prepare underpinning reports associated with their specialism:

- Monitoring technologists would prepare protocols and procedures for designing and implementing the monitoring system.
- Discipline Leads would prepare protocols and procedures related to DQOs.
- Data Scientists would prepare protocols and procedures for data treatment and storage.
- The Quality Manager would support the preparation of all procedures and protocols, ensuring they are consistent with programme-wide approaches, and would have particular input to procedures and protocols associated with data audits.

8.2 Production and Review of a QAPP

8.2.1 Gathering Relevant Information

To produce a comprehensive QAPP, it is important to gather relevant information that informs its development. This includes obtaining the quality management plan that outlines the organisation's QMS. This document provides valuable guidance on the processes, procedures, and standards to be incorporated into a QAPP. Additionally, reviewing existing plans related to the implementation and maintenance of the monitoring system offers insights into the technical aspects of the monitoring programme and informs the development of a QAPP.

8.2.2 Referencing Organisational Quality Management System:

A QAPP should align with the QMS implemented at the organisational level to ensure consistency and adherence to established quality standards. This involves reflecting and aligning the QAPP with the organisation's QMS, incorporating its principles and guidelines. Additionally, relevant standard operating procedures from the organisational QMS should be identified and incorporated into the QAPP to provide guidelines for conducting specific monitoring activities. In addition to interfacing with the QMS, a QAPP would also have to interface with the other documentation describing the monitoring programme presented in Section 2 and Figure 2-4.

8.2.3 Schedule

A QAPP should be available at the start of the process for designing a monitoring programme. It is required to understand the information and processes that are to be used in design work, such as choosing sensors and their position within the repository. Indeed, an outline QAPP, with the structure of protocols and procedures that underpin it, should be produced as early as possible in a repository programme so that long-term activities (such as collation of the knowledge on which the design will be based) can be planned in advance.

However, a QAPP requires the Monitoring Programme Strategy (or an initial version of it) to be available prior to preparation, as the strategy for the programme will dictate how the QAPP is structured and will identify issues that a QAPP would have to respond to.

9. How this Guidance Addresses Key Challenges in Repository Monitoring

As summarised in Section 1.3, repository monitoring is subject to unique challenges. Quality issues specific to repository monitoring stem from the long duration envisaged for the programme and the potential that some monitoring equipment may not be accessible for maintenance or replacement following installation.

The primary manner in which this guidance responds to these challenges is to propose a comprehensive structure and content for a QAPP. The structure and content are consistent with good practice as defined by the ISO [16], the IAEA [17] and the US EPA [20]. In particular, this guidance is consistent with good practice because it proposes that quality is at the centre of all decisions throughout the life cycle of the repository monitoring programme.

The guidance in this document incorporates approaches consistent with the PDCA cycle (Figure 2-2). However, for a repository monitoring programme, the ability to act or change the monitoring approach is limited once the monitoring system is installed. Therefore, emphasis is placed on using the knowledge that exists from many decades of successfully operating URL experiments and undertaking site investigations to ensure that the design of the monitoring system will provide the necessary quality of data from the outset. The guidance recognises that much of this knowledge is not available in structured, transparent and traceable databases (it is mainly held as expert knowledge by individuals), and therefore recommends the development of databases on which to base design decisions. Other knowledge management approaches may also be relevant.

The guidance also supports appropriate definition of the repository monitoring programme by referencing structured methods for defining the strategic approach to be adopted in the programme. These include use of the MoDeRn Monitoring Workflow (Figure 3-1) and the Modern Screening Methodology (Figure 3-3) to identify the objectives of the programme, to identify process, parameter and technology combinations, and to ensure that the programme responds to stakeholder needs, including the needs of the national context, the safety case, regulators and civil society. An appropriate strategic approach would obviate any potential problems introduced by sensor failure (e.g., by placing important sensors in accessible locations or by allowing for failure of monitoring equipment in the overall monitoring approach).

Keeping quality at the centre of all decisions, is also facilitated by providing and recording the decisions made throughout the life cycle of the repository monitoring programme. This includes development of DQOs on sensors, and requirements on other components of the monitoring system, to ensure that selection of monitoring equipment is consistent with the needs of the programme.

A variety of tools are proposed throughout this guidance to check plans, and to ensure transparency and traceability throughout the monitoring programme. These include the use of 3D models of the monitoring system layout to support design, the recording of daily logs to track monitoring system installation, use of naming conventions for ease of reference, procedures and protocols for daily checking of data (including responsibilities and reporting lines), and procedures and protocols for treatment and management of data.

This guidance envisages that the monitoring programme would be actively managed and would be part of daily activities throughout the programme life cycle. This active approach would ensure that knowledge and understanding of the programme is maintained and would facilitate the training and induction of new staff into the programme through time, mitigating any potential problems associated with staff turnover.

Part of this active management would be periodic revision and publication of a QAPP and the associated monitoring programme documentation alongside periodic updates to the safety case. This periodic revision would provide an opportunity to incorporate technological advancements into the programme, or to respond to evolving objectives.

Section 1.3 recognised five specific quality issues specific to repository monitoring. The way in which this guidance addresses these challenges is presented in Table 9-1.

Table 9-1 – Response of this guidance to key challenges in repository monitoring.

Challenge	Description	How the Challenge is Addressed in this Guidance
Monitoring System Failures	Repository monitoring is expected to continue over several decades, during which time there is a potential for the monitoring system to fail, sometimes in unpredictable ways.	Use of structured methods to develop an appropriate strategic approach to the monitoring programme (Sections 3.1 and 3.2). Incorporating procedures for checking the monitoring system's performance regularly (Section 6). Describing protocols for equipment calibration, maintenance, and data validation (Section 5). Emphasizing the importance of verifying and validating data to identify any anomalies or indications of potential system failures (see Section 6).
Staff Turnover and Decision Understanding	Owing to the long timeframes envisaged for monitoring programmes, there will be changes in the staff responsible for managing and executing the monitoring activities.	Documenting the decision-making processes used during the design (Section 4) and implementation (Section 5) of the monitoring programme. Providing clear and comprehensive documentation (Section 3.5), including the rationale behind the choices made, ensuring that future staff can understand the programme's objectives and underlying principles. The documentation proposed in this guidance would support knowledge transfer (Section 3.4), and maintenance of consistency and continuity in the monitoring programme.
Technological Advancements	Over the lifespan of a monitoring programme, there could be advancements in monitoring equipment, and data treatment, management and analysis software.	Ensuring that data acquired during the early stages of the monitoring programme remain accessible and usable in the later stages of it by having a plan for software and hardware upgrades (Section 5.3.1). Including in a QAPP strategies for data treatment (Section 6.3) and data management (Section 6.4), including the storage of the data, and migration to compatible formats, thereby preserving access to historical data and ensuring its compatibility with future technologies.
Flexibility for Changing Objectives	As monitoring programmes span several generations, the objectives and priorities of the programme may evolve.	Providing a framework that allows for flexibility in refining the objectives of the monitoring programme. Section 7 (Feedback to the Monitoring Programme) summarises quality-relevant information on the modification or change to the monitoring programme during repository operation considering input from regulators, stakeholders, and future generations of decision-makers. This flexibility would ensure that the programme remains relevant and aligned with current and future needs.
In Situ Monitoring Challenges	In the majority of cases, it will not be possible to access and maintain *in situ* sensors	Incorporating appropriate QA procedures to account for the limitations in accessing and maintaining *in situ* sensors. These procedures can involve remote connectivity, diagnostic tools, automated sensor anomalies detection system that notify operators (Section 6.3); guidance in Section 6 (Checking the Monitoring Data) covers QA-relevant aspects of monitoring data treatment. By considering redundancy measures in the design (Section 4.3), a QAPP would ensure that data collection continues even when direct access to sensors is not possible.

10. Summary and Conclusions

The focus of the MODATS WP is monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. In particular, MODATS is focusing on confidence in monitoring data. A QAPP documents the planning, implementation, and assessment procedures for a particular monitoring programme, as well as any specific QA and QC activities. This document contributes to the aims of MODATS by providing generic guidance on the structure and content of a QAPP for repository monitoring systems. It is envisaged that each repository programme would tailor the guidance in this document to the needs and context of the programme in question.

The guidance proposes that a QAPP is structured in five sections:

- Organisation of the Monitoring Programme: This section would outline:
  - The monitoring programme objectives, and the strategic approach to it.
  - The processes and parameters to be monitored and the technologies used to do so, as well as the method used to select the process, parameter and technology combinations.
  - The programme schedule.
  - The roles and responsibilities of the actors involved in the programme.
  - The documentation produced.
- Design of the Monitoring System: This section would detail the quality-relevant information on the design of the monitoring system. It would describe the knowledge on which the design of the system is based. It would present DQOs for sensors and requirements for other components of the monitoring system, selection procedures for specific technologies (i.e., particular sensors), and procedures and protocols for describing the monitoring system layout.
- Implementation of the Monitoring System: This section would cover the practical implementation of the monitoring system from installation to decommissioning. It would include the procedures for equipment deployment, calibration, and maintenance.
- Checking Monitoring Data: This section would describe methods for verification and validation of monitoring data to ensure they meet the DQOs. It would encompass QA and QC aspects relating to data storage, treatment and management, and would outline processes and procedures that cover data QA measures including periodic data audits. Adherence to the procedures and protocols identified in this section would ensure the effective execution of the monitoring activities according to the established design and protocols.
- Feedback to the Monitoring Programme: This section would describe procedures and protocols related to the modification or change of the monitoring programme during its operation. It would describe the processes for proposing, agreeing, and implementing monitoring programme changes, including consultation with regulators and stakeholders during the decision-making process. The feedback section may also address continuous improvement strategies, lessons learned, and adjustments to the monitoring programme based on the requirements of the safety case, stages in repository implementation and stakeholder input.

Examples of good practice quality processes from URL experiments are also included to illustrate the guidance provided in this document.

The guidance in this document envisages that a QAPP would act as a gateway to a document management system that would be used to store and access the procedures and protocols to be followed during the design, installation, operation and decommissioning of the repository monitoring programme.

It is proposed that a QAPP is developed at the earliest possible opportunity in a repository programme to ensure that all work undertaken in designing and implementing the monitoring programme are undertaken in a quality-assured manner.

A repository monitoring programme is subject to specific QA issues owing to the long duration envisaged for the programme and the potential that some monitoring equipment may not be accessible for

maintenance or replacement following installation. The guidance in this document addresses these challenges by:

- Covering the full life cycle of the repository monitoring programme, and providing approaches whereby quality can be at the centre of all decisions throughout the life cycle of the programme.
- Placing an emphasis on using knowledge gained from successfully operating URL experiments and undertaking site investigations, and thereby ensuring that the design of the monitoring system will provide the necessary quality of data from the outset.
- Identifying the need for the repository monitoring programme to be appropriately defined at the outset.
- Recording decisions in a transparent and traceable manner.
- Identifying tools that can be used to check plans and ensure transparency and traceability.
- Proposing that the monitoring programme is actively managed.

Therefore, the guidance on QAPPs provided in this document offers a framework for addressing the challenges posed by repository monitoring. By structuring a QAPP into five main sections and offering flexibility in its implementation, WMOs 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 monitoring programmes remain effective, credible, and beneficial over the entire duration of repository operations.

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