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Deliverable D2.3: Responding to Monitoring Results

Work Package 2

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Contributor(s)	Matt White, Jo Farrow and Sally Scourfield (Galson Sciences Limited), Claudia Vivalda (Nidia), Camille Espivent (IRSN), Bernd Frieg (Nagra), Michael Jobmann (BGE Technology), Mansueto Morosini and Assen Simeonov (SKB) and Simon Norris (RWM)
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RE	Restricted to a group specified by the partners of the Modern2020 Project	
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Final	Version 1: responds to peer review by David Luterkort (SKB) and Frédéric Plas (Andra), plus additional comments from Piet Zuidema and Peter Simmons (Rapporteurs of the Modern2020 Conference on Repository Monitoring) and Johan Andersson (SKB)	Galson Sciences	18/06/2019

Reviewed by:

This report has been reviewed according to the Modern2020 Quality Plan and the Deliverables Review Procedure therein. Formal review according to a Review Plan has been undertaken by David Luterkort (SKB) and Frédéric Plas (Andra), and documented in Review Statements.

Approved by:

This report has been approved by:

- Manno Morosini, Work Package 2 Leader, ***20/05/2019***
- Johan Bertrand, the Modern2020 Project Co-ordinator (on behalf of the Modern2020 Project Executive Board), ***31/05/2019***

Executive Summary

Introduction and Objectives

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project aims to provide the means for developing and implementing an effective and efficient repository operational monitoring programme. The main focus of the Project is monitoring of the repository near-field during the operational period to support decision making and to build further confidence in the post-closure safety case.

This report is the report from Task 2.3 of the Modern2020 Project. The objectives of Task 2.3 and this report are:

- To set out recommendations and observations on planning for evaluating and responding to monitoring results.
- To consider how monitoring focused on building further confidence in the post-closure safety case can contribute to decision making during repository operation and closure.

Evaluation of monitoring results needs to consider both individual results (i.e. monitoring of the same parameter, potentially in multiple locations and/or with multiple types of sensor) and integrated consideration of the full range of monitoring data. Evaluation of individual results needs to be undertaken on a continuous basis during repository operations, whereas integrated evaluation would be undertaken periodically (e.g. 5-10 yearly, or when prompted by specific monitoring results).

For continuous evaluation of specific parameters, the main aspect will be to compare results to the anticipated domain of predicted parameter values. For this evaluation, three types of results are envisaged:

- Monitoring values and trends are consistent with the domain of predicted parameter values.
- Results are inconsistent with domain of predicted parameter values, but insignificant to safety.
- Results are inconsistent with predicted parameter values and require further evaluation.

Results that are inconsistent with the predicted parameter values could act as an early trigger for undertaking a periodic evaluation that considers the integrated data set.

The Modern2020 Project has identified the following recommendations and observations on planning for evaluating and responding to monitoring results:

- It is not possible to define a direct link to safety for all monitoring parameters (in all locations and at all times).
- Response plans should be developed to describe actions that could be taken following unanticipated monitoring results.
- Response plans need to be adaptable as the details of unexpected repository system behaviour cannot be predicted in advance, and responses should consider the overall repository system behaviour.
- Assessment of monitoring results might need to consider processes that have not been previously identified as being significant (although extensive research on repository processes means that there should be no new processes identified).
- Usually, the first response to unexpected results is to check data quality/interpretation, and then to consider the implications for safety.
- Monitoring results should be compared to the expected variation of the parameter values in time and space.
- Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the monitoring dataset.

- Periodic evaluation might occur in response to the outcome of a continuous evaluation and/or at a regular interval.
- Response plans should include the organisational set-up for responding to monitoring results.
- The approach to responding to monitoring results can be guided by consideration of a generic action list, comprising desk-based actions and physical actions.
- Responding to monitoring results can be undertaken in dialogue with stakeholders, as determined by programme-specific and country-specific procedures and regulations.
- Decision making is a complex process where monitoring is only one input.

Planning for responding to monitoring results has focused on identification and description of the following generic responses:

- Desk-based responses:
    - Check results.
    - Report results.
    - Evaluate sensor performance.
    - Root cause analysis.
    - Revise models / safety assessment.
    - Update monitoring plan.
- Monitoring Programme Responses:
    - Continue monitoring in the same way.
    - Change monitoring.
- Disposal Programme Responses:
    - Change operations.
    - Change design.
    - Engineering intervention.
    - Reversal / retrieval.

Responding to monitoring results is considered to be a stepwise process that includes the following steps:

- Acquire data and information.
- Compare to parameter predictions.
- Integrated evaluation of monitoring results.
- Continue monitoring in the same way.
- Change the monitoring programme.
- Change the disposal programme.
- End the monitoring programme.

The recommendations and observations presented in this report and the consideration of the processes used to respond to monitoring results have allowed additional detail to be added to the implementation and governance aspects of the MoDeRn Monitoring Workflow. The revised Workflow is shown in Figure E.1.

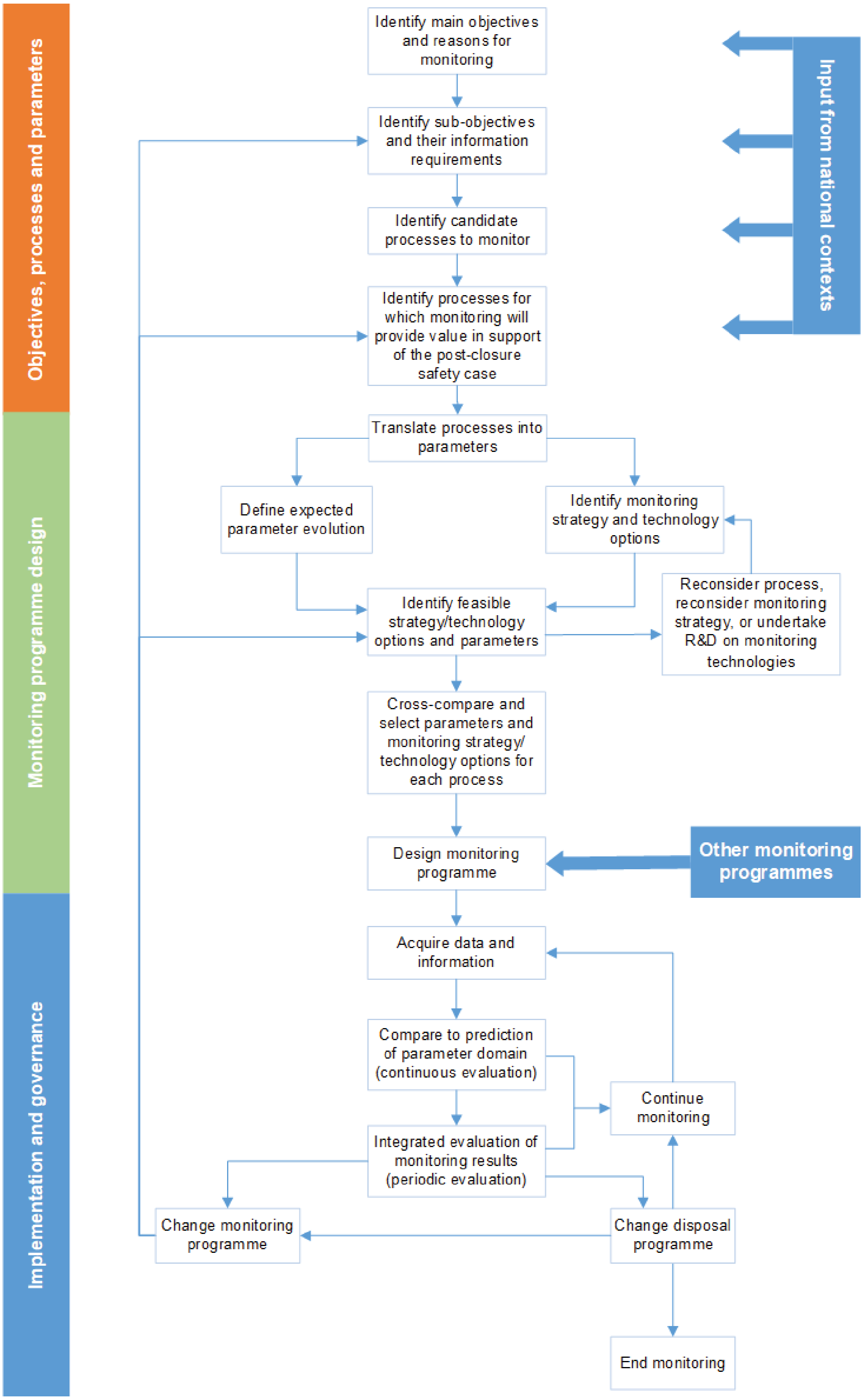

Figure E.1: The MoDeRn Monitoring Workflow, revised to take account of the recommendation and the consideration of the processes used to respond to monitoring results presented in this report.

List of Modern2020 Project Partners

The partners in the Modern2020 Project are listed below. In the remainder of this report each partner is referred to by its short name:

Partner name	Short name	Country
Agence Nationale pour la Gestion des Déchets Radioactifs	Andra	France
Amberg Infraestructuras	Amberg	Spain
Arquimea	Arquimea	Spain
Bundesgesellschaft für Endlagerung	BGE Technology	Germany
CeskeVysoke Uceni Technicke v Praze	CTU	Czech Republic
Electricite de France	EDF	France
Agenzia Nazionale per le Nuove Tecnologie, L'Energia e lo Sviluppo Economico Sostenibile	ENEA	Italy
Empresa Nacional de Residuos Radiactivos S.A.	ENRESA	Spain
Eidgenoessische Technische Hochschule Zuerich	ETH Zurich	Switzerland
European Underground Research Infrastructure for Disposal of Nuclear Waste In Clay Environment	EURIDICE	Belgium
Galson Sciences Limited	GSL	UK
Institut de Radioprotection et de Sûreté Nucléaire	IRSN	France
Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle	Nagra	Switzerland
Nidia SRL	Nidia	Italy
Nuclear Research and Consultancy Group	NRG	Netherlands
Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies / Nationale Instelling voor Radioactief Afval en Verrijkte Splijtstoffen	ONDRAF/NIRAS	Belgium
Orano	Orano	France
Posiva Oy	Posiva	Finland
Radioactive Waste Management Limited	RWM	UK
Radioactive Waste Management Funding and Research Center	RWMC	Japan
Svensk Karnbranslehantering AB	SKB	Sweden
Radioactive Waste Repository Authority	SURAO	Czech Republic
Technicka Univerzita v Liberci	TUL	Czech Republic
Universiteit Antwerpen	UAntwerpen	Belgium
Goeteborgs Universitet	UGot	Sweden
Universite de Mons	UMons	Belgium
Universite de Limoges	ULim	France
University of Strathclyde	UStrath	UK
Teknologian tutkimuskeskus VTT Oy	VTT	Finland

Acronyms

CCS:	Carbon capture and storage
DB:	Dummy borehole
EBS:	Engineered barrier system
EC:	European Commission
EO:	External organisation
ETS:	Emissions Trading Scheme
EU:	European Union
FE:	Full-Scale Emplacement
HA:	Highly-active
HLW:	High-level waste
IDP:	Implementer decision point
ILW:	Intermediate-level waste
KDP:	Key decision point
LTRBM:	Long-Term Rock Buffer Monitoring
MB:	Monitoring borehole
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
Modern2020:	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal
MVA:	Monitoring, Verification and Accounting
RD&D:	Research, development and demonstration
RDP:	Regulator decision point
THMCR:	Thermal, hydraulic, mechanical, chemical and radiological
WMO:	Waste management organisation
WP:	Work Package

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1 Introduction

1.1 Background

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project is a European Commission (EC) project funded by the Euratom research and training programme 2014-2018. The Project is running over the period June 2015 to May 2019, and 29 waste management organisations (WMOs), and research and consultancy organisations from 12 countries are participating.

The overall aim of the Modern2020 Project is to provide the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account requirements of specific national programmes. The Project is divided into six Work Packages (WPs):

- WP1: Coordination and project management.
- WP2: Monitoring programme design basis, monitoring strategies and decision making. This WP aims to define the requirements on monitoring systems in terms of the parameters to be monitored in repository monitoring programmes with explicit links to the safety case and the wider scientific programme (see below).
- WP3: Research and development of relevant monitoring technologies, including wireless data transmission systems, energy supply, new sensors, and geophysical methods. This WP will also assess the readiness levels of relevant technologies, and establish a common methodology for qualifying the elements of the monitoring system intended for repository use.
- WP4: Demonstration of monitoring implementation in repository-like conditions. The intended demonstrators, each addressing a range of monitoring-related objectives, are the Full-scale *in situ* System Test in Finland, the Highly-Active (HA) Industrial Pilot Experiment in France, the Long-Term Rock Buffer Monitoring (LTRBM) Experiment in France, and the Full-Scale Emplacement (FE) Experiment in Switzerland. Assessment and synthesis of other tests and demonstrators will also be undertaken.
- WP5: Effectively engaging local citizen stakeholders in research, development and demonstration (RD&D) on monitoring for geological disposal.
- WP6: Communication and dissemination, to include an international conference, a training school, and the Modern2020 Synthesis Report.

The Modern2020 Project focuses on monitoring of the underground repository system (including the engineered barriers and near-field host rock) during the operational period to support decision making and to build further confidence in the post-closure safety case (referred to as *repository monitoring* within the Project). This is where the greatest challenges lie in terms of strategy and technology, and where the greatest gains can be made through international collaboration. Challenges related to repository monitoring are associated with the slow rate at which the majority of relevant processes occur relative to the duration of the monitoring period, relating short-term transient processes to long-term performance of the disposal system, the potential detrimental impacts of monitoring on passive safety, and the long-term operation of monitoring equipment and the related confidence in monitoring results.

This report is Deliverable D2.3 of the Modern2020 Project and is the summary report for Task 2.3 (WP2.3), the third task in WP2. Task 2.3 aimed to develop decision-making methods, tools and workflows for responding to monitoring information, and to develop recommendations and observations on responding to monitoring results. It has received input information from Task 2.1 (White *et al*., 2017), which aimed to evaluate monitoring strategies, consider decisions requiring support from monitoring data, and develop methodologies for screening monitoring parameter lists, and Task 2.2 (Farrow *et al*., 2019), which evaluated safety cases for repositories in France, Switzerland, Finland, Sweden, Germany, the Netherlands, and the Czech Republic, and developed a common approach for identifying potential monitoring parameters.

1.2 Objectives of this Report

The objectives of this report are:

- To set out recommendations and observations on planning for evaluating and responding to monitoring results.
- To consider how monitoring focused on building further confidence in the post-closure safety case can contribute to decision making during repository operation and closure.

1.3 Scope

European WMOs are at different stages in developing operational period monitoring programmes focused on building further confidence in the post-closure safety case. Most WMOs are at the early stages of developing such monitoring programmes. However, it is expected that monitoring of specific components of the engineered barrier system (EBS) will be undertaken during the operational period of all programmes. Such monitoring could provide information that can be used to enhance the robustness of the post-closure safety case. This could include, for example, monitoring to provide a greater understanding of processes and their inherent couplings relevant to the *in situ* functioning of components of the EBS and near-field host rock.

General strategies for conducting such monitoring during the operational period have been elaborated by various WMOs and include, for example:

- The implementation by Andra of an Industrial Pilot Phase, which will include a small number of HLW cells and, potentially, seal demonstrators. These will allow many decades of monitoring before implementation (approximately 50 years in the case of HLW disposal cells and approximately 100 years, or more, for the seal demonstrators).
- The development by Posiva of a monitoring programme with five sub-programmes (rock mechanics, hydrology and hydrogeology, hydrochemistry, surface environment, and EBS).
- SKB's EBS monitoring strategy, which is based on monitoring of specifically designed EBS in situ tests.
- Plans by Nagra to monitor in a pilot facility, in emplacement rooms and access tunnels, and in a test facility (a facility for underground geological investigations).

In addition to these general strategies for monitoring during the operational period of geological repositories, monitoring programmes have been developed for existing radioactive waste disposal facilities. These include operating geological repositories, near-surface disposal facilities and repositories under construction. The strategies listed above, and the monitoring strategies under consideration by other WMOs participating in Modern2020, are described in Farrow *et al*. (2019).

Some WMOs have relatively mature monitoring programmes. For example, in Finland, Posiva has already established the monitoring practices, processes and parameters for four of its five sub-programmes (the exception is the EBS sub-programme). However, detailed monitoring programmes are yet to be developed by most WMOs, including identification of specific parameters to be monitored during the operational period to build further confidence in the post-closure safety case and the technologies that will be used to monitor these parameters. As discussed in the MoDeRn Project (MoDeRn, 2013a), each specific monitoring programme will respond to the relevant programme context, which includes national legislation and regulatory guidance, the wastes to be disposed of (including differences between programmes that focus on one type of waste (e.g. the SKB repository for spent fuel), and those programmes that have multiple types of waste (e.g. the Cigéo repository in France, in which Andra plans to dispose of

HLW and long-lived intermediate-level waste; and programmes with large inventories requiring repository operation over many decades and those with more restricted inventories that can be operated and closed in a shorter timeframe) the geological environment, and the repository design.

Therefore, it is not yet feasible to develop specific plans for responding to monitoring results and using the information gained in decision making. Instead, this report is focused on the development of generic guidance on planning for evaluating and responding to monitoring results, and the use of monitoring in decision making. This generic guidance reflects a common understanding of WP2 partners at the time of the Project. The generic guidance so developed will need to be translated to national programmes according to each national context.

The recommendations and observations set out in this report build on previous strategic work undertaken within the MoDeRn Project (MoDeRn, 2013a) and within the earlier tasks of WP2 of the Modern2020 Project. In particular, the recommendations and observations build on the structured approaches to repository monitoring programmes defined in this previous work. These include the MoDeRn Monitoring Workflow, a structured approach to development and implementation of a monitoring programme (MoDeRn, 2013a) (Figure 1.1), and the Modern2020 Screening Methodology, a generic methodology for selecting the parameters to be monitored (Farrow *et al*., 2019) (Figure 1.2). The objectives, processes and parameters part of the MoDeRn Monitoring Workflow was discussed in the MoDeRn Monitoring Reference Framework (MoDeRn, 2013b). The Modern2020 Screening Methodology provides additional detail to the monitoring programme design section of the MoDeRn Monitoring Workflow (a summary of the selection of monitoring parameters is provided in Section 2.3). The recommendations and observations set out in this report are specifically focused on understanding the implementation and governance aspects of the MoDeRn Monitoring Workflow.

1.4 Approach

The recommendations and observations presented in this report were developed through a series of workshop discussions, each focusing on specific aspects of responding to monitoring results:

- Workshop 3.1: Planning task activities and inputs.
- Workshop 3.2: Identification of decision-making methods, tools and workflows.
- Workshop 3.3: Setting of system performance measures.
- Workshop 3.4: Identification of response plans.
- Workshop 3.5: Task results, conclusions, and recommendations and observations.

The agenda and a list of participants for each workshop are provided in Appendix A.

In addition, a review of literature on the role of monitoring in decision making in carbon capture and storage (CCS) projects was undertaken. A summary of the literature review is provided in Appendix B. The review concluded that monitoring of CCS projects is focused on the operational aspects of injection of CO_2 and the migration of the injected gas. This contrasts with the focus of monitoring the EBS and near-field rock in support of building further confidence in the post-closure safety case, which is more likely to focus on processes occurring in response to the emplacement of waste and the EBS. Therefore, no direct lessons on decision making in CCS projects have been applied during the development of the recommendations and observations presented in this report.

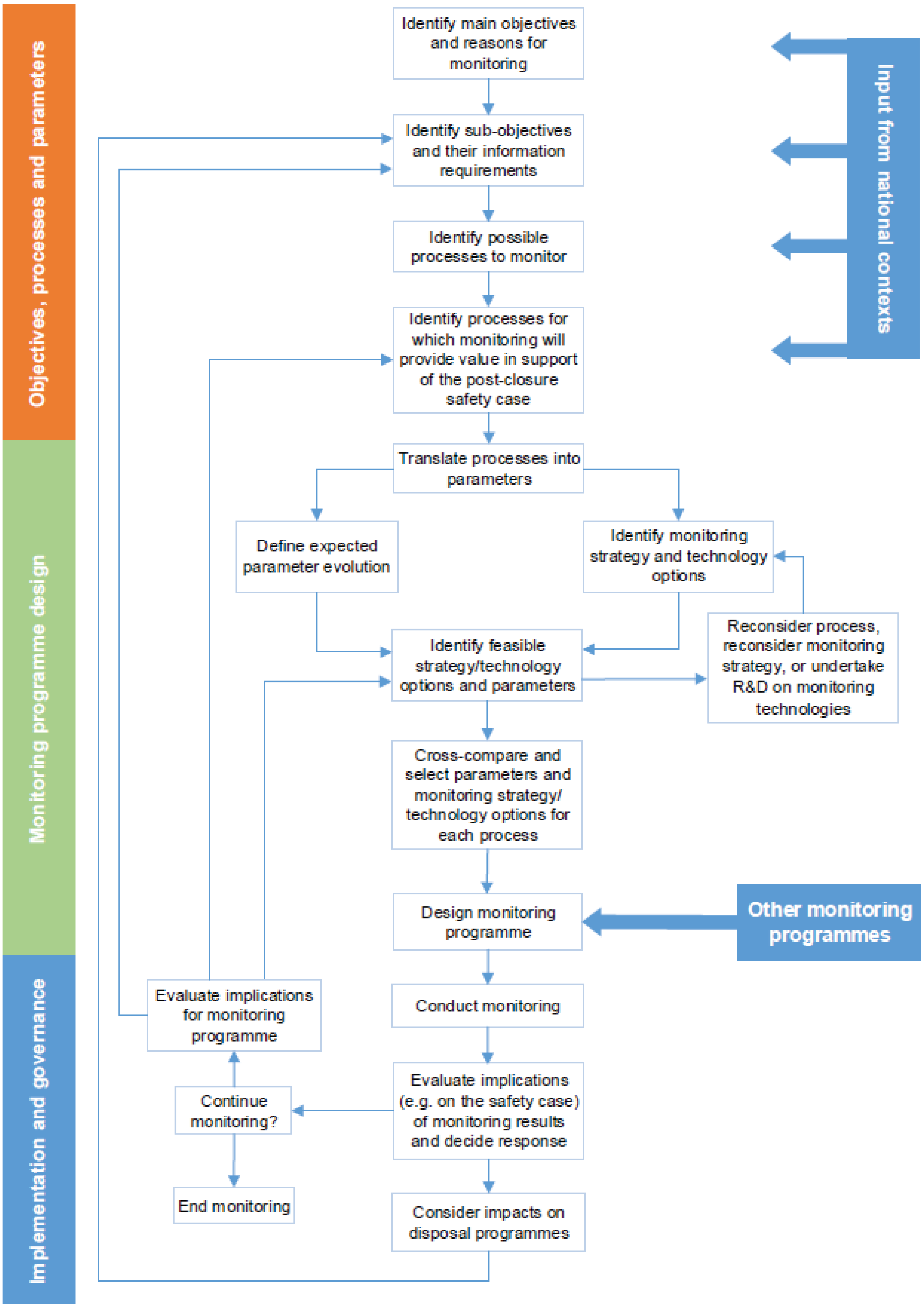

Figure 1.1: The MoDeRn Monitoring Workflow. For description see Farrow *et al.* (2019) and MoDeRn (2013a).

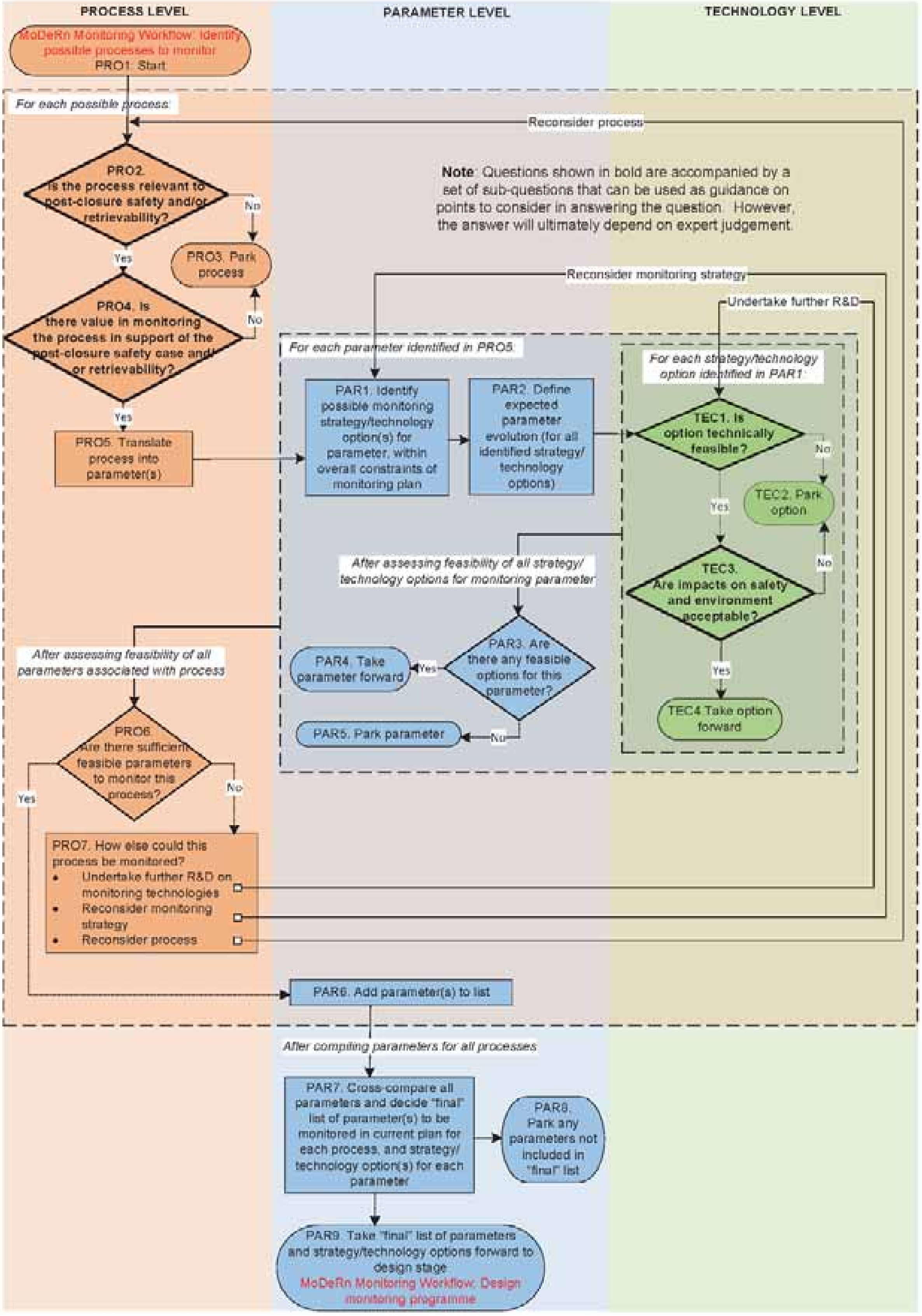

Figure 1.2: The Modern2020 Screening Methodology. For description see Farrow *et al.* (2019).

1.5 Report Structure

The remainder of this report is set out as follows:

- Section 2 provides the context to the discussions including the expectations regarding the processes that will be monitored, the parameters used to monitor these processes, and the data and information expected to arise from monitoring programmes focused on building further confidence in the post-closure safety case.
- Section 3 discusses the way in which WMOs might plan for responding to the results from repository monitoring programmes, including the way in which information may be evaluated and the types of responses that may be considered. A generic list of responses to monitoring results is developed and presented.
- Section 4 uses the discussions in the preceding sections to develop a generic process for responding to monitoring results.
- Section 5 presents the report conclusions, and the recommendations and observations on planning for evaluating and responding to monitoring results.
- Appendix A provides the agenda and participant lists for the workshops at which the recommendations and observations were developed.
- Appendix B presents a review of the approaches used in the monitoring of CCS projects and draws conclusions on the relevance of this information to developing approaches to decision making in geological disposal programmes.
- Appendix C illustrates the decision-making process developed in Section 5 using a test case based on the boundary conditions that apply to the German high-level waste (HLW) repository programme.

2 Context for Evaluating and Responding to Monitoring Results

Prior to conducting monitoring, a WMO will need to establish plans for evaluating the resulting data and information, and responding to the results. This section provides the context for planning for evaluating and responding to monitoring results, including discussion of when planning should be undertaken (e.g. relationship to the MoDeRn Monitoring Workflow shown in Figure 1.1), the use of parameter value predictions, and a summary of the conclusions from Task 2.2 regarding the monitoring parameters and technologies that might be part of a monitoring programme.

2.1 Relationship to MoDeRn Monitoring Workflow

Planning for evaluating and responding to monitoring results presents the final step in the preparations undertaken by a WMO in development of a monitoring programme. However, the expectation is that a monitoring programme will be developed iteratively. Therefore, although planning for evaluating and responding to monitoring results is the last step in preparations for conducting monitoring, such planning might require iterative reconsideration of earlier stages in development of the monitoring programme (i.e. the earlier steps in the MoDeRn Monitoring Workflow, Figure 1.1).

Furthermore, although not explicitly represented in the MoDeRn Monitoring Workflow illustration (Figure 1.1), planning for evaluating and responding to monitoring results is considered to be part of the Design Monitoring Programme step, which follows the identification of the monitoring parameters using the Modern2020 Screening Methodology.

In the Modern2020 Screening Methodology (Farrow *et al*., 2019), identification of the processes (and their associated parameters) to be addressed by the monitoring programme, and the repository components in which these processes will be monitored, will be guided by the post-closure safety case. These processes will relate both to specific components of the near field and to the performance of the near field as an integrated system. Processes to be monitored may relate directly to safety functions of the EBS or geological barrier, or may focus on more general thermal, hydraulic, mechanical, chemical and radiological (THMCR) processes[1] that can be related to overall system evolution (not necessarily as direct indicators of safety function performance). The types of parameters to be monitored are discussed further below.

In addition, it is anticipated that decisions related to choosing which processes will be monitored in each component of the multi-barrier system will be made by the WMO with input from a range of other organisations such as regulators and citizen stakeholders. Who has a say, and the degree of sway held by each participant, will vary from programme to programme.

It is expected that the Modern2020 Screening Methodology will be iterated several times as repository operations progress. The extent of this iteration and the steps that are iterated will be programme-dependent, and might be pre-planned or triggered by specific events. For example, there might be a plan for iterating the screening of monitoring parameters in conjunction with the production of a periodic safety case (see Farrow *et al*., 2019), whereas a trigger to reconsider the monitoring programme might be acquisition of unexpected monitoring results as discussed in this report. Other triggers may also be identified.

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[1] In this report we use THMCR in a general way to refer to both specific thermal, hydraulic, mechanical or chemical processes such as heating, and to refer to coupled processes, for example the interaction between mechanical deformation and fluid flow. We also use THMCR to refer to different types of coupling (TH, THM, TC etc.).

2.2 The Post-Closure Safety Case and Parameter Predictions

Extensive modelling, calculations and argumentation in support of the post-closure safety case will have been undertaken prior to licensing, including consideration of variant scenarios. This will include modelling of the THMCR processes occurring in the near field, and the testing and verification of this modelling against underground research laboratory (URL) experiments, site-specific rock characterisation facilities and commissioning tests. Such understanding will include estimation of the range of responses that would be expected owing to variations in boundary conditions (such as temporal and spatial variability in groundwater flow into repository excavations). Modelling will also include safety assessment calculations to estimate doses or risks from the repository system. Modelling in support of the safety case will continue to be undertaken during the operational period, to demonstrate that any new information is consistent with the safety case.

Furthermore, during site characterisation and prior to EBS components being emplaced, regions of the repository that show characteristics that are incompatible with the operational and post-closure safety cases (e.g., in crystalline rock, localised groundwater inflow at a rate likely to cause bentonite erosion, and, for clay and salt host rocks, interbedded horizons that might provide significant reduction in rock stability) will have been ruled out from use for waste emplacement, or been subject to mitigation (e.g. for the crystalline example, grouting, in this example, to manage groundwater inflow rates, and, for the clay and salt host rock examples, introduction of additional ground support). Therefore, it can be assumed that no waste emplacement will take place in regions of the repository that have geological characteristics incompatible with the post-closure safety case.

Understanding from modelling and the wider RD&D programme will inform the identification of monitoring parameters, and development of a prediction of parameter values over the monitoring period. The parameter value prediction will represent a ‘base case’ spatial and temporal estimate for specific components of the waste, EBS and host rock. It will be based on existing knowledge, with input from modelling and experimental data and will include uncertainty. The prediction of parameter values needs to consider an understanding of the performance of monitoring devices (including how the performance of the device might change with time, and the variability of the performance of identical devices measuring identical parameters), the possible influence of the sensor and measuring system on the local THMCR evolution of the EBS, and will be an *a priori* prediction of the suite of information that should be provided subsequently via monitoring of specific components of the EBS in the operational phase, encompassing the expected domain of parameter values. Therefore, a prediction of parameter values, considering uncertainty, is required at a relatively early stage in the development of the monitoring programme in order to check the technical feasibility of monitoring a candidate parameter and as a basis for monitoring programme design (i.e. as a basis on which to select sensors, to develop their specification and to determine their location within the repository).

The Modern2020 Screening Methodology (Farrow *et al*., 2019) recognises that, for the purpose of monitoring programme design, the level of detail of the prediction should be consistent with how the parameter will be evaluated, and will depend on the programme implementation stage and how much information is available. It could vary from estimates with a precision of an order-of-magnitude (or greater) based on scoping calculations guided by expert judgement, to a detailed numerical model with model parameters derived from the WMO’s RD&D programme (e.g. the results from full-scale mock-ups).

It may not be feasible or necessary to develop a full numerical model for every parameter at all locations in the repository. For example, in crystalline rock, there could be significant variation in groundwater flow from one location to another, which could impact the spatial variability of many processes. To account for spatial variability, a statistical approach could be applied, in which predictions are based on consideration of whether the monitored data would lie within expected distributions rather than predicting exact values at specific locations. The importance here would be to define the domain of expected values consistent with the safety case, i.e. the parameter values that demonstrate that the repository is evolving in a way that supports the arguments presented in the safety case. It is important to note that the prediction of monitoring parameter values is not necessarily the same as the values assumed in the safety case, as the safety case typically uses conservative values to account for uncertainty (see discussion in White *et al*., 2017). The domain of values used in the safety case is therefore expected to be greater than the domain of predicted parameter values used in the monitoring programme.

2.3 Monitoring Parameters and Technologies

As noted during the development of the Modern2020 Screening Methodology in Task 2.1 (White *et al*., 2017) and the conduct of test cases in Task 2.2 (Farrow *et al*., 2019), monitoring programmes focused on the near field are not yet mature and challenges remain in identifying parameters that can be monitored to provide further confidence in the post-closure safety case during the operational period. Nonetheless, the Modern2020 Project recognises the potential value in undertaking such monitoring, and possible monitoring parameters were identified during the test cases (Farrow *et al*., 2019).

Consistent with previous international collaborations on monitoring (e.g., MoDeRn, 2013a), the Modern2020 Project recognises that monitoring during the operational period might be undertaken to build further confidence in the post-closure safety case. However, what constitutes confidence in one programme may not be the same as what constitutes confidence in another programme, it has not been possible within the Project to define how monitoring could provide confidence in all situations (i.e. for all programmes and all stakeholders). For example, where one programme may come to the conclusion that monitoring a specific component would provide further confidence, a different programme may take the alternative view that such monitoring would imply a lack of confidence in the existing knowledge base. Confidence is therefore a programme-specific issue.

Monitoring parameters might be identified through consideration of the safety functions of each component of the disposal system. A structured approach can be used to identify the processes that support these safety functions, and the parameters relating to these processes listed as potential monitoring parameters. As such, it is possible that a range of THMCR parameters will be monitored to provide specific information on processes acting on specific components and to check the results against criteria identified prior to commencement of the monitoring programme. It may be necessary to monitor a suite of such parameters to meet the objectives of the monitoring programme, for example, if the objective is to build further confidence in the post-closure safety case through detailed understanding of the processes occurring in a disposal tunnel, or if there is an objective for the monitoring to feed into ongoing design consideration as in the German programme (see Appendix C).

Alternatively, it may be possible to undertake monitoring of a limited set of individual parameters as an indicator of overall component performance. Monitoring of a limited set of parameters might be used to demonstrate understanding of overall near-field performance, for example, monitoring of temperature might be used as an indicator of overall near-field evolution[2]. An example of such monitoring is the compliance monitoring of the WIPP facility where ten compliance monitoring parameters were selected for monitoring during the pre-closure phase of repository operations (see Appendix B in White *et al*., 2017). This approach could also consider the use of proxy parameters, for example, monitoring the flow across a deposition tunnel plug in the KBS-3V concept as a proxy for understanding the saturation state of the backfill in the deposition tunnel. However, monitoring of single parameters or a limited set of parameters cannot necessarily provide a conclusion regarding repository

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[2] Further clarification of what constitutes "individual basis" or "specific parameters" would be required in the context of each programme and the technologies applied. Many sensors monitor more than one parameter by default (e.g. combined pressure and temperature sensors, with the temperature included to allow correction of pressure data).

performance/safety, and it may be necessary to monitor a significant number of parameters, convolving the acquired data to derive the required process understanding.

Also, in specific circumstances, monitoring parameters may be specifically requested by the safety authorities.

In relation to any one specific component that is subject to monitoring, information will be collected over extended periods (i.e. decades) and may need to be spatially distributed such that an understanding of heterogeneity in the monitored parameter can be achieved. In this way, an understanding of variability and heterogeneity of changes to properties of the component can be achieved.

A range of THMCR processes are typically monitored in URL experiments, and associated parameters might be considered as candidates for monitoring during repository operations. As yet, no European programme has decided the parameters that are definitely going to be monitored in the actual repository EBS[3] (White *et al*., 2017). Several potential monitoring parameters were identified in the test cases undertaken in Task 2.2, and these were listed in the Task 2.2 report (Farrow *et al*., 2019). The parameters identified (which are only examples of what might be monitored) included: temperature; thermal conductivity; relative humidity; water content/saturation; swelling pressure; gas pressure; groundwater pressure; groundwater movement; density; displacement / strain; water chemistry (e.g. pH and Eh); and corrosion.

The monitoring of these parameters would be achieved using sensors placed in the component being measured or using technologies which measure properties remotely using geophysical techniques (referred to as intrusive and non-intrusive monitoring technologies respectively). Intrusive technologies might transmit the data measured using wires or wirelessly. Monitoring technologies could be placed in the EBS, in boreholes outside the EBS, at the surface or in the air (White *et al*., 2004). The impact of the monitoring sensors and data transmission equipment on the post-closure safety case will need to be assessed prior to the systems being deployed.

It can reasonably be assumed that all data gathered during the operational period will be subject to rigorous QA/QC pursuant to the implementer’s published procedures. In addition, the technology used to monitor these processes will have been exhaustively tested prior to deployment in the operational repository, in conditions that replicate those anticipated as the repository evolves during the operational period. Information on the expected lifetime of sensors will be available. The extent to which the equipment’s accuracy and precision changes over time and as the repository evolves will also be understood. Expected variability in relation to how a suite of nominally identical monitoring devices responds to specific processes (e.g. heat conduction and groundwater pH evolution) will be known (including, for example, variability in manufacturing quality and the potential variability in sensor readings with respect to sensor placement), and an understanding of the variation in monitoring devices will be factored into an analysis of what the data gathered can be taken to imply in relation to conditions at the monitoring location. Furthermore, use can be made of reference sensors, i.e. sensors placed outside of the disposal galleries that can be used to acquire information on the long-term operation of monitoring equipment.

2.4 Decisions to be Supported by Repository Monitoring

Decision-making requirements on monitoring were discussed in the Task 2.1 report (White *et al*., 2017). Building on the discussion therein, three types of decisions are recognised in which monitoring may play a role:

- Technical and engineering decisions: These decisions include those related to the installation of engineered barriers and excavation of the host rock at later stages in the programme. Dependent on the specific programme approach, these might include, for

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[3] Parameters have been identified for the WIPP programme and are subject to monitoring during the operation of the facility. See Appendix A of White *et al*. (2017) for a summary and references therein.

example, decisions on the final design of the closure system or decisions on the timing of backfill installation in specific parts of the repository.

- Disposal programme decisions: These decisions relate to the main stages in the disposal programme, as illustrated in the generic scheme depicted in Figure 2.1, and moving from one stage to the next.
- Governance decisions: These decisions are those that relate to the overall approach to management of radioactive waste and control of the programme. Such decisions may lead to, for example, changes in the role and responsibilities of the relevant organisations, and the manner in which stakeholders are involved in the programme. These decision might include a decision to retrieve waste, for example for the case that the waste is redesignated as a resource or if an alternative waste management to geological disposal was identified following initial waste emplacement (but not retrieval of waste in the case of an accident, which would be covered under disposal programme decisions).

Further discussion of the types of decisions that may be taken in response to monitoring data are provided in Sections 3 and 4.

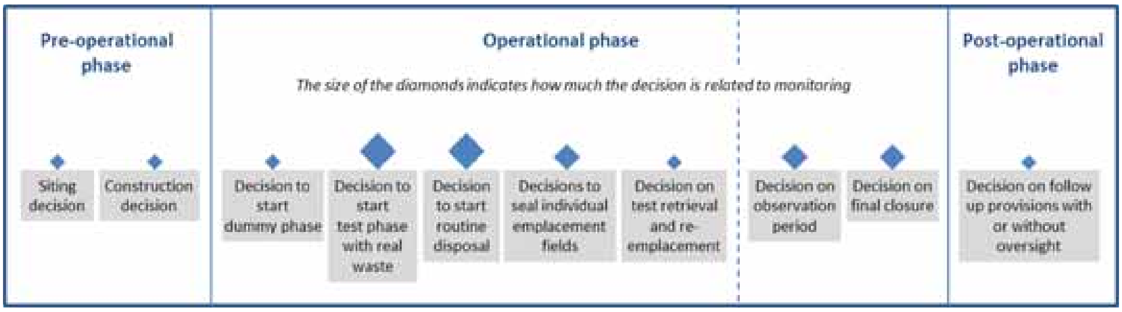

Figure 2.1: Generic repository lifecycle phases and major decision points (NEA, 2012). This generic scheme may be altered in specific programmes, and a specific programme might not include all of the identified steps. Furthermore, it is recognised that disposal may not be a sequential process, and some steps in the process may be overlapping (e.g., waste emplacement may be undertaken in parallel with construction).

2.5 Summary

Although no European WMO has yet developed a mature programme for monitoring of the EBS during the operational phase to develop further confidence in the post-closure safety case, it is possible to consider the context for such monitoring by making the following assumptions:

- Repository monitoring might be linked to safety functions or to process understanding.
- Repository monitoring might focus on multiple parameters that provide an integrated understanding of system performance or indicator parameters used to demonstrate compliance.
- The post-closure safety case will provide the basis for the repository monitoring programme, including detailed process understanding developed through associated RD&D.
- The performance of monitoring technologies would be understood for the specific environment.
- The safety case understanding would allow development of a prediction for each parameter, in each component in which the parameter is to be monitored.
- Decision making can be undertaken at different levels, including technical and engineering decisions, disposal programme decisions and governance decisions.

3 Monitoring Result Classification and Associated Responses

In Section 2, the context for planning for evaluating and responding to monitoring results, and current expectations regarding monitoring during the operational period to build further confidence in the post-closure safety case were defined. This section considers how monitoring results might be classified and the types of responses that might be invoked following preliminary consideration of the resulting information.

Responses to monitoring programme results might be based on evaluation of data on an individual basis (i.e. parameter-by-parameter) and/or evaluation of data and information as an integrated data set. Evaluation of an individual parameter might be undertaken against specific evaluation criteria (the prediction of the parameter values) as it is acquired. Such evaluation is referred to here as “continuous evaluation”. The manner in which continuous evaluation might be undertaken is discussed in Section 3.1.

However, monitoring of individual parameters would not provide sufficient information to act as a check on integrated repository performance. Performance depends on the coupled behaviour of processes occurring in the repository, not just on individual parameters. For the example of temperature monitoring, temperatures in the near field might be higher than expected, but, if significant, this (negative performance) might be offset by better than expected performance of other parameters, such as a slower rate of saturation delaying the onset of container corrosion (positive performance). For this reason, it is necessary to consider parameter evolution in terms of the impact on the safety case rather than in terms of individual results.

Therefore, in addition to continuous evaluation of individual parameter results, some programmes may decide it is necessary to cross-compare a broad set of data to gain a holistic understanding of repository performance. Integrated evaluation of monitoring results will be less frequent as it involves more in-depth consideration, such as the running of THMCR process models or safety assessment calculations. Such evaluation is referred to here as “periodic evaluation”. Periodic evaluation of monitoring results is discussed in Section 3.2.

The performance of the repository following emplacement of the waste is expected to be consistent with the safety case. Extensive RD&D, backed up by QA/QC during operations, will have been conducted to ensure this is the case. The sensitivity of the safety case to variant scenarios, including scenarios where barriers are performing less well than expected, will have been taken into account in repository design. Therefore, it is not feasible to develop response plans to describe actions that would be taken in response to specific monitoring results; if such results can be imagined, they will be taken into account during the development of the safety case.

Analysis of FEPs in the safety case using a structured process will aim to address all processes that could affect the performance of the disposal system. This includes unlikely events and all types of processes. Nonetheless, there remains the possibility that repository performance is inconsistent with the safety case (non-compliant results), for example that there are unknown unknowns that are not considered in the safety case. Therefore, plans should be put in place to respond to results that are inconsistent with the safety case, and much of the focus on planning for responding to monitoring results is on development of the understanding of the type of responses that might occur and development of processes to implement these responses if necessary. Generic responses are identified in Section 3.3 based on the discussions in Sections 3.1 and 3.2.

3.1 Continuous Evaluation

Depending on the extent and complexity of the monitoring programme, the resources available, and the slow evolution of the relevant processes, it may be impractical to evaluate all data in detail in real time. The frequency at which continuous detailed evaluation of data would occur would be defined on a programme-by-programme basis. It would be expected, however, that the frequency at which monitoring results were considered would be consistent with developing an understanding of the trend of the data (i.e. providing sufficient granularity that unexpected behaviour could be detected ahead of time or expected behaviour could be demonstrated by the data), and therefore would be related to the expected rate of change of the parameter in question.

For continuous monitoring, the monitoring frequency could be a short period, e.g. daily, weekly or monthly depending on the parameter, but the term "continuous" is adopted here to indicate relatively rapid evaluation of data to ensure a continuous watch over the repository as far as is practicable (for programmes where this is part of the monitoring strategy).

For continuous evaluation of specific parameters, the main aspect will be to compare results to the domain of predicted parameter values. Evaluation of monitoring results would include a check that the data were compliant with parameter-specific criteria, and also that the trend of the data indicated that the results would remain compliant in the future. Owing to the conservative approach adopted for repository design, the predicted values of a parameter may be better than required to meet the safety case.

Three types of results are envisaged for the continuous evaluation of individual parameters:

- Monitoring results lie within the domain of predicted parameter values and trends indicate that they will continue to do so. For simplicity, these are referred to as consistent results below.
- Monitoring results lie outside the domain of predicted parameter values and/or trends indicate that they will do so in the future, but the results do not contradict assumptions made in the safety case, i.e. the results are insignificant to safety. For simplicity, these are referred to as inconsistent but insignificant results below.
- Monitoring results lie outside the domain of predicted parameter values and/or trends indicate that they will do so in the future, and the results have the potential to contradict assumptions made in the safety case, i.e. the results are potentially significant to safety. For simplicity, these are referred to as inconsistent and potentially significant results below.

3.1.1 Responding to Consistent Results

Consistent results are defined herein as those that lie within the upper and lower values of the domain of predicted parameter values of a monitored parameter and have a trend indicating that they will continue to do so. The response to acquisition of consistent results would be to continue monitoring and feed the results into a periodic update of the safety case at the appropriate time. These results will contribute to decisions on the future monitoring programme and on the progress in the repository programme.

3.1.2 Responding to Inconsistent but Insignificant Results

Inconsistent but insignificant results are those where the acquired data lie outside the domain of predicted parameter values and/or trends indicate that they will do so in the future, but the results do not contradict assumptions made in the safety case, i.e. the results are insignificant to safety. For some parameters, numerical criteria might be defined to identify results as inconsistent but insignificant. For example, for temperature, a requirement on maximum temperature might be determined during repository design. The domain of predicted parameter values of temperature during the monitoring period might be somewhat below this maximum temperature. A result inconsistent with the domain of predicted parameter values, but judged to be insignificant to safety, could be one that lies between the maximum temperature requirement and the maximum values predicted by the domain of predicted parameter values (or shows a trend that indicates that the predicted domain, but not the maximum temperature requirement, will be exceeded in the future).

Inconsistent but insignificant results would be ones where individual parameter performance remained consistent with the post-closure safety case. Therefore, responding to this kind of monitoring result would not require immediate intervention. Instead a range of responses could be envisaged for this case:

- Evaluate sensor performance: One of the first steps might be to re-check[4] the performance of the sensors through analysis of the raw data. Analysis of raw data can assist, for example, in identifying failures in the monitoring system (see Jobmann, 2013, Chapter 7 for a discussion on detection of monitoring system failures).
- Check results: In addition to checking the raw data, it may be necessary to check the analysis of the raw data in providing results from the monitoring data (e.g. conversion of resistance to temperature for resistance temperature devices) and to cross-compare monitoring results from multiple sensors.
- Report deviating results: Depending on programme-specific approaches, there may be a procedure included in the monitoring programme through which it is required to report all results that deviate from the domain of predicted parameter values. The organisations receiving any reports would also be programme-specific, and could include regulators and other stakeholders. This report might include justification of the deviating result being classified as unlikely to be significant to safety and review/acceptance of the classification by oversight groups.

The analysis of inconsistent but insignificant results will ultimately feed into a periodic evaluation of all monitoring results. For results classified as inconsistent but insignificant, it is envisaged that consideration of their implication through periodic evaluation will be undertaken to pre-planned timescales and there would be no need to invoke an additional periodic evaluation. For some programmes, a procedure might be introduced that requires a reconsideration of the design should any results be inconsistent with the predicted parameter values, i.e. act as a trigger to re-evaluate the design. For example, this is consistent with the learning strategy adopted in Germany for responding to monitoring results. However, other programmes may manage such results as part of regular periodic evaluation, as noted above, and described in more detail below.

3.1.3 Responding to Inconsistent and Potentially Significant Results

Inconsistent and potentially significant results are results where the acquired data are unexpected and significantly divergent from the domain of predicted parameter values. These results are unexpected and, therefore, no specific action can be defined in advance. Responses to results classified in this manner are likely to be similar to those undertaken for deviating results that are judged to be insignificant to safety. However, dependent on the initial assessment of the results, more significant actions might be undertaken, including halting emplacement operations whilst further evaluation of the data is undertaken, or undertaking a supplementary periodic evaluation involving additional monitoring data and/or models, as described in Section 3.2 below. More significant actions, for example, initiating design changes, might be taken following a periodic evaluation triggered by such results, in which the full range of data available from the monitoring programme and other ongoing activities would be considered.

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[4] The term "re-check" is used because a feature of any monitoring programme would be quality assurance of data as it is acquired. However, given that this scenario envisages data inconsistent with expectations, it is suggested that the quality assurance check is repeated and/or reviewed.

3.2 Periodic Evaluation

Periodic evaluation is expected to be the main route through which monitoring data are evaluated and response plans formulated. As has been noted elsewhere in this section, integrated assessment of the coupled behaviour of the near field is the primary basis through which monitoring results can be used to check THMCR process understanding and to develop conclusions related to building further confidence in the overall performance of the repository.

Building on the discussion above, three triggers for undertaking a periodic evaluation of results are envisaged:

- In response to specific results that are inconsistent and potentially significant.
- Planned periodic updates to the safety case.
- As the result of an external decision (e.g. a request from the regulator or other Government agency).

Periodic evaluation of monitoring data is required in order to use monitoring results to check existing understanding of THMCR processes occurring in the near field in response to disposal of radioactive waste and emplacement of the other parts of the EBS. Checking the coupled THMCR behaviour of the repository would be one method to build further confidence that there are no “unknown unknowns” affecting repository performance.

Periodic evaluation of monitoring data could also involve re-running safety assessment calculations utilising information gained from the monitoring programme and other new information gained from the wider programme. In order to re-run safety assessment calculations periodically (e.g. every decade during repository operations in support of periodic updates to the safety case), a detailed traceable and transparent record of the safety assessment is required and the ability to re-run safety assessment calculations must be maintained.

A range of responses is envisaged to periodic evaluation:

- Root cause analysis: Acquisition of results that are inconsistent with the domain of predicted parameter values requires explanation. Therefore, a root cause analysis would be undertaken to develop an understanding of the reason for the deviation. This could include specific investigations including additional RD&D activities in order to better understand the issue and to understand the driving process or processes.
- Revise models / safety assessment: The outcome from a root cause analysis might be identification of a need to revise THMCR models (and the data used in these models) and/or a safety assessment calculation.
- Continue monitoring: Should the evaluation of the monitoring data demonstrate that overall repository performance is either as expected, or consistent with regulations if not as expected, one response to the periodic evaluation might be to continue monitoring as before.
- Change monitoring: One outcome from periodic evaluation of the monitoring data might be to change the monitoring programme, if feasible. Change is used here in a general sense, to mean any modification of the monitoring programme, from minor adjustments to complete redesign of the programme (e.g. changing the monitoring strategy and parameters monitored). This could be undertaken in several different ways and could be associated with:
    - An increase in monitoring (if the periodic evaluation indicated that there was some cause for concern or if additional data over and above that which was already planned to be collected was required).
    - A decrease in monitoring (if the periodic evaluation concluded that sufficient confidence had been gained through the monitoring programme to date).

Changes in the monitoring programme could relate to changes in:

  - The frequency of data acquisition using the current monitoring system. Examples might be to decrease the frequency of monitoring where power consumption might be an issue (e.g. where results are transmitted wirelessly) or where there is an operational safety hazard in acquiring the data (if data acquisition requires human access underground).
  - Monitoring the same parameter(s) with additional sensors of the same type (additional redundancy).
  - Monitoring the same parameter(s) with different sensors (increased diversity).
  - Monitoring of additional parameters.

For large and diverse programmes (e.g. programmes with different types of waste, which are to be disposed over different periods) there will be a need to change the monitoring programme to respond to disposal of different wastes at different times (for example, HLW that has experienced different periods of interim storage), and to compare the behaviour of disposal galleries constructed and operated at different times. In addition, for programmes that extend over several decades or more, the evolution of the monitoring plan will also probably be guided by technology development.

- Change operations: There could be a change in operations as a result of periodic evaluation of monitoring results. Monitoring data will be part of the range of information considered when moving from one phase of the repository programme to another (cf. Figure 2.1). The most significant of these changes might be a decision to close the repository. Monitoring data would support such decisions by feeding in to updates to the safety case. In some programmes (for example the German programme described in Appendix C), monitoring data might be used to support step-by-step progress in the disposal programme. In contrast acquisition of unexpected monitoring results might lead to disposal operations being paused or stopped altogether, or disposal of certain types of waste by stopped.

- Change design: Periodic evaluation, including re-running of the safety assessment, may identify options to improve the design implemented at later stages of the operational phase. It is not anticipated that monitoring would lead to changes to the design, but this could not be ruled out at the start of the monitoring programme. Changes would most likely be minor, e.g. modification of the spacing between waste packages based on temperature monitoring, but, again, more significant changes are not ruled out. The ability to change the design is also affected by the monitoring strategy implemented. For example, a monitoring strategy involving an industrial pilot phase (as proposed in France (see Farrow *et al*., 2019)), might be specifically designed to allow a period of design re-evaluation following initial monitoring. As noted above, continual re-evaluation of the design is part of the monitoring approach to be adopted in Germany.
- Engineering intervention: Periodic evaluation may identify the need to intervene in the parts of the repository in which waste has already been emplaced. A range of engineering interventions could be envisaged, including grouting (e.g. emplacement of a grout curtain), *in situ* vitrification of the waste (treating the waste using heat to convert it into a glasslike substance) and construction of additional plugs and seals. Any such activities are likely to require the necessary regulatory approval according to national regulations.
- Reversal/retrieval: Reversal of the disposal process and/or retrieval of the waste might be considered following periodic evaluation of monitoring data. Reversal of the disposal process or retrieval of the waste would not be based on monitoring data alone, as discussed further in Section 4.

3.3 Generic Responses

Based on the discussion of continuous and periodic evaluation of monitoring results in Sections 3.1 and 3.2, a set of generic responses to monitoring results has been identified by the Modern2020 Project (Table 4.1). The monitoring responses have been classified into three generic types of response:

- Desk-based responses: these responses relate to the evaluation and understanding of the monitoring results and discussion with stakeholders.
- Monitoring programme responses: these responses relate to responses to monitoring results focused on acquisition of monitoring data.
- Disposal programme responses: these responses relate to physical intervention in the disposal programme as a result of decision supported by monitoring data (as explained further in Chapter 5).

3.4 Summary

Generic ways in which monitoring data could be evaluated and the types of responses that could be envisaged prior to undertaking monitoring include:

- Monitoring of individual parameters would be undertaken continuously, and requires comparison against the predicted values for that parameter; results can be consistent with the predicted parameter values, inconsistent but not significant, and inconsistent and potentially significant.
- Individual parameters cannot indicate overall system performance/safety.
- Integrated evaluation of monitoring results would be undertaken periodically in response to specific results, at a defined period in the repository programme, or in response to an external decision or request.
- A range of generic actions can be identified in response to monitoring results.
- Responding to monitoring results would not follow pre-described actions, as unexpected behaviour should be accounted for in the safety case. Instead, decision making should follow a pre-defined process. Decision-making processes are discussed in Section 4.

Table 3.1: Generic responses to monitoring results.

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 THMCR 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.

4 Process for Responding to Monitoring Results

This section focuses on the process through which monitoring results could support decision making and the stepwise management of the disposal process during the operational period. It is recognised that monitoring is only one input to decision making. Even readily implemented responses to monitoring results, for example pausing waste emplacement while monitoring results are investigated, could have wider implications that may need to be identified, discussed and agreed before action is taken. Therefore, the type of decisions discussed in this section are those decisions related to the monitoring programme. These decisions include those in response to all three types of individual parameter monitoring results defined in Section 3 (i.e. consistent, inconsistent but insignificant, and inconsistent and potentially significant) and also from periodic evaluation of integrated monitoring datasets.

Section 4.1 uses the discussion in Sections 2 and 3 to define a generic process for responding to monitoring results. Section 4.2 discusses the integration of this generic process in the MoDeRn Monitoring Workflow (Figure 1.1).

4.1 A Generic Process for Responding to Monitoring Results

In Section 3, generic responses to monitoring results were discussed. The purpose of this section is to describe a generic process that a WMO might follow to implement to respond to monitoring results and to make decisions based on, or supported by, information from the monitoring programme. The process is a stepwise approach to consideration of both individual monitoring results and periodic evaluation of integrated datasets as defined in Section 3. The main steps in the process are:

- Acquire data and information.
- Compare results to prediction of parameter domain.
- Integrated evaluation of monitoring results (including consideration of the impact on the safety case, and the relationship between the parameter monitored, the process it represents and the relationship of the process to the safety function provided by the component being monitored).
- Continue monitoring in the same way.
- Change the monitoring programme.
- Change the disposal programme.
- End the monitoring programme.

Each step in the process is described below and is visualised in Figure 4.1.

The discussion of the generic process for responding to monitoring results is supported by an illustration of stepwise decision making in Appendix C. This illustration is based on the German ANSICHT Project, and is relevant to the national context of the German programme. Other disposal programmes have different national contexts, and, therefore, may follow a different approach to responding to monitoring results, in particular the extent to which monitoring data is used to support decisions on the progression of the repository programme.

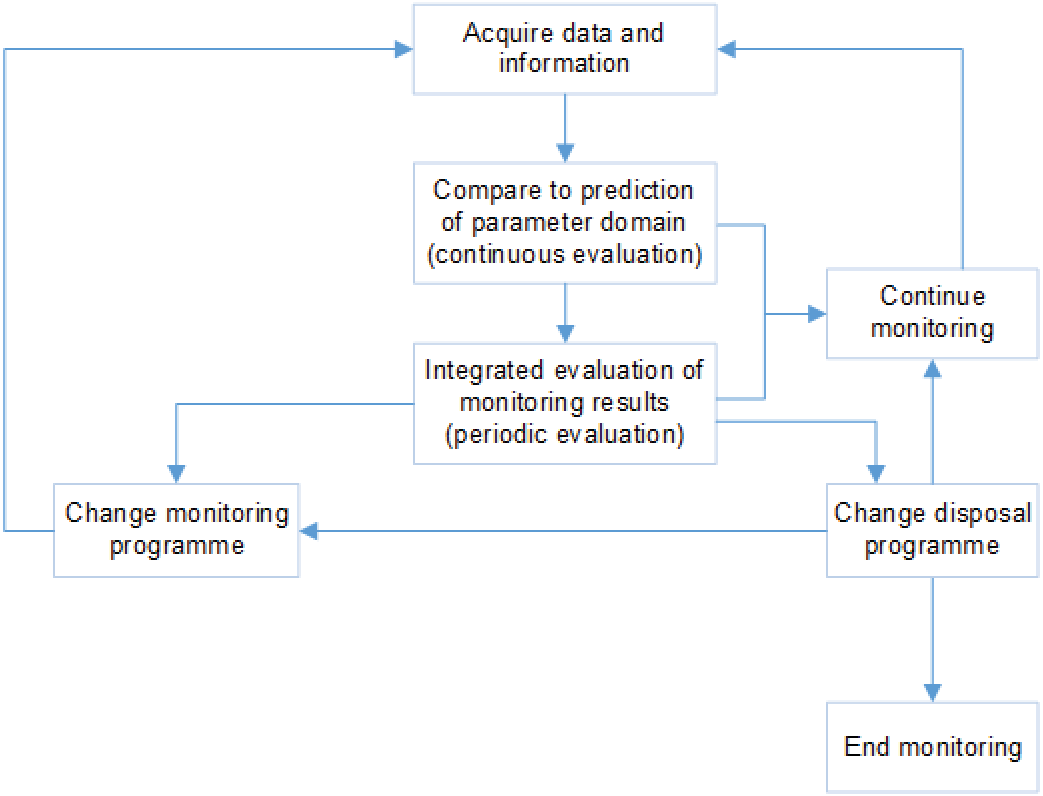

Figure 4.1: Workflow for responding to monitoring results.

4.1.1 Acquire Data and Information

All monitoring data gathered during the operational period (and at other times) will be subject to rigorous QA/QC pursuant to the implementer's documented / published procedures. This will ensure that the sensors have been installed as intended and that data has been handled as intended. Further effort will be required to demonstrate that the data can be trusted and used as an input to the decision process. Processes used for this should recognise, for example, measurement uncertainty and monitoring device performance, and potential evolution. There is also a need to plan for the evolution of data management technology and to plan for changes in the systems used to store and analyse data. Data quality will be checked at all stages of the monitoring programme for errors; uncertainty in data should be made evident. Using such an approach for analysing data will help identify obvious instances of monitoring device failure. General aspects related to measurement performance and failure detection have been described in Jobmann (2013). The development of a generic qualification process for monitoring technology has been discussed in Task 3.6 of the Modern2020 Project (IRSN *et al*., 2019).

Once raw monitoring data are assured, the data will need to be transferred into interpretations and information, including adjustment and calibration of the data for the *in situ* environmental conditions. This will involve application of documented methodologies for data interpretation, and will require further quality assurance. The outcome will be parameter values and time-dependent results that can be compared to the prediction.

4.1.2 Comparison with Predicted Parameter Values (Continuous Evaluation)

As discussed in Section 2.2, a "base case" for the predicted parameter values (spatially and temporally) for specific components of the near field will be derived prior to monitoring on the basis of existing knowledge and with the input of modelling and experimental data. The predicted parameter values need to consider an understanding of the performance of monitoring devices and will be an *a priori* prediction of the suite of information to be provided subsequently via the repository monitoring programme.

Once monitoring data have been collected, assured and converted to information, the information will be compared to the predicted parameter values. Comparison will follow internal procedures to determine whether or not information derived from monitoring is consistent with the predicted parameter values. These procedures will include when data should be evaluated, how the evaluation should be done, what needs to be part of the evaluation, who should be responsible for evaluation, and who should be consulted regarding the results and when.

The process of comparison may be straightforward, as consistency with the predicted parameter values could be in relation to one data point, or more complex, with consistency judged based on the trend of information over time.

The results of continuous evaluation of monitoring data might form part of stakeholder dialogue activities, and such dialogue (e.g. holding meetings or publishing newsletters) might provide an appropriate opportunity for stakeholders to be informed about ongoing repository operations and repository system behaviour.

The outcome of the comparison would be a classification of the data as consistent, inconsistent but insignificant or inconsistent and potentially significant. Acquisition of monitoring data of the latter two types could act as a trigger for a periodic evaluation.

4.1.3 Integrated Evaluation of Monitoring Results (Periodic Evaluation)

As noted in Section 3.2, there are three reasons that an integrated evaluation of monitoring results could be triggered: at a planned interval; in response to results inconsistent with the predicted parameter values; and as a result of an external decision. Periodic evaluation will require a detailed evaluation of the behaviour of the disposal system at a large scale, and will, therefore, take an extended period to undertake. This will therefore be a work-in-progress over much of the monitoring period. However, the periodic evaluation will need to operate with a fixed dataset, so management principles such as data freezes will need to be applied.

Regardless of the reasons for undertaking an integrated evaluation of monitoring data, it is expected that the process of evaluation will be the same and that all data will feed into an update of the post-closure safety case. This update of the safety case could be manifested in several different ways, including:

- Updating parameter values used in the underpinning models or in the safety assessment calculations.
- Inclusion of new processes in underpinning models (e.g. THMCR coupled models) or in the safety assessment calculation, should the monitoring data indicate that processes not previously included in models are potentially significant. This might include revising the prediction of monitoring parameter values.
- Inclusion of a new scenario or new sensitivity calculation within the safety assessment.

Given that a robust safety case is required for licensing, it is not expected that such actions will be undertaken (for a periodic safety case not triggered by inconsistent monitoring results the parameter values, models and scenarios may remain the same or similar, but the possibility remains open that new information might lead to the need for some reconsideration of the safety case.

A periodic update of the safety case will not only rely on monitoring data, but will also incorporate new information from the wider RD&D programme, from collaborative research undertaken by the waste management community, and from the wider scientific community.

As part of the use of the new information and data to update the safety case (and the underpinning safety assessment), the significance of it can be assessed, in particular to decide if any data inconsistent with the parameter-specific predictions is insignificant or significant to safety, and whether the overall system is behaving within the bounds assumed in the updated safety case or not. This will also provide a basis for deciding to continue monitoring in the same way, to change the monitoring programme, or to change the disposal programme, as discussed below.

It is envisaged that WMOs will record detailed information of the process that led to any decision (including references where appropriate) as part of the justification for the decision undertaken. This would provide long-term traceability and enable decision justification.

4.1.4 Continue Monitoring

Once monitoring data are measured, if they remain within the predicted parameter values, the monitoring could continue as planned. However, the implementing organisation could face the need to make some decisions. For expected information derived from monitoring, decisions could be made within the implementing organisation on:

- The need for further monitoring, potentially to confirm the veracity of data received to date.
- The duration of any programme of further monitoring.

These decisions would consider the full range of information collected from the monitoring programme, so would be considered as part of a periodic evaluation of monitoring data, as discussed in Section 4.1.3.

4.1.5 Change Monitoring Programme

The outcome of a periodic evaluation might be a decision to continue the monitoring programme albeit with a modification of the way monitoring data are collected or processed, or by performing additional monitoring activities. This could, for example, be a decision made in response to collecting data that was inconsistent with the predicted parameter values but not judged to be significant to the safety case. Continuation of the monitoring programme under this circumstance would be caveated, for example the frequency of data collection might be enhanced, and additional analysis of data gathered to date, including more broadly than in relation to any one specific repository component, might be undertaken, to consider if additional information can be derived.

Furthermore, a programme of potential future action could be derived, to be enacted in circumstances such as forward data gathering confirms the information available to date, or allows an inference to be drawn that the evolution of the specific repository component is becoming more removed from the safety case assumption with time.

The above does not preclude further analyses of the data gathered to date, and its potential significance, being undertaken. Such analyses could well include a re-consideration of how the specific repository component could evolve in the post-closure period, including related coupled THMCR processes. The question ought to be asked of whether the data gathered to date could imply processes occurring that have either not been considered in the implementer-led work to date, or processes that have been considered but have been ruled out (from the post-closure base case and variant evolution scenarios). Also, although data gathering in relation to specific repository components is considered herein, it must be recognised that the evolution of the repository is dependent on interactions between the components and the operation of coupled processes – the effects of such coupling also need to be recognised and considered.

Depending on the programme, dialogue with stakeholders could be important where the operator decides to undertake any significant changes to the monitoring programme. In Finland, for example, this means dialogue with authorities. In practice, it means that Posiva has the right to update the monitoring programme and must inform STUK, but it is not required that the changes are approved by STUK. Instead, Posiva needs to define the programme by itself, taking into account the authority requirements set for monitoring. Dialogue with other stakeholders is not required under Finnish regulations.

4.1.6 Change Disposal Programme

Given the detailed RD&D, comprehensive safety case and regulatory scrutiny required to grant a licence for disposal of radioactive waste in a geological repository, it is expected that monitoring will provide further confidence in the safety case. As such, ongoing results from the monitoring programme would be expected to provide data and information to support a decision to move to the next phase of the disposal programme, including a decision to close the repository. A decision to close the repository would not be based on monitoring data and information alone, but would also consider any parallel RD&D activities, quality control and quality assurance records and any other relevant developments since the time of licensing. In addition, a decision to close the repository would not necessarily lead to an end to the monitoring programme, as closure activities are likely to take several years, and would also most likely be subject to monitoring, and quality control and quality assurance.

However, should the implementer reach a conclusion that the nature of information available to date is significant enough to mandate new repository-based action, the options to be pursued could be wide-ranging, and could be influenced by the advancement of the respective repository programme, and stakeholder dialogue.

Intervening in the repository through engineering actions (including reversal/retrieval) would expose workers to an operational hazard. The implications of this hazard, in comparison to a radiological dose that could be received in the post-closure period were intervention not to proceed, should be considered, and advantages and disadvantages of different options assessed as part of the identification of the approach that reduces risk to as allow as reasonably achievable. Again, stakeholder dialogue could be included in identification of the preferred approach where appropriate.

Intervening in the repository programme could have significant consequences on a GDF programme overall, including cost and duration. Confidence in the implementing organisation may be affected. Furthermore, there is a possibility of a knock-on reduction in confidence affecting other repository programmes. However, intervention may be essential and unavoidable, dependent on the situation at hand and on weighing up the pros and cons of various options.

4.1.7 End Monitoring Programme

If enough information is available for the implementer to be sufficiently confident in its understanding of the evolution of the specific EBS component that is the subject of monitoring to identify that no further information is needed, monitoring can cease, if agreed by the regulators and if allowed by the national regulatory framework. The timing at which the monitoring programme ends is also programme-specific. Some programmes are required to undertake monitoring following closure, whereas no post-closure monitoring will be undertaken in others (in these programmes, environmental monitoring and surveillance may be undertaken by other national organisations). Ultimately, the monitoring programme will end when future generations decide that sufficient data has been collected.

4.2 Integration in the MoDeRn Monitoring Workflow

As noted in Section 1.3, the expectation is that responding to monitoring results forms the last part of the MoDeRn Monitoring Workflow. Therefore, the further consideration of responding to monitoring results in this report has led to a revision of the MoDeRn Monitoring Workflow, which is presented in Figure 4.2. As well as being relevant to monitoring programmes for geological repositories, the MoDeRn Monitoring Workflow is also relevant to monitoring of other radioactive waste disposal facilities, such as near-surface disposal facilities.

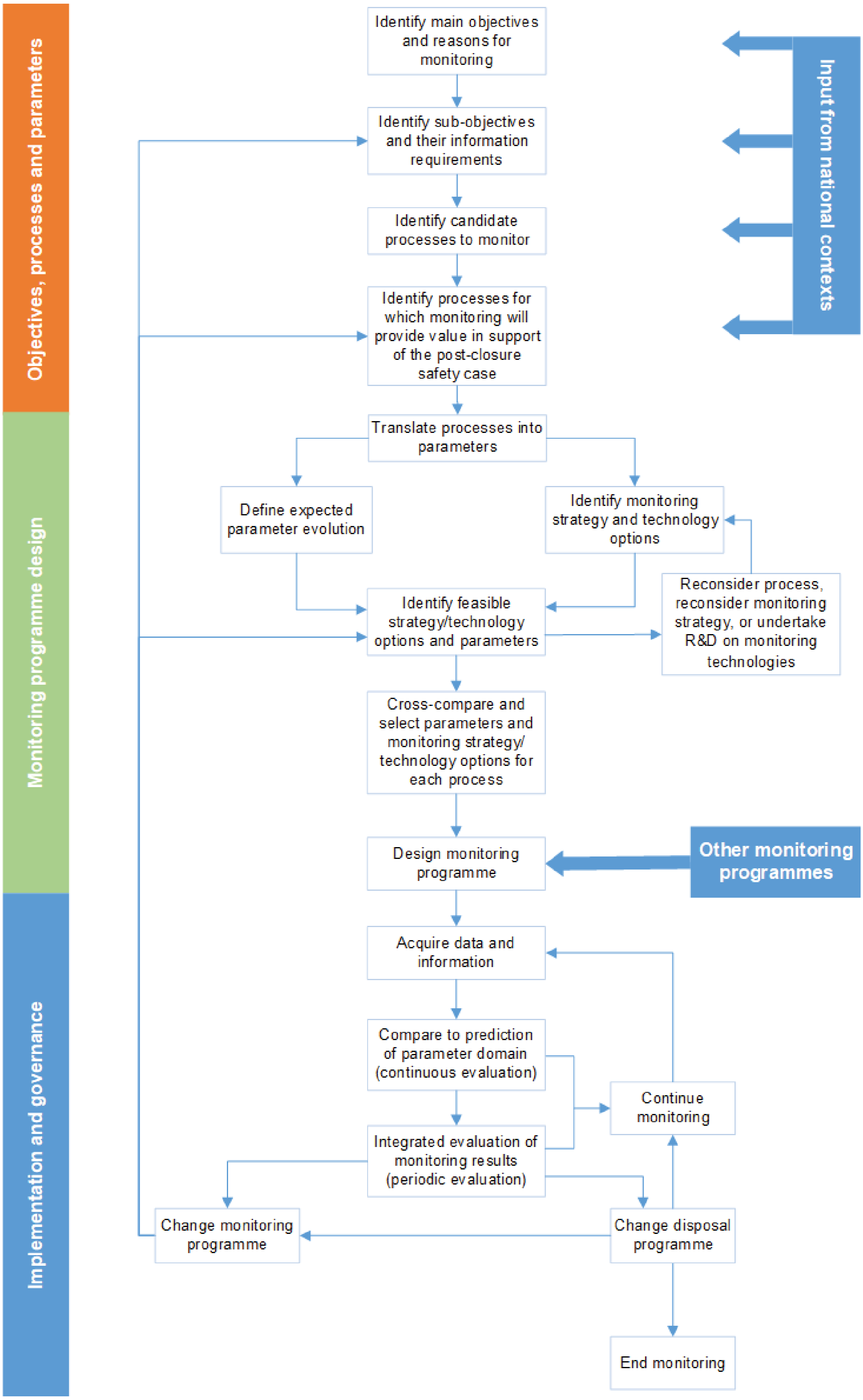

Figure 4.2: A revised version of the MoDeRn Monitoring Workflow, incorporating the additional consideration of the implementation and governance phase of the Workflow in this report.

5 Conclusions

This section presents the conclusions of Task 2.3 of the Modern2020 Project. Section 5.1 focuses on parameters and recommendations and observations on responding to monitoring results and the role of monitoring in decision making. Section 5.2 addresses monitoring results and the decision-making process.

5.1 Recommendations and Observations on Response Plans

Evaluation of monitoring results will consider both individual results (i.e. monitoring of the same parameter, potentially in multiple locations and/or with multiple types of sensor) and integrated consideration of the full range of monitoring data.

Evaluation of individual results will be undertaken on a continuous basis, whereas integrated evaluation would be undertaken periodically.

For continuous evaluation of specific parameters, the main aspect will be to compare results to the domain of predicted parameter values. For this evaluation, three scenarios are envisaged:

- Monitoring values and trends consistent with domain of predicted parameter values.
- Results inconsistent with domain of predicted parameter values, but insignificant to safety.
- Results inconsistent with predicted parameter values and requiring further evaluation.

Results inconsistent with the predicted parameter values would act as a trigger for undertaking a periodic evaluation considering the integrated data set.

The Modern2020 Project has identified the following guidance on planning for evaluating and responding to monitoring results:

- It is not possible to define a direct link to safety for all monitoring parameters (in all locations and at all times), for example, negative performance of one parameter might be offset by better than expected performance of other parameters.
- Response plans should be developed to describe actions that could be taken following unanticipated monitoring results.
- Response plans need to be adaptable as the details of unexpected repository system behaviour cannot be predicted in advance, and responses should consider the overall repository system behaviour.
- Assessment of monitoring results might need to consider processes that have not been previously identified as being significant (although extensive research on repository processes means that there should be no new processes identified).
- Usually, the first response to unexpected results is to check data quality/interpretation, and then to consider the implications for safety.
- Monitoring results should be compared to the expected variation of the parameter values in time and space.
- Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the monitoring dataset.
- Periodic evaluation might occur in response to the outcome of a continuous evaluation and/or at a regular interval.
- Monitoring programmes should include the organisational set-up for responding to monitoring results.
- The approach to responding to monitoring results can be guided by consideration of a generic action list, comprising desk-based actions and physical actions.

- Responding to monitoring results can be undertaken in dialogue with stakeholders, as determined by programme-specific and country-specific procedures and regulations.
- Decision making is a complex process where monitoring is only one input.

As responding to monitoring results must be flexible and consider unexpected repository evolutions, planning for responding to results has focused on identification of generic responses and consideration of the decision-making process:

- Desk-based responses:
    - Check results.
    - Report results.
    - Evaluate sensor performance.
    - Root cause analysis.
    - Revise models / safety assessment.
    - Update monitoring plan.
- Monitoring Programme Responses:
    - Continue monitoring in the same way.
    - Change monitoring.
- Disposal Programme Responses:
    - Change operations.
    - Change design.
    - Engineering intervention.
    - Reversal / retrieval.

5.2 Responding to Monitoring Results

Responding to monitoring results is considered to be a stepwise process that includes:

- Data Acquisition on a parameter-by-parameter basis.
- Comparison of data to predicted parameter values.
- Integrated evaluation of monitoring results.
- A decision to continue monitoring in the same way.
- A decision to change the monitoring programme.
- A decision to change the disposal process.
- A decision to end the monitoring programme.

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Appendix A: Workshop Agenda and Participants

This Appendix provides the agenda and participant lists for the five workshops held to develop the recommendations and observations presented in this report:

- Workshop 3.1: Planning task activities and inputs.
- Workshop 3.2: Identification of decision-making methods, tools and workflows.
- Workshop 3.3: Setting of systems performance measures.
- Workshop 3.4: Identification of response plans.
- Workshop 3.5: Task results, conclusions, and agreement on recommendations and observations.

Workshop 3.1: Planning of Task Activities and Input
Stockholm: 3 December 2015

Agenda

Session 1: T2.3 Preliminary Work Plan Presentation, Participants Contribution and Stakeholders Involvement

8:30-9:00	Introduction to Task 2.3: Objectives and strategies (C. Vivalda)
9:00–9:15	Challenges (C. Vivalda)
9:15 – 10:15	Draft planning presentation (C. Vivalda)
10:15 – 10:45	Coffee Break
10:45 – 11:00	Expected input from T2.1, T2.2 and other WPs and T2.3 output (C. Vivalda)
11:00 – 11:30	Participants contribution (C. Vivalda)

Session 2: Review of the Preliminary Work Plan and Finalisation

11:30 -12:00	Discussion with participants on the proposed planning (T2.3 Participants)
12:30 – 13:15	Lunch Break
13:15 – 13:45	Stakeholders view/recommendations (Stakeholders)
13:45 – 14:35	Suggestions for finalisation of T2.3 Activity Plan (Assembly)

Session 3: Short Term Plan of Actions

14:35 – 15:00	Way forward and actions (C. Vivalda/T2.3 Participants/Assembly)

Workshop 3.1: Participants

Name	Institution
Aliouka Chabiron	Andra
Johan Bertrand	Andra
Michael Jobmann	DBE-TEC
Mauro Cappelli	ENEA
Jo Smith	Galson Sciences
Matt White	Galson Sciences
Camille Espivent	IRSN
Michael Tichauer	IRSN
Bernd Frieg	Nagra
Claudia Vivalda	Nidia
Simon Norris	RWM
Jiro Eto	RWMC
Manno Morosini	SKB
Edgar Bohner	VTT
Marie Garcia	Andra
Thomas Schröder	NRG
Kari Koskinen	Posiva
Ilona Pospiskova	SURAO
Göran Sundqvist	University of Gothenburg
Hannes Lagerlöf	University of Gothenburg
Anna-Laura Liebenstund	University of Antwerp
Kris Van Berendoncks	University of Antwerp
Anders Bergman	Sweden
Hugo Goulemans	Belgium (Mol)
Geert Lauwens	Belgium (Dessel)

Workshop 3.2: Decision Making Methods, Tools and Workflows
Amsterdam: 6-7 September 2016

Agenda

Session 1: The Current Situation

14:00 – 14:30	Objectives of the task (Claudia Vivalda)
14:30 – 15:00	Literature review (Claudia Vivalda)
15:00 – 15:30	Coffee Break
15:30 – 16:15	Present the preliminary finding of the questionnaire (Claudia Vivalda)

Session 2: Discuss and Request Contributions for Task 2.3

09:00 – 09:45	Difficulties and problem about the decision-making process (Matt White)
09:45 – 10:30	Discuss orientation of the work for the task 2.3 (Johan Bertrand)
10:30 – 11:00	Coffee Break
11:00 – 12:00	Action plan (Claudia Vivalda)

Workshop 3.2: Participants

Name	Institution
Aliouka Chabiron	Andra
Johan Bertrand	Andra
Michael Jobmann	DBE-TEC
Juan Carlos Mayor	ENRESA
Jo Smith	Galson Sciences
Matt White	Galson Sciences
Camille Espivent	IRSN
Bernd Frieg	Nagra
Claudia Vivalda	Nidia
Jaap Hart	NRG
Thomas Schröder	NRG
Christophe Depaus	ONDRAF/NIRAS
Simon Norris	RWM
Manno Morosini	SKB
Assen Simeonov	SKB
Erik Thurner	SKB
Anne Bergmans	University of Antwerp

Workshop 3.3: Decision Making Workflows and Introduction to Performance Measures and Response Plans

Paris: 1-2 March 2017

Agenda

1 March 2017

15:30 – 16:30	Introduction to Performance Measures and Response Plans (Matt White)
16:30 – 18:00	Discussion of Performance Measures and Response Plans (Matt White)

2 March 2017

08:30 – 09:30	Introduction (C. Vivalda)
09:30 – 10:00	Break-out sessions introduction and directions: Review and redraw workflow (Claudia Vivalda)
10:00 – 10:30	Coffee Break
10:30 – 11:30	Break out session #1 (WG Leaders: Johan Bertrand, Assen Simeonov, Matt White)
11:30 – 12:30	Session #1 Working Groups results presentation and discussion in plenary
12:30 – 13:30	Lunch
13:30 – 14:30	Break out session #2: Data Falling Outside the Trigger Values (WG Leaders: Johan Bertrand, Assen Simeonov, Matt White)
14:30 – 15:30	Session #2 Working Groups results presentation and discussion in plenary (WG Reporters)
15:30 – 16:00	Coffee Break
16:00 – 17:00	Final agreement on Decision Making Workflows (Moderator: Manno Morosini)

Workshop 3.3: Participants

Name	Institution
Aliouka Chabiron	Andra
Johan Bertrand	Andra
José Luis Garcia-Siñeriz	Amberg
Juan-Carlos Mayor	ENRESA
Jan Verstricht	EURIDICE
Jo Farrow	Galson Sciences
Matt White	Galson Sciences
Bernd Frieg	Nagra
Claudia Vivalda	Nidia
Jaap Hart	NRG
Christophe Depaus	Ondraf/Niras
Johanna Hansen	Posiva
Tuomas Pere	Posiva
Simon Norris	RWM
Johan Andersson	SKB
Manno Morosini	SKB
Antonin Vokal	SÚRAO
Pieter Cools	University of Antwerp
Anna-Laura Liebenstund	University of Antwerp
Hannes Lagerlöf	University of Gothenburg
Vesa Jalonen	Finland (Eurajoki)
Ilona Sjöman	Finland (Eurajoki)
Hugo Ceulemans	Belgium (Mol; MONA)
Geert Lauwen	Belgium (Dessel; STORA)

Workshop 3.4: Performance Measures and Response Plans
Paris: 4-5 September 2017

Agenda

4 September 2017

09:00 - 09:10	Introduction (Manno Morosini)
09:10 - 10:10	Recap on Performance Measures and Action Plans (Matt White)
10:30 - 11:00	Deposition Tunnel Plug (SKB)
11:00 - 11:30	Performance targets and action limits (Posiva)
11:30 - 12:00	Monitoring Related to Retrievability (Andra)
12:00 - 13:00	Lunch
13:00 - 13:30	Borehole Abutment Displacement (DBE TEC)
13:30 - 14:00	Nagra Example (Nagra)
14:00 - 14:25	Discussion (M. Morosini)
14:25 - 14:30	Introduction to Break-out Group Sessions (M. White)
14:30 - 15:00	Break
15:00 - 16:30	Break-out Groups (Session 1): High-level Topics: Terminology on Performance Measure and Response Plans Development of a Generic Performance Measures Scheme (Chair: Antonin Vokal) Development of a Generic Action List (Chair: Simon Norris) High-level Guiding Principles (Chair: Edgar Bohner)
16:30 - 17:30	Plenary Feedback on High-level Topics (M. White)

5 September 2017

08:50 – 10:30	Break-out Groups (Session 2): In-depth Topics: Determining quantitative performance measure metrics (Chair: Edgar Bohner) Evaluating quantitative performance measure metrics (Chair: Simon Norris) Modifying the monitoring programme in response to monitoring results (Chair: Johan Bertrand)
10:30 – 11:00	Coffee Break
11:00 - 12:00	Plenary Feedback on In-depth Topics (M. Morosini)
12:00 – 13:00	Lunch
13:00 – 14:00	Wrap-up on Performance Measures and Action Plans (M. White)
14:00 – 16:00	Sub-task 2.2.2: Decision-making Workflow (C. Vivalda)

Workshop 3.4: Participants

Name	Institution
Johan Bertrand	Andra
Jiri Svoboda	Czech Technical University
Michael Jobmann	DBE TEC
Jo Farrow	Galson Sciences
Matt White	Galson Sciences
Bernd Frieg	Nagra
Claudia Vivalda	Nidia
Tuomas Pere	Posiva
Simon Norris	RWM
David Luterkort	SKB
Manno Morosini	SKB
Ilona Pospiskova	SÚRAO
Antonin Vokal	SÚRAO
Pieter Cools	University of Antwerp
Edgar Bohner	VTT

Workshop 3.5: Results, Conclusions, and Recommendations and Observations
Uppsala: 28 February – 1 March 2018

Agenda

Day One, 28 February 2018: Performance Measures and Response Plans

0845-0900: Introduction (Manno Morosini)
0900-1030: Proposal for Collective Opinions on Performance Measures and Response Plans (Matt White)

1030-1100: Break

1100-1115: SKB View – Johan Andersson
1115-1200: General Opinions on Performance Measures and Response Plans (Matt White)

1200-1300: Lunch

1300-1500: Setting Performance Measures, the Generic Responses and the Generic Performance Scheme (Matthew White)

1500-1530: Break

1530-1730: Changes to the Monitoring Programme and Responding to Monitoring Results (Matt White)

Day Two, 1 March 2018: Governance and Decision-making Workflow

0830-09:15: Summary of Conclusions on Governance, Decision-making and Insights from CCS (Claudia Vivalda)
09:15-10:00: Break out in groups to discuss extent of decision level and reporting (Groups chair)

1000-1030: Break

1030-1230: Final version of the Workflow

1230-1330: Lunch

1330-1400: Conclusion of discussions on the Workflow (Chair of roundtable)
1400-1430: Structure and content of D2.3 (Claudia Vivalda)
1430-1500: Wrap-up, reporting and actions (Claudia Vivalda and Matt White)

Workshop 3.5: Participants

Name	Institution
Aliouka Chabiron	Andra
Johan Bertrand	Andra
Michael Jobmann	DBE TEC
Jo Farrow	Galson Sciences
Matt White	Galson Sciences
Camille Espivent	IRSN
Bernd Frieg	Nagra
Claudia Vivalda	Nidia
Jaap Hart	NRG
Tuomas Pere	Posiva
Simon Norris	RWM
Johan Andersson	SKB
Manno Morosini	SKB
Erik Thurner	SKB
Ilona Pospiskova	SÚRAO
Axelle Meyermans	University of Antwerp
Hannes Lagerlof	University of Gothenburg

Appendix B: Review of Carbon Capture and Storage Monitoring Approach

This Appendix provides a review of monitoring approaches in CCS projects, with the objective of identifying lessons that might be valuable to planning for evaluating and responding to monitoring results, and using monitoring in support of decision making during repository operation.

CO_2 capture and storage is a three-stage process consisting of the capture of CO_2 at production facilities, the transportation of CO_2 to a storage location, and the long term isolation of CO_2 from the atmosphere (in order to reduce atmospheric carbon emissions).

The general attributes of monitoring of CCS projects can be classed into three distinct mandates:

- Operations: This involve monitoring/controlling actual *in situ* processes by changing injection/production strategies based on monitoring results. There are minimal regulatory requirements, and the need for monitoring of operations is determined by the complexity of the injection/production process.
- Scientific or Verification: This involves monitoring with the aim of understanding of complex processes occurring *in situ* during the injection process. Scientific or verification monitoring is generally concerned with migration and leakage.
- Environmental: This involves monitoring aimed at safeguarding against health, safety and environmental risks. Depending on the risk level of the project, aspects of environmental monitoring may be part of operational monitoring scenarios. Environmental monitoring is generally concerned with seepage.

Monitoring is an important part of the overall risk management strategy for geological storage projects and plays a key role in the detection of carbon emissions.

An example of the approach used to develop a monitoring programme for CCS projects (referred to as the Workflow for the Preparation of a Risk-Based Monitoring, Verification and Accounting (MVA) Plan) is presented in Figure A.1 (Det Norske Veritas, 2009).

Relevant parameters to monitor include injection rate and injection well pressure, repeated seismic surveys for tracking the underground migration of CO_2, sampling of groundwater and the soil between the surface and water table for directly detecting CO_2 seepage, and CO_2 sensors at the injection wells for detecting seepage. There are a range of available measurement techniques for detection and quantification of seepage from geological storage, although their accuracy is site and situation specific. Furthermore, baseline data improve the reliability and resolution of all measurements and are essential for detecting small rates of seepage. The role of monitoring results for recalibration of models used for predicting the behaviour of CO_2 injected into a geological formation expands the knowledge base for risk assessment and optimisation of operation.

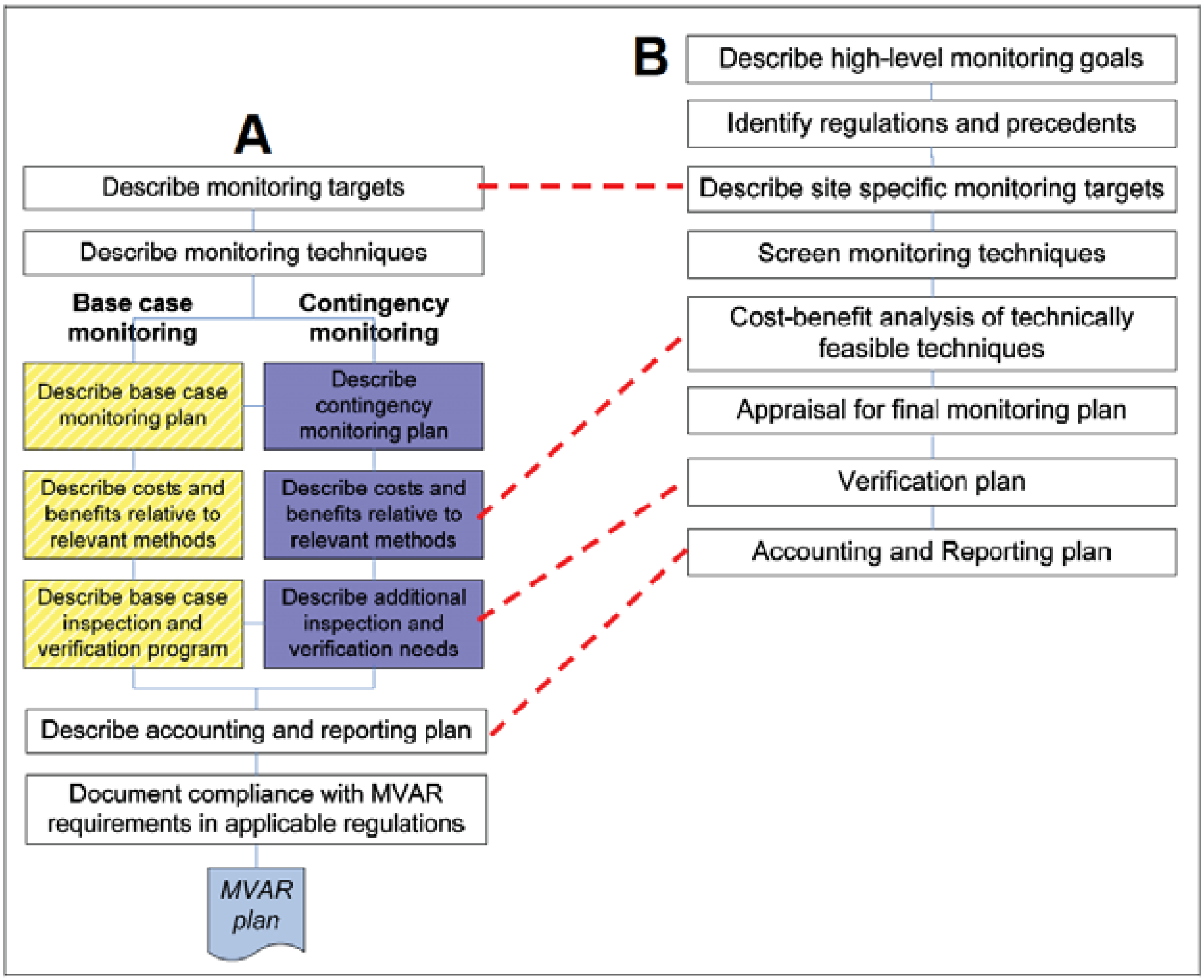


Figure B.1: Workflow for the Preparation of a Risk-Based MVA Plan. From Det Norske Veritas (2009).

Requirements on monitoring of CCS projects are provided in the European Union (EU) CCS Directive (European Parliament and the Council of the EU, 2009a) and EC (2011) include:

- Monitoring is essential to assess whether injected CO2 is behaving as expected, whether any migration or leakage occurs, and whether any identified leakage is damaging the environment or human health.
- The operator is required to monitor the storage complex and the injection facilities on the basis of a monitoring plan.
- The operator needs to report the results of the monitoring to the competent authority at least once a year.
- Member States are required to establish a system of inspections to ensure that the storage site is operated in compliance with the requirements of the EU CCS Directive.
- Applications to the competent authority for storage permits shall include a proposed monitoring plan including details on the monitoring in accordance with the guidelines established by Article 14 and Article 23(2) of the EU Emissions Trading Scheme (ETS) Directive (European Parliament and the Council of the EU, 2003).
- The plan shall be updated every five years to take account of changes to the assessed risk of leakage, changes to the assessed risks to the environment and human health, new scientific knowledge, and improvements in best available technology.
- The monitoring plan shall be established according to the risk analysis and updated with the purpose of meeting the monitoring requirements at the different CO_2 storage project phases.

- The established monitoring plan shall provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring.
- The monitoring plan shall include continuous or intermittent monitoring of some prescribed items such as:
    - Fugitive emissions of CO_2 at the injection facility.
    - CO_2 volumetric flow at injection wellheads.
    - CO_2 pressure and temperature at injection wellheads (to determine mass flow).
    - Chemical analysis of the injected material.
    - Reservoir temperature and pressure (to determine CO_2 phase behaviour and state).
- The choice of monitoring technology shall be based on best practice available at the time of design.
- The following options shall be considered and used as appropriate:
    - Technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at surface.
    - Technologies that provide information about pressure-volume behaviour and areal/vertical distribution of CO_2 plume to refine numerical 3D simulation to the 3D-geological models of the storage formation.
    - Technologies that can provide a wide areal coverage in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO_2 out of the storage complex.
- The monitoring data shall be collated and interpreted.
- The observed results shall be compared with the behaviour predicted in dynamic simulation of the 3D-pressure-volume and saturation behaviour undertaken in the context of the safety characterisation.
- Where there is a significant deviation between the observed and the predicted behaviour, the 3D model needs to be recalibrated to reflect the observed behaviour.
- Where new CO_2 sources, pathways and flux rates or observed significant deviations from previous assessments are identified as a result of history matching and model recalibration, the monitoring plan shall be updated accordingly.
- After a storage site has been closed, the operator remains responsible, amongst other things, for monitoring (post-closure period).
- After the transfer of responsibility, monitoring should be reduced to a level which still allows for identification of leakages or significant irregularities, and it should again be intensified if leakages or significant irregularities are identified.

In addition, the following emission sources at a storage site have to be monitored under an amendment to the EU ETS Directive (European Parliament and the Council of the EU, 2009b):

- Combustion emissions at the injection site.
- Fugitive emissions and emissions from venting at the injection site.
- Emissions from vents and flaring at enhanced hydrocarbon recovery.
- Leakage from the storage reservoir into the water column or atmosphere.

CO_2 is non-hazardous. Therefore, the direct health consequences of leakages from CCS sites would be negligible, although indirect consequences owing to the contribution of the leaking CO_2 to global warming would occur. However, the recognition that the site can leak could have an impact on the opinion of concerned stakeholders, and is therefore minimised.

In addition to the monitoring for ensuring CO_2 containment in the reservoir and therefore absence of near surface emissions, during the operation of the storage site, the main features that are monitored to guarantee its performance are the injection rate and injection well pressure, and the impurities in the CO_2 gas stream. The presence of impurities has an impact on the engineering process of injection, e.g. by affecting the compressibility of the injected CO_2. Furthermore, gas impurities in the CO_2 stream take up available storage space. Impurities also affect trapping mechanisms and the storage capacity depending on the type of geological storage. When discrepancies between the design parameters and the measured values occur, and these discrepancies are confirmed, the main decision to be taken by the operator is to stop injecting in the concerned well and redistribute the CO_2 flowrate among the other wells. In case of major discrepancies affecting field performance, the injection is stopped and this decision affects the full carbon capture and storage chain, including the CO_2 production facility and the transport line.

Possible remediation measures could involve standard well repair techniques or the extraction of CO_2 by intercepting its leak into a shallow groundwater aquifer. Seepage remediation options are usually described in connection with an analysis of the most likely seepage scenarios. The operator is the first decision maker about the identification of the most appropriate measures but in most cases they need to receive formal approval from the concerned authorities. Indirect stakeholders in these cases are the local citizens living in the area where the remediation works are carried out.

In general terms and focusing on site operation and management, responsibility for effective site operation lies with the private or state-owned company licensed to store CO_2. Licensing could be handled by a variety of international, national, or sub-national agencies; however, once assigned, it is likely that operation permits would govern only the short-term responsibility for injection operations of CO_2. If the operational phase lasts longer than two or three decades, the post-closure responsibility is expected to be transferred to a relevant state after an agreed period (e.g. 30 years). Site operations should remain under continuous monitoring for irregularities. All data related to site operation, monitoring, and verification must be collected and stored in a robust format.

In standard cases, storage sites will need to be covered by extended insurance for the long-term liability and potential risks posed by leakage, seepage, trespass (migration into other areas), and possible contamination. Because all geologic storage of CO_2 implies some non-zero probability of leakage assignment of liability has become a key regulatory issue.

Ultimately, the performance of a CCS site can be confirmed by monitoring gas migration in the geosphere, owing to the dynamic nature of the storage system, and is not focused on the health impacts of any migrating gas. This contrasts with geological disposal of radioactive waste, which is focused on isolating and containing waste to protect humans, flora and fauna from harmful effects, and relies on a multiple-barrier system to do so. Therefore, although there is similarity in the monitoring approaches undertaken in CCS and radioactive waste disposal, there are not significant lessons to be learned relating to the use of monitoring in decision making during operations.

The main outcome of this literature review is, therefore, that there are many similarities in the approaches in addressing the monitoring of CCS sites and radioactive waste repositories because of the depths considered and the need for post-closure safety assurance. However, the two applications are fundamentally different, with CCS relying on injection of CO_2 into permeable geological formations, whereas radioactive waste disposal relies on emplacement of waste packages in a multi-barrier system consisting of an EBS and a low-permeability (stable) geological barrier.

It follows that the decisions that are supported by monitoring results mainly involve the control of the injection phase of the CO_2 and not the handling of the stored CO_2 or the sequestration rock, in contrast to radioactive waste repositories where the near field is expected to play only a supporting role in decision making. Therefore, no specific lessons were used in developing the recommendations and observations on responding to monitoring and decision making as discussed in the Modern2020 Project.

Appendix C: Decision Making Supported by Monitoring: The ANSICHT Example

In Farrow *et al*. (2019), a monitoring concept for the German geological repository for spent fuel, HLW and L/ILW in a clay host rock was developed. This was referred to as the ANSICHT test case. The repository concept considered in the ANSICHT test case included disposal of canisters containing spent fuel and HLW in vertical boreholes, as illustrated in Figure C.1.

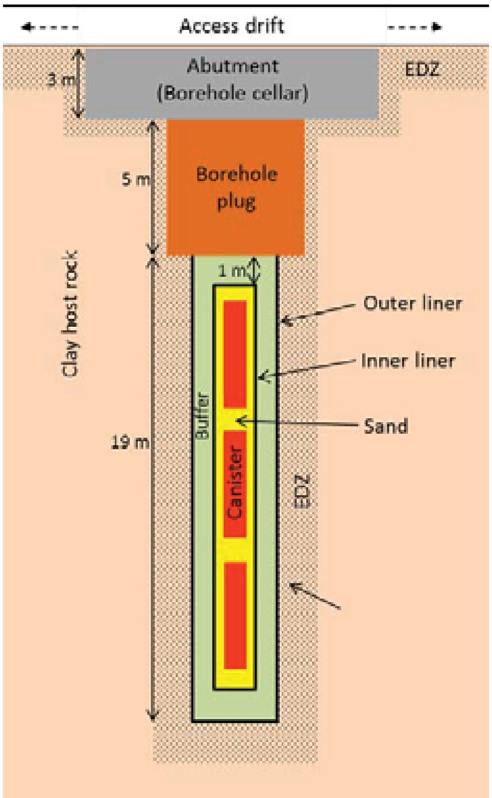


Figure C.1: Illustration of the disposal concept for the northern Germany site considered in the ANSICHT test case. The borehole plug would be constructed from bentonite and the abutment would be constructed from cementitious materials.

The monitoring strategy envisaged in the ANSICHT test case included monitoring of both waste and dummy canisters (heaters) within the repository emplacement area (Figure C.2). The monitoring concept has been developed as a process concept which explicitly includes learning during the whole operational phase and the feedback of such learning to the disposal process. The process concept will be structured by milestones. The approach is to focus monitoring on specific emplacement fields, specific emplacement boreholes, and specific seals. In order to benefit from the experience gained in previous monitoring activities, monitoring will start with the first emplacement field in which waste will be emplaced (identified as 1 in Figure C.2). Monitoring in a further five emplacement fields is envisaged in the test case in order to address potential spatial variability within the repository footprint (Figure C.**2**).

This appendix describes the anticipated use of monitoring data in decision making for the ANSICHT text case.

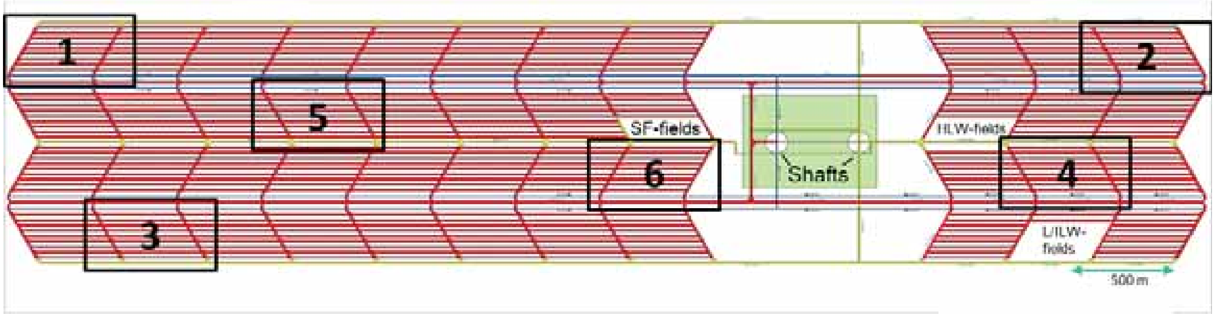


Figure C.2: Potential arrangement of monitoring fields as envisaged in the ANSICHT test case. Monitoring fields are indicated by the black rectangles with the numbering indicating the order in which the monitoring fields will be implemented.

C.1 Decisions in Relation to the Dummy Phase

After the first part of the repository construction, when the first emplacement drifts in the first emplacement field have been excavated and made ready for emplacement, the operational phase starts with a so-called "Dummy Phase". The first three boreholes in the first drift (referred to as the "test drift") are intended to be equipped with electrical heaters instead of real waste canisters. The main purpose of the dummy phase is to check the proper working of the borehole plug. Monitoring the plug behaviour plays an important role and a couple of intermediate decisions have to be made during this phase. The dummy phase is the first step within the learning concept described above and provides the first step of preparing decisions based on the evaluation of monitoring data obtained from plug monitoring. Figure C.3 illustrates the decision sequence of the dummy phase related to plug monitoring. The approach is based on the general flow chart presented in Figure 4.1. Processing and preparation of the input data is assumed to be a routine operation performed on a regular basis.

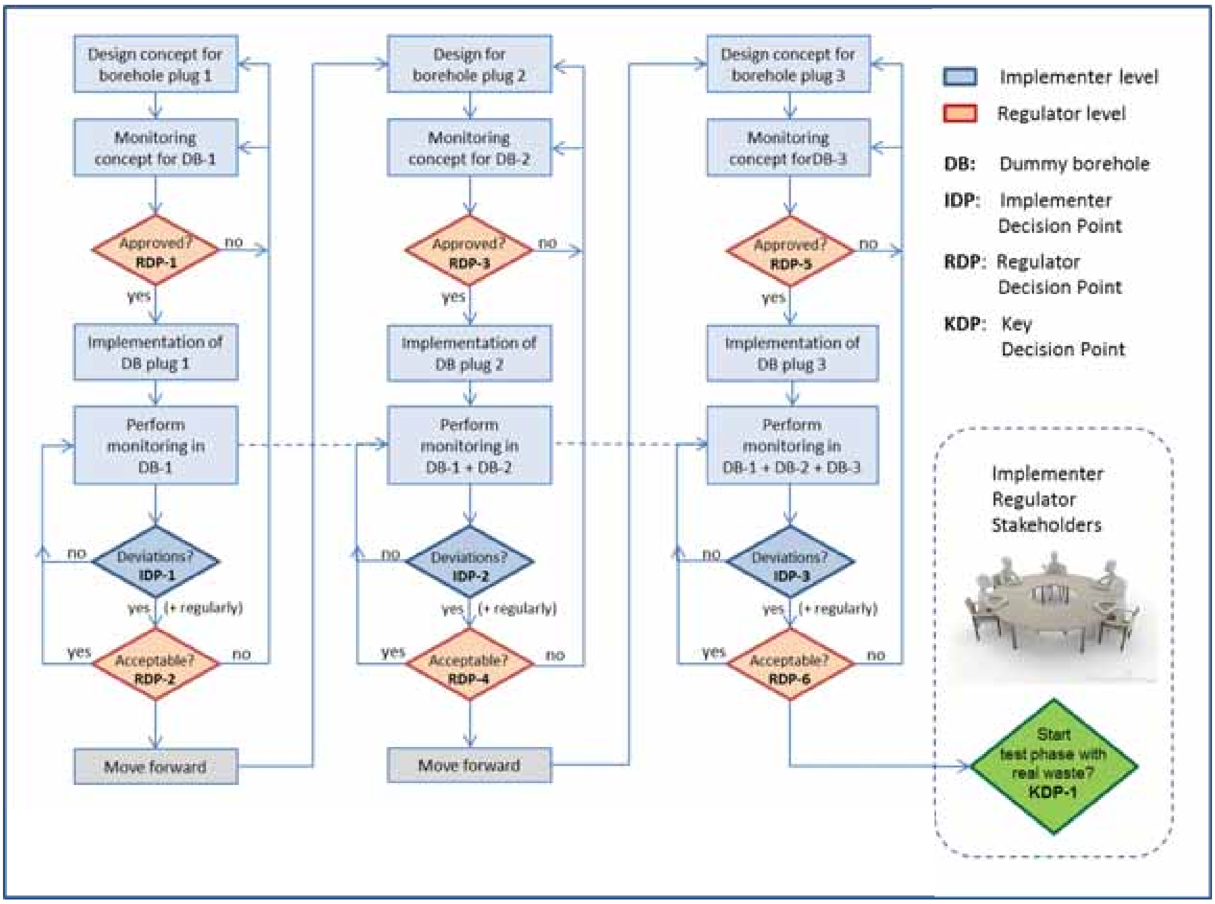


Figure C.3: Decision sequence of the dummy phase related to plug monitoring.

The diamonds in dark blue and orange represent decision points where the implementer is responsible (IDP) and where the regulator is responsible (RDP) respectively. Starting with Dummy Borehole One (DB-1), a monitoring concept for the plug has to be developed by the implementer and approved by the regulator (RDP-1). After implementation of the plug and monitoring system, a continuous monitoring of the plug behaviour will follow. At this point, the first decision point of the implementer is approached (IDP-1). An evaluation has to be performed whether the monitoring data provide evidence that the plug behaves as expected or if deviations from the predicted parameter values are observed. Where the monitoring data are consistent with the predicted parameter values, monitoring will be continued in the same manner. Where the monitoring data provide indications that deviations from the predicted parameter values might occur, the implementer has to inform the regulator and discuss with him the consequences, especially in terms of possible improvements of the borehole sealing concept. The decision whether to re-build and/or improve the borehole plug, or to move forward and use the lessons learned for the design of the plug and monitoring concept for the second dummy borehole, lies with the regulator (RDP-2).

The decision sequence for the second and the third dummy borehole is similar except that the monitoring data from the previous boreholes will be included in the evaluation, and might also be used to develop proposals for design improvements to be applied at the selected monitoring boreholes in the emplacement fields. At the end of the dummy phase, which is proposed to last about three years, the first "Key Decision Point" is approached (KDP-1) represented by the green diamond in Figure C.3. At this point in time a round table discussion is assumed to take place including all responsible people involved (the implementer, the regulator, and stakeholders). Based on a final evaluation of the dummy phase and the monitoring results obtained so far, this group will decide if the Test Phase with real waste shall be started or if further investigations or tests are necessary (e.g. an extension of the Dummy Phase).

C.2 Decisions in Relation to the Test Phase

After successfully finishing the dummy phase, the "Test Phase" will start This is the first time when real waste canisters will be disposed of in emplacement boreholes. The first emplacement borehole is assumed to be a monitoring borehole (MB). The lessons learned about plug implementation and installation of a monitoring system obtained during the dummy phase will be a sound basis for doing similar work in the real emplacement boreholes. The necessary decisions to be made in order to move forward in the stepwise approach are illustrated in Figure C.4.

The first decision point is on the regulator level (RDP-7) and deals with the approval of the plug design and the corresponding monitoring system. Once approved and implemented, the next decision point is on the implementer level (IDP-4). The implementer has the responsibility of performing the plug monitoring and in case significant deviations are observed, he has to inform the regulator and discuss with him possible consequences. If the deviations are seen as acceptable, then the procedure of waste emplacement in the following emplacement boreholes can be continued as planned. If the deviations are seen as non-acceptable, response options are to be considered based on the list in Table C.1. The test phase ends after the last emplacement borehole has been filled in the first drift. This last borehole is assumed to be the second monitoring borehole. The evaluation responsibilities and corresponding decision points are similar to the first monitoring borehole except that the result evaluation will include the monitoring data from both of the monitoring boreholes MB-1 and MB-2 in this drift. Again, if significant deviations are observed the implementer has to communicate this to the regulator for discussion and consequence evaluation. The same response options as mentioned above are valid to be considered here as well (Table C.1).

If an evaluation of the monitoring results obtained in MB-1 and MB-2 gives rise to the assumption that the plug evolution will be within the expected domain, the regulator may decide to finish the test phase and move forward to the second key decision point (KDP-2). At this key decision point the round table of implementer, regulator, and stakeholders are asked to make a decision to either start the routine waste emplacement or to consider an additional waiting period prior to the routine waste emplacement. The idea of this waiting period has been elaborated in the final report of the German repository commission without a proposal of its duration.

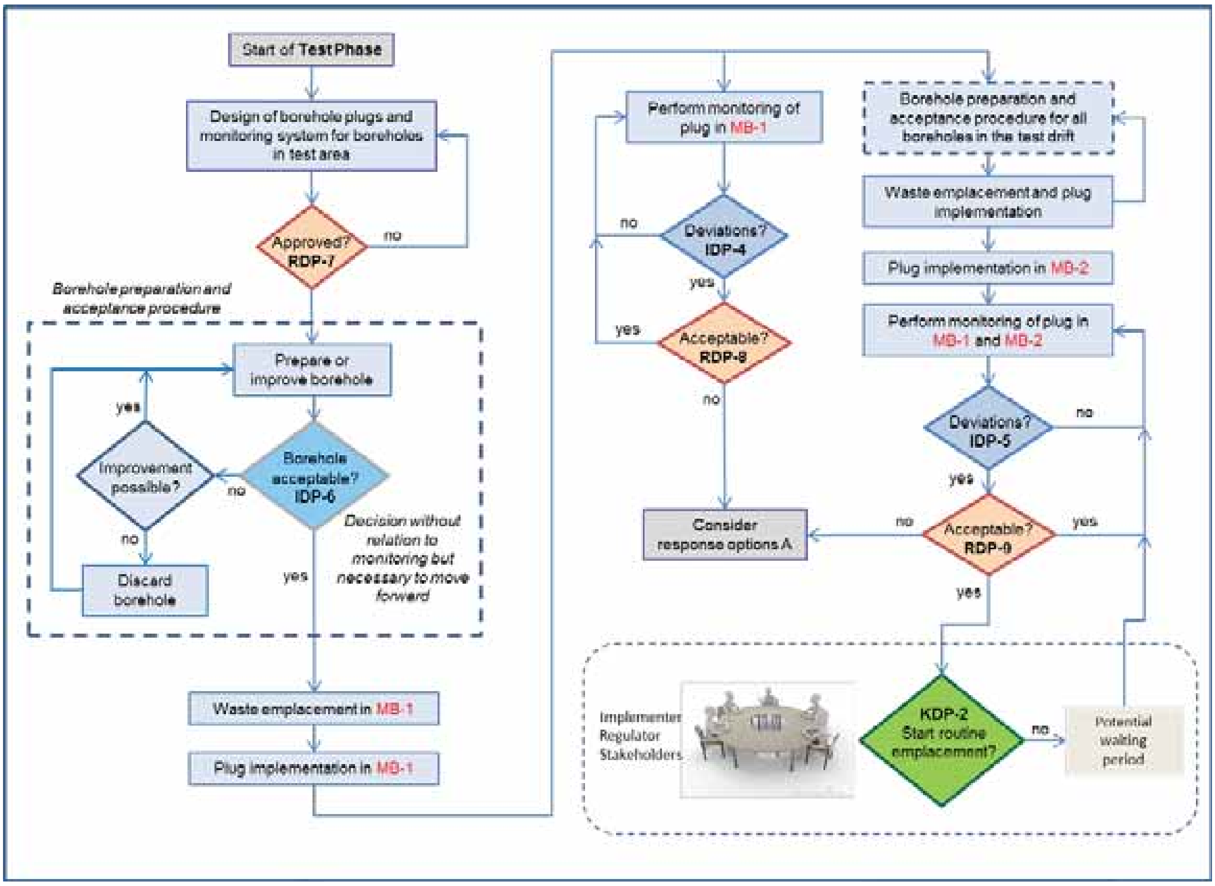


Figure C.4: Decision sequence of the dummy phase related to plug monitoring.

Table C.1: Possible response options to be considered during the test phase.

No	Response	Remark
1	**Monitoring system behaviour**	
1.1	Consider system failure and check system.	This should be the first step prior to any interpretation, even though the quality of the data will have been checked on a regular basis.
1.2	Consider sensor recalibration if possible.	Some sensors might allow an external recalibration without recovering them.
1.3	Consider signal correction.	If a systematic error has occurred, the signals may be corrected or compensated. Systematic errors and the compensation applied have to be evaluated on a regular basis.
1.4	Consider to ignore sensor signals.	The plug monitoring concept will be designed using a certain amount of redundancy. The loss of a single sensor can thus be coped with.
1.5	Consider to exchange sensors.	An exchange of a sensor depends on the accessibility of the sensor, which means on its location and corresponding radiation risk. The potential weakening of the plug due to the exchange activities has also to be considered. The time when the failure occurs plays a significant role. At early times of plug saturation an exchange might be possible. At later times, after saturation and swelling pressure evolution, exchange activities should be avoided, since a significant plug weakening is to be expected.
1.6	Consider to improve sensors of the same type to be installed at following monitoring boreholes and drift seals (or use other sensor types).	This reflects part of the "Learning Concept" in the stepwise approach to a final repository.

No	Response	Remark
2	**Plug behaviour**	
2.1	Check whether deviations are the result of monitoring-system-induced weakening of the barrier performance.	Monitoring system-induced deviations are important to identify to avoid misinterpretations.
2.2	Consider whether installation improvements of system components are necessary for future installations in following boreholes.	Each installation shall be accompanied by formal installation protocols seriously indicating potential problems that occurred during the work. These protocols could be a basis for improvement evaluations.
2.3	Consider to go back to the dummy phase to perform further tests.	This would include a stop of the test phase until new results are available.
2.4	Consider to improve the plug.	If, for example, the uplift of the abutment deviates from expectations, an additional support for the abutment could be considered.
2.4	Consider to re-build the plug or part of the plug.	
2.5	Consider to stop waste emplacement until plug performance is confirmed again.	

C.3 Decisions in Relation to Routine Disposal and Sealing

After the end of the test phase with or without an additional waiting period, the routine waste emplacement can commence. The decision sequence related to the routine emplacement activities is illustrated in Figure C.5. There are three decision points on the implementer level (IDP-6 to IDP-8). The first one (IDP-6) is a decision without a relation to monitoring activities but which is necessary to move forward. It is about whether a prepared emplacement borehole is acceptable for waste emplacement or not. The other two are decision points related to monitoring the different borehole seals in the monitoring boreholes (IDP-7) and the individual monitoring drift seals (IDP-8). In all cases the responsibility of the implementer is to continuously evaluate the monitoring data on a daily basis and to decide whether to inform the regulator immediately about potential observed deviations. Irrespective of these decisions, the regulator should be informed on a regular basis about the status of the monitoring data. For example, this regular basis could be a period of three months.

The responsibility of the regulator is to approve the barrier design prior to its implementation (RDP-11) and to evaluate the monitoring data and discuss it with the implementer (RDP-10 and RDP-12). In case of deviations assumed as significant, the regulator has to decide whether to accept it or to fall back on available response options. Potential response options should have been developed earlier as part of the closure concept and in relation to considerations about retrievability actions. All information from the disposal operation and the two monitoring activities at the borehole plugs and the drift seals, marked in yellow in Figure C.5, are feeding the key decision point KDP-3 (green diamond in Figure C.5). At this decision point representatives from all groups involved; i.e., from the implementer, the regulator, and the stakeholders should come together, discuss the current status of the repository evolution, and decide whether the current emplacement field shall be sealed and the operation be continued in the next emplacement field or if other measures need to be done.

This key decision point KDP-3 is a repeating decision point, indicated by the (R) in the green diamond, that needs to be undertaken after each of the individual emplacement fields is filled. Assuming an operational period of about 50 years and considering the amount of emplacement fields (>50), this leads to a frequency of about one KDP-3 meeting per year. This frequency seems reasonable to keep track of the repository evolution especially for those who are not engaged in the daily work.

The previous given decision level schemes are compatible with the decision levels as defined in Section 4 insofar as implementer decisions are primarily “technical/engineering” decisions, regulator decisions are principally related to “disposal programme decisions” while implementer, regulator and other stakeholders decisions may be related to both “disposal programme” and “governance decisions”.

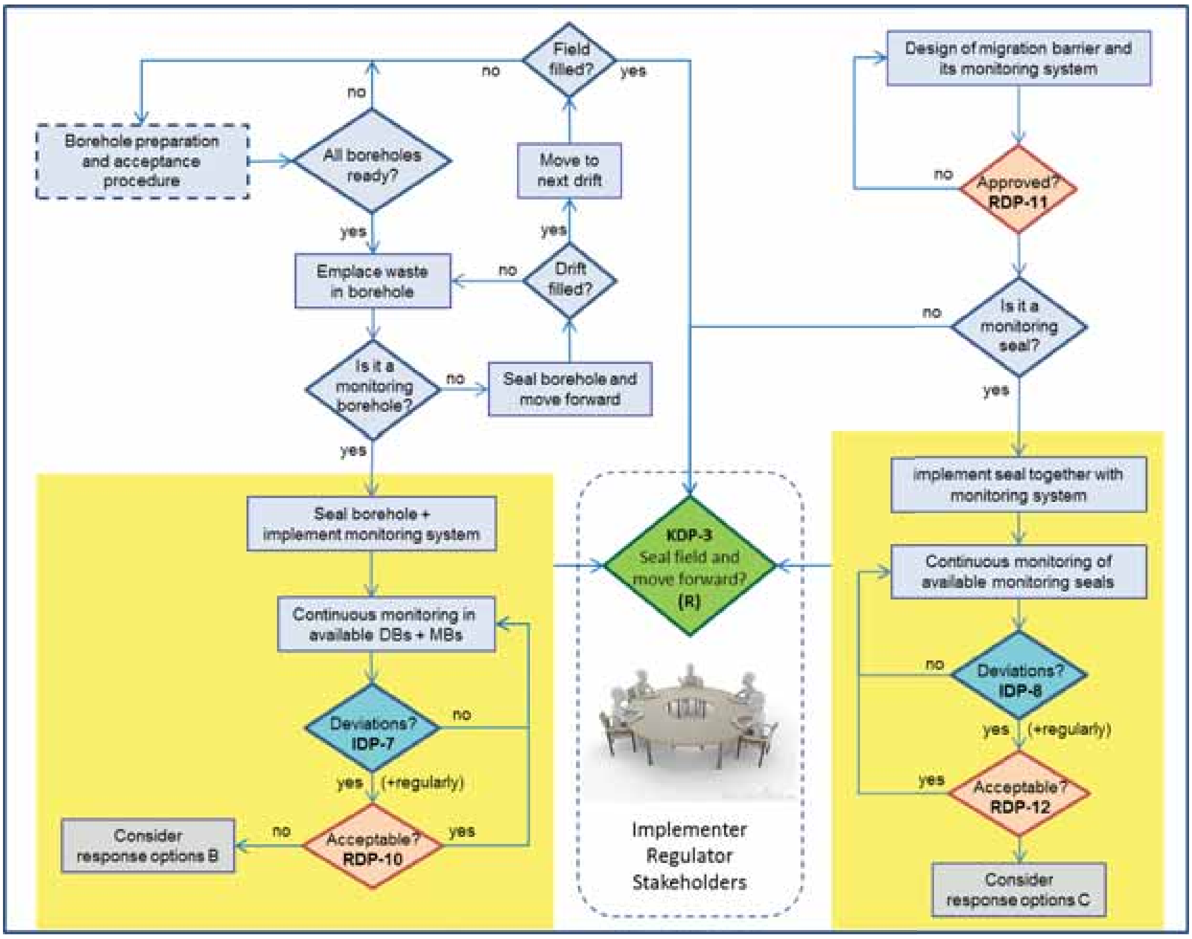


Figure C.5: Decision sequence of the routine disposal phase related to borehole plug and migration barrier monitoring. The areas marked in yellow are monitoring related and feed their information into the key decision point KDP-3.

C.4 Confidence Building and Related Decisions in the German ANSICHT Case

As mentioned above, the monitoring concept is seen as a learning concept. The subdivision of the operational period into three phases: the Dummy Phase; the Test Phase with its potential waiting phase, and the routine disposal phase with its field-by-field decisions provides the possibility of a step-by-step optimisation of individual barriers, the monitoring concept and equipment as well as the installation procedures. As disposal progresses, the number of monitored borehole seals and migration barriers increases. This is illustrated in Figure C.6 showing the amount of monitored plugs over time during the operational phase.

Eventually, 45 borehole plugs and 14 migration barriers (small drift seals) will be monitored. The stepwise approach allows increasing the understanding not only of the evolution of the barrier performance but also of its interaction with the host rock. With regard to confidence building, it is not expected that the provision of monitoring data does not foster everybody's confidence, but, for the German case, is a fundamental part of a confidence-building programme, with the aim of achieving confidence by the time the repository is closed.

The point in time when everybody needs to have confidence in the final repository is when the final decision has to be made that the repository is to be closed indicated by the blue arrow in Figure C.7.

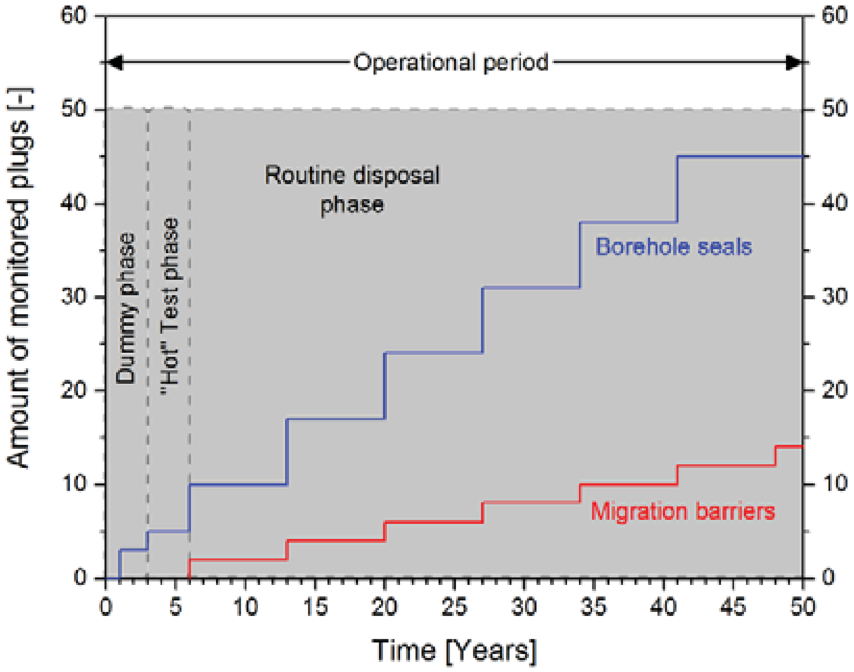


Figure C.6: Increasing amount of monitored plugs over time during the different operational phases.

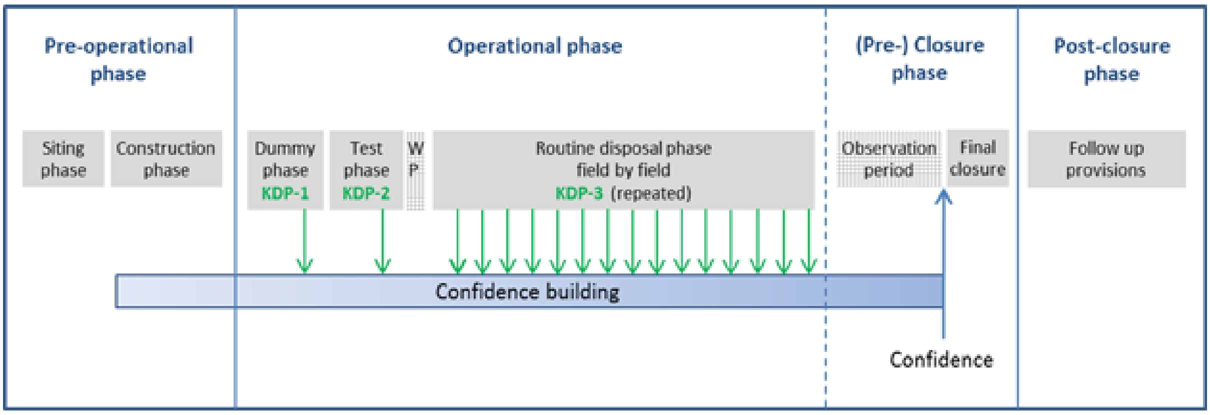


Figure C.7: Confidence building until final closure of the repository.

In the German case, monitoring of the EBS (in addition to quality assurance) is viewed as the only opportunity to check whether the man made barriers are evolving in a way that demonstrates that they will fulfil their assigned safety function. Without monitoring the EBS, at least in a representative way, there is no opportunity to achieve the "learning effect", which is assumed to be the basis of the monitoring concept. Currently, in the German programme monitoring of a representative engineered barrier in a separate underground area will not be sufficient to build the confidence of all stakeholders in EBS behaviour. The German programme has considered the known drawbacks of EBS monitoring in a real repository:

- Monitoring equipment might weaken the engineered barrier performance.
- Failures of monitoring equipment cannot be excluded and may lead to misinterpretations.
- The lifetime of sensors is potentially limited.

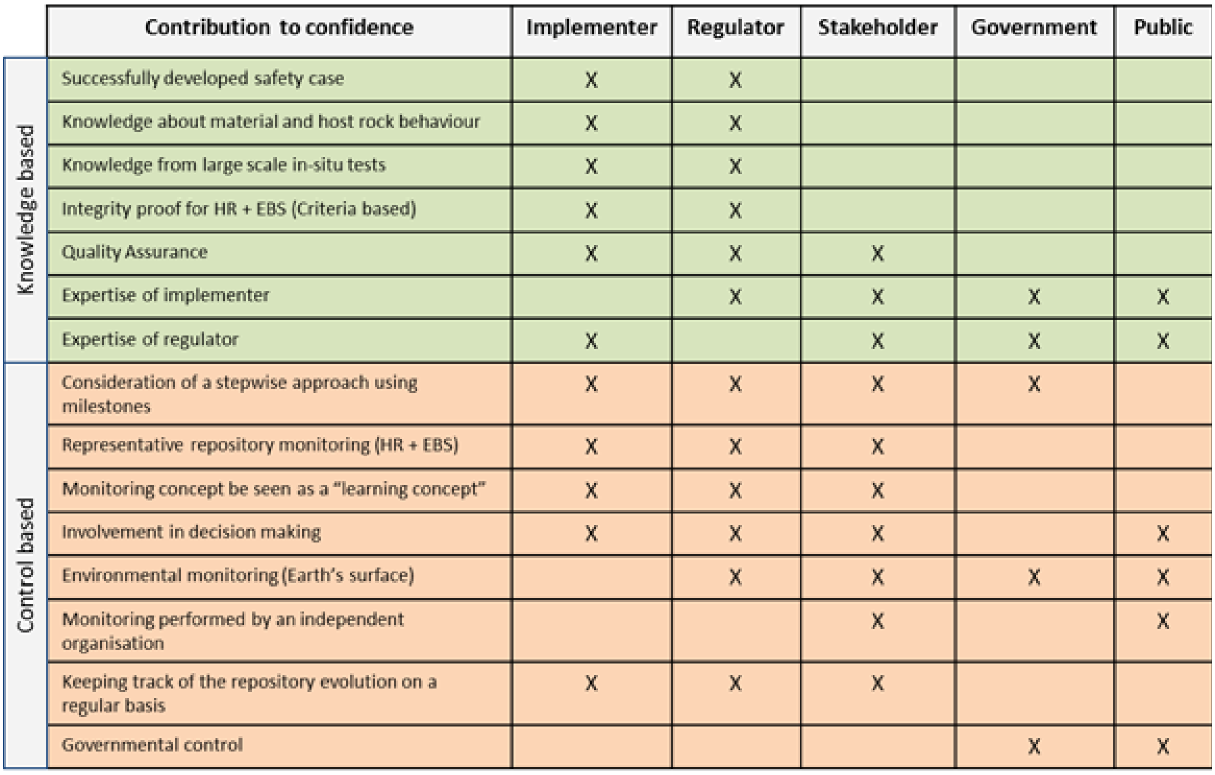
The first bullet is something which can be solved by proper concepts involving R&D on wireless data transmission. The second bullet is of course worth to be considered but a potential miss-interpretation can never be an argument for not doing monitoring at all, because if you are not doing it, the good information without failures would be lost as well.

Evaluating the increasing amount of monitoring data on a regular basis, discussing the interpretation of the monitoring results with all people involved and concerned at least at the installed (repeating) key decision points (KDPs) are seen as a tool to successively build confidence over the several decades of the operational phase.

When speaking about confidence building the question comes up what in particular contributes to confidence building and to whom. In Table C.2, several issues are listed that are assumed to be part of the confidence building process. In addition, different groups of people are listed that may find different of these issues be helpful for building their own confidence. It should be noted that the list is not assumed to be comprehensive. The issues have been grouped to those which are more "knowledge-based" (green) and those which are more "control-based" (orange) and each of the issues are assigned to the different groups of people by a cross. By looking at this cross table one may find a trend that by going from implementer to public the issues contributing to confidence building changes from the more knowledge-based ones to the more control-based ones. This makes sense since as the specific knowledge about the safety case is assumed to be limited in the public and the government and if at the same time the trust in the expertise of implementer and regulator is limited as well then control is the only way of getting confidence. Monitoring is seen as a tool that feeds the control demands.

As an option, decisions on the implementer level (IDPs) could be made by an independent institution. This might contribute to confidence building for the public. The round table (e.g. Figure C.5) would be added by a representative of the external organisation (EO). Implementer and EO will evaluate the monitoring data and potentially inform the regulator (responsibility: EO). The responsibility of the regulator should not be touched. It has to be noted that the responsibility of the plugging and sealing and installation of the monitoring systems shall be left to the implementer. The evaluation and interpretation of the monitoring results shall be done in co-operation with the EO.

Table C.2: Contribution to confidence to different groups of people.



	Contribution to confidence	Implementer	Regulator	Stakeholder	Government	Public
Knowledge based	Successfully developed safety case	X	X			
	Knowledge about material and host rock behaviour	X	X			
	Knowledge from large scale in-situ tests	X	X			
	Integrity proof for HR + EBS (Criteria based)	X	X			
	Quality Assurance	X	X	X		
	Expertise of implementer		X	X	X	X
	Expertise of regulator	X		X	X	X
Control based	Consideration of a stepwise approach using milestones	X	X	X	X	
	Representative repository monitoring (HR + EBS)	X	X	X		
	Monitoring concept be seen as a "learning concept"	X	X	X		
	Involvement in decision making	X	X	X		X
	Environmental monitoring (Earth's surface)		X	X	X	X
	Monitoring performed by an independent organisation			X		X
	Keeping track of the repository evolution on a regular basis	X	X	X		
	Governmental control				X	X