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Deliverable D2.1: Repository Monitoring Strategies and Screening Methodologies

Work Package 2

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the partners of the Modern2020 project	
CO	Confidential, only for partners of the Modern2020 project	

History chart			
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Final	Final Version	GSL	08/02/2017

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 Johan Andersson (SKB), Frederic Plas (Andra) and Irina Gaus (Nagra), and documented in Review Statements.

Approved by:

This report has been approved by:

- Mansueto Morosini, Work Package 2 Leader, *16/01/2017*
- Johan Bertrand, the Modern2020 Project Co-ordinator (on behalf of the Modern2020 Project Executive Board), *08/02/2017*

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, taking into account requirements of specific national programmes. The main focus of the project is monitoring of the repository and repository near-field during the operational period to support decision making and to build further confidence in the post-closure safety case (including verification of the as-built repository through monitoring of processes in the short period following emplacement).

Deliverable D2.1 is the summary report for Task 2.1 of Work Package 2, which is focused on monitoring programme design basis, monitoring strategies and decision making. This task aimed to address several remaining generic issues not previously addressed in international collaborative projects. D2.1 addresses these through undertaking work related to the following objectives:

- Evaluate the role of monitoring within the post-closure safety case.
- Evaluate high-level monitoring strategies.
- Consider the range of decisions to be made during repository implementation that will require information from monitoring.
- Develop screening methodologies used to develop monitoring parameter lists for different national monitoring contexts.

Approach

A questionnaire was developed and distributed to collate information about specific monitoring strategies being adopted in different countries, and the decisions expected to be underpinned by monitoring. In parallel, a literature review of monitoring programmes related to three radioactive waste disposal programmes was undertaken (the Waste Isolation Pilot Plant in New Mexico, USA; the New Low-level Waste Facilities in Dounreay, UK; and monitoring during the construction of the ONKALO underground rock characterisation facility in Finland). These programmes were selected to provide varied case studies illustrating the role of monitoring in repository implementation (such as decision making), and ways in which monitoring parameters have been screened. Outputs from the literature review have been used to underpin guidance on monitoring strategies developed in this report.

The preliminary findings from the questionnaire and literature review were discussed at a workshop held in December 2015, and these discussions were also used as an input into this report. At the workshop, initial ideas for screening parameter lists were discussed. These were subsequently developed into a screening methodology, referred to as the Modern2020 Screening Methodology, which underwent iterative testing using three case studies. The outcomes of this task were presented at a final workshop held in June 2016, after which the Screening Methodology was further revised. Feedback from that workshop has also been incorporated into the version of the Screening Methodology presented in this report.

Monitoring and the Post-closure Safety Case

Explicit consideration of the post-closure safety case, and how monitoring can be integrated with other methods to build confidence and demonstrate safety, needs to be clearly set out to ensure that monitoring programmes are discussed and developed in a wider context. Safety following closure is demonstrated through multiple lines of reasoning, including conduct of a safety assessment and comparison of the results with safety criteria. Residual uncertainties in the post-closure performance of a repository will be managed in the safety case, both by applying specific approaches to the safety assessment and through other means. Uncertainty can be accounted for through mitigation, qualitative argument, or quantitative assessment approaches, none of which rely on monitoring. The development of design requirements, and demonstration of compliance with these through limits, controls

(including quality control) and conditions, is used to verify that the as-built repository is consistent with the safety case.

However, the repository will be partially open and accessible for monitoring for several decades during the operational period and this provides an opportunity for gathering information on the performance of the disposal system following emplacement of the waste and the EBS. Consistent with stepwise implementation of geological disposal, periodic updates to the safety case will be produced during the operational period, and information from monitoring will be one input to these periodic updates. Information from repository monitoring could be compared with the arguments used to build the safety case to check whether the parameters of the repository system are evolving in a domain that is consistent with the safety case. The results from such monitoring could also form part of an ongoing stakeholder engagement plan and form part of stakeholder dialogue during repository operation.

High-level Monitoring Strategies

A range of high-level strategies can be used to conduct monitoring during the operational period to support decision making and to build further confidence in the post-closure safety case. Differences in strategy are largely a result of differences in national legislation and regulatory requirements, and differences in geological environment, which drive requirements on the disposal system (and, therefore, the selected disposal concept) and monitoring system, and lead to different monitoring concepts. High-level strategy includes consideration of *what* will be monitored, and *where* and *when* monitoring will take place. For each of these aspects, generic high-level strategy elements have been identified, each of which has associated strengths and weaknesses:

- Where: Monitoring *in situ*, with or without retrieval of monitored components; monitoring in a pilot facility; monitoring in an on-site underground research facility.
- What: Waste packages (and surrounding EBS); dummy packages (and surrounding EBS); specific elements of the EBS; geological barrier.
- When: Before repository operation or during commissioning; during the period of earliest waste emplacement; after closure of the repository.

In addition, three "end member" monitoring concept examples with contrasting strategies are described in this report:

- *In situ* monitoring of relatively broad scope represented by Andra's monitoring programme.
- Limited monitoring focused on EBS elements/dummy packages, represented by the KBS-3V concept.
- Monitoring in a pilot facility, represented by Nagra's monitoring programme.

Decision-making Requirements on Monitoring

Previous work has identified that monitoring can support management decisions in a staged programme of repository development. The accumulation of information progressively enhances confidence in the design concept, informing both major programme decisions and continuous engineering decisions. The MoDeRn Project is an example of previous work, in which an overall strategic approach to monitoring, the MoDeRn Monitoring Workflow, was developed.

The main stages in the lifecycle of a repository, and therefore the major programme decisions needed to move between phases, are similar for all programmes, and include decisions on siting, construction, starting and ending waste emplacement, backfilling, closure and post-operational provisions. In addition, for programmes with a requirement for retrievability, the decision to reverse any of the major stages or to retrieve waste would need to be supported by monitoring data. Such decisions are likely to involve holistic review of all data collected as part of the monitoring programme and this aspect of monitoring is considered in Task 2.3 of the Modern Project. Therefore, specific parameters to support programme decisions are not considered in this report.

Engineering decisions are highly programme-specific. This report presents examples of how monitoring data is expected to support engineering decisions in various programmes, in addition to a more generic list produced by the IAEA. These include potential future design enhancements identified by Andra, and decisions associated with the implementation of the German clay concept.

Identifying and Screening Monitoring Parameters

It is widely recognised that a monitoring programme should be practically feasible, proportionate and justified in the context of a specific disposal programme. Therefore, it is necessary to identify parameters to monitor that:

- Provide information about processes relevant to post-closure safety (and/or retrievability, if applicable).
- Offer value in support of the post-closure safety case, above that gained from other aspects of the wider science programme.
- Are technically feasible to monitor.
- Are appropriate in the context of other parameters proposed for monitoring.

A major outcome of Task 2.1 is the development of a generic approach for identifying such parameters (the Modern2020 Screening Methodology), which recognises and accommodates the role of expert judgement, and is adaptable to suit specific needs. The Methodology is visualised through a diagram (Figure E-1) and accompanied by a detailed explanation of each of the steps.

The Methodology is intended to be iterated multiple times, and to fit into a process of higher-level engagement with regulators and public stakeholders. It is fully compatible with the MoDeRn Monitoring Workflow.

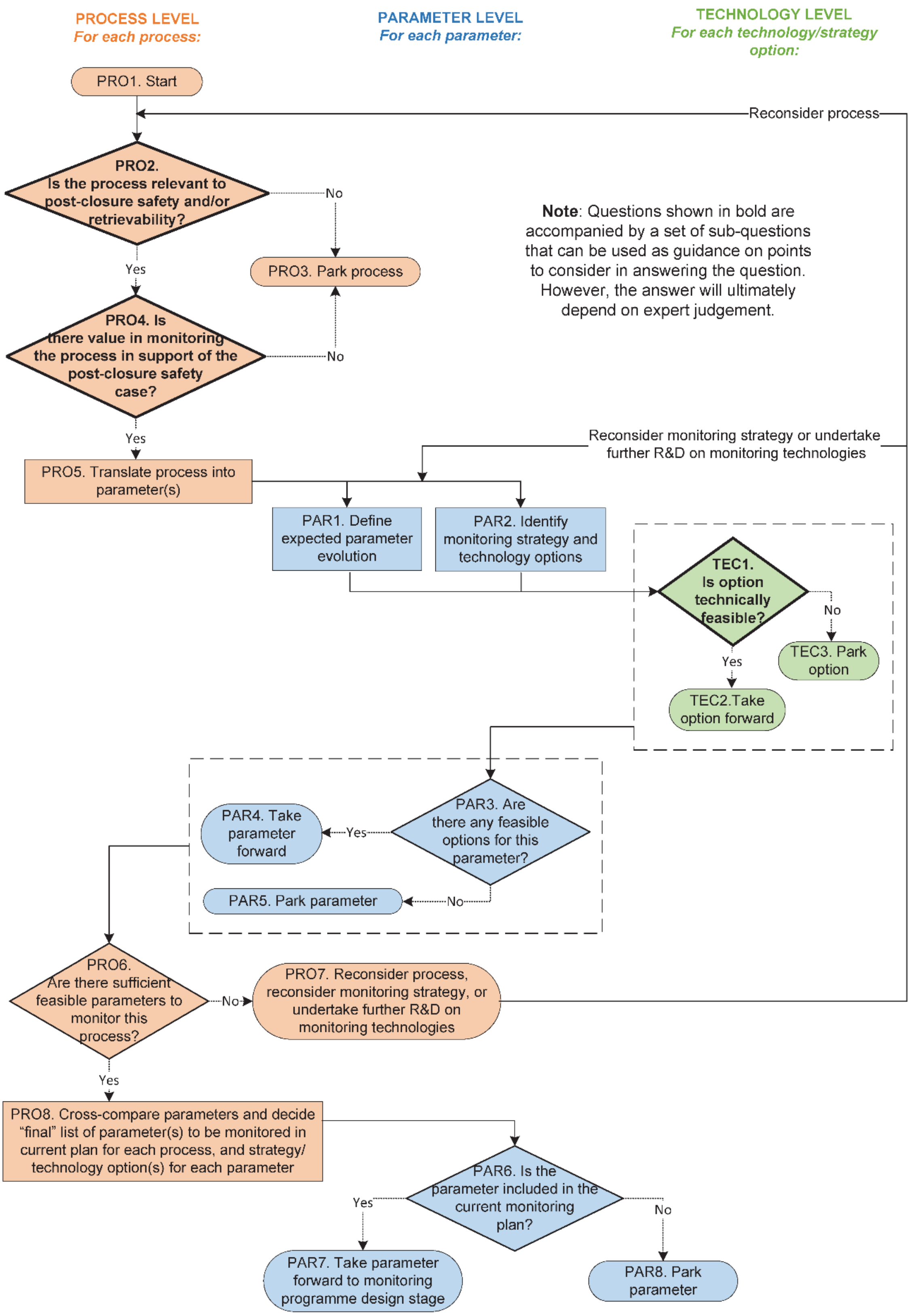

Figure E-1: The Modern2020 Screening Methodology.

List of Acronyms

BPM:	Best Practicable Means
CCA:	Compliance Certification Application (USA)
COMP:	Compliance monitoring parameter (USA)
DiP:	Decision-in-Principle (Finland)
DOE:	Department of Energy (USA)
DSRL:	Dounreay Site Restoration Limited (UK)
EBS:	Engineered barrier system
EC:	European Commission
EPA:	Environment Protection Agency (USA)
ESC:	Environmental Safety Case (UK)
ETN:	European Thematic Network
EU:	European Union
FE:	Full-scale Emplacement
FEP:	Features, events and processes
GEOSAF:	International Intercomparison and Harmonisation Project on Demonstrating the Safety of Geological Disposal
GRA:	Guidance on Requirements for Authorisation (UK)
HA:	Highly-active
HAZOP:	Hazard and operability
HLW:	High-level waste
IAEA:	International Atomic Energy Agency
ICRP:	International Commission on Radiological Protection
ILW:	Intermediate-level waste
IRF:	Instant release fraction
LLW:	Low-level waste
LTRBM:	Long-term Rock Buffer Monitoring
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
Modern2020:	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal – Horizon2020
NEA:	Nuclear Energy Agency
NLLWF:	New Low-level Waste Facilities (Dounreay, Scotland)
NRC:	Nuclear Regulatory Commission (USA)
OECD:	Organisation for Economic Cooperation and Development
PC:	Performance Confirmation
RCRA:	Resource Conservation and Recovery Act (USA)
R&D:	Research and development

RD&D:	Research, development and demonstration
RSA 93:	Radioactive Substances Act 1993 (UK)
SEPA:	Scottish Environment Protection Agency (UK)
SNL:	Sandia National Laboratories (USA)
SSG:	Specific Safety Guide
TECDOC:	Technical Document
THMC:	Thermal, hydraulic, mechanical and chemical
TRU:	Transuranic
URCF:	Underground rock characterisation facility
URL:	Underground research laboratory
WIPP:	Waste Isolation Pilot Plant (New Mexico, USA)
WMO:	Waste management organisation
WP:	Work package

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 as indicated:

Partner name	Short name	Country
Agence Nationale pour pa Gestion des Dechets Radioactifs	Andra	France
Asociación para la Investigación y Desarrollo Industrial de los Recursos Naturales	AITEMIN	Spain
AREVA NC SA	AREVA NC SA	France
CeskeVysoke Uceni Technicke v Praze	CTU	Czech Republic
DBE Technology GmbH	DBE TEC	Germany
Electicite 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 Surete Nucleaire	IRSN	France
Nationale Genossenschaft für die Lagerung radioaktiver Abfälle	Nagra	Switzerland
Nidia SRL	Nidia SRL	Italy
Nuclear Research and Consultancy Group	NRG	Netherlands
Nationale Instelling voor Radioactief Afval en Verrijkte Splijstoffen	NIRAS	Belgium
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	RAWRA/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

Glossary

This glossary provides definitions of key terms used in this report. In particular, it provides the definition of the Modern2020 Screening Methodology and the terms and concepts used within it.

Access gallery	See **Gallery**.
Alternative scenario	See **Scenario**.
As-built state	The as-built state represents the real state of the disposal system at a given time.
Batch tests	A **monitoring strategy** envisaged by SKB, consisting of small-scale process- or component-specific *in situ* experiments, located in the repository but away from emplaced waste, in which copper, buffer materials etc. could be installed. Batch tests could capture some aspects of **EBS** evolution, and complement other monitoring strategies.
Baseline monitoring	The establishment of baseline (undisturbed) conditions at a site prior to undertaking a potentially perturbing activity (such as sinking boreholes, constructing a repository, emplacing waste), usually as part of **site characterisation**. Baseline monitoring is defined differently in different programmes (and in some cases, for different components). For example, in the Swiss concept, baseline monitoring starts at least one year before any shafts are sunk, while in the French concept the baseline is established after repository construction but before the arrival of any waste. It is possible that site characterisation activities could evolve during operations into a means of providing information about **EBS** evolution, and could then be considered part of **repository monitoring**. See also **Site characterisation** and **Initial state**.
Commissioning test	Tests that are carried out in a repository in advance of waste emplacement as part of repository commissioning. These tests are likely to be monitored to provide information about the *in situ* behaviour of repository components. Use of commissioning tests to undertake such monitoring can therefore be considered to be a **monitoring strategy**. Commissioning tests may be inactive (not involving any waste) or active (involving waste packages) and can be carried out at a range of scales. Andra's **Industrial pilot** is an example of this monitoring strategy.
Compliance assessment	A systematic programme of measures applied (either by a WMO or a regulatory body) to demonstrate that the provisions of regulations are met in practice. May also be referred to as "compliance assurance" or "compliance demonstration".
Construction monitoring	Monitoring that takes place during the construction of the repository.
Current structure	In the French programme, it is planned that monitoring will be undertaken using a system of cells with different levels of monitoring. Current structures have minimal instrumentation and their performance is calibrated against results from **surveillance structures** using key **parameters**.

Design basis	The set of **requirements** and conditions that are taken into account in design. Many design bases incorporate a hierarchical structure, from high-level requirements reflecting component **safety functions**, down to detailed design specifications.
Design premises	Term used by SKB to described requirements which, if met by a repository, will ensure that post-closure safety is maintained. Design premises relate to the **initial state** of the repository, unlike safety function indicator criteria, which are intended to be fulfilled throughout the one-million-year assessment period.
Design target	The boundaries within which, at the start of the post-closure phase, the state of the disposal system is designed to fall.
Disposal cell	In the French concept for disposal of HLW, a disposal cell is the excavation in which waste is emplaced. Sometimes also referred to as an emplacement cell.
Disposal gallery	See **Gallery**.
Disposal panel	See **Emplacement field**.
Dummy package	A package with the same or similar properties of interest (e.g. size, package materials, thermal properties) as a waste package, but not containing any waste.
Element	One of the features or parts that make up the repository system (e.g. container, backfill, plug, host rock).
Emplacement field	Term used in the German programme to describe a set of drifts (including main drifts, access drifts and emplacement drifts) and boreholes that make up an area of a repository in which some or all of a specific type of waste (e.g. spent fuel, HLW, ILW) will be emplaced. Posiva (and other organisations) has a similar concept called a **disposal panel** consisting of a series of disposal tunnels.
Engineered barrier system (EBS)	The man-made components of the multi-barrier system, typically comprising the wasteform, the waste container, the buffer, the backfill, and the plugs and seals.
Engineering decision	Engineering decisions are based on routine operational monitoring and observation – e.g. monitoring of the effluent and ventilation stack, monitoring the position of a tunnel boring machine to decide how to direct it, and observing the tunnel outline to decide where to grout. They do not include more significant **programme decisions** (such as a decision to start or end waste emplacement), which are likely to involve more stakeholders and consideration of repository monitoring data.
Environmental monitoring	Monitoring that takes place at ground level, primarily undertaken for the purpose of characterising changes in the state of the surface environment, which includes people, flora, fauna, water bodies, soils etc.
Features, events and processes (FEPs)	Features are distinct parts or characteristics of a system. Events are changes to a system that may be characterised by a frequency of occurrence. Processes are ongoing chemical and physical changes in a system. FEPs are normally restricted to features, events and processes potentially relevant for the evaluation of long-term safety of a geological waste repository. They are often organised into FEP catalogues, which may be generic or site-specific.

Full-scale experiment	A test of a repository sub-system undertaken at approximately 1:1 scale. Such experiments would usually be carried out in advance of repository operations in support of safety case development and licence applications, and would typically be located in a separate location to the planned location of disposal operations.
Gallery	Term used by some WMOs to refer to excavated tunnels in the repository. Different types of gallery can be recognised (denoted by an appropriate modifier). The term **disposal gallery** is used by ENRESA, NRG and ONDRAF/NIRAS, for example, to refer to tunnels where waste will be emplaced and which will generally be backfilled immediately after emplacement; and **access gallery**, is used by Andra, ENRESA and ONDRAF/NIRAS, for example, to refer to excavations from which **disposal cells** will be accessed and which may be kept open for a period of time following waste emplacement.
Industrial pilot	A test phase in the French programme, lasting approximately ten years, which will be undertaken as the repository is progressively constructed. During the pilot phase, both "inactive" tests (on **dummy packages**) and "active" tests (on waste packages) will be conducted. Waste emplacement cells will not be backfilled, although there will be backfilling test zones. This is an example of a **commissioning test** and monitoring of the test form part of a **monitoring strategy**.
Initial state	The state of a system or component(s) of a system at the start of a defined process (such as excavation of a repository or emplacement of waste packages), for example as determined by **site characterisation** and **baseline monitoring**. As with baseline monitoring, the initial state may be defined differently in different programmes and/or for different components. For example, in the Swedish concept, the initial state of the geosphere and the biosphere is the natural system prior to excavation, while the initial state of the fuel and the engineered components is that immediately after emplacement.
Institutional control	Control of a radioactive waste site by an authority or institution designated under national law (such as, but not necessarily, a regulatory body). This control may be active (e.g. monitoring, surveillance, remedial work) or passive (e.g. land use control). The term is most commonly used to describe controls over a disposal facility after closure. The exact definition and requirements of institutional control varies in different national contexts.
Long-term safety	The safety of the repository (in terms of the protection of people and the environment) over the timeframe for which the waste emplaced in the repository remains hazardous. Often used interchangeably with **post-closure safety**, as the vast majority of this timeframe will occur after the repository has been closed, and the same processes and arguments are important to both.
Materials testing	An activity that forms part of the wider science programme, in which materials for specific purposes (such as buffer materials to be emplaced in deposition holes and concrete for use in plugs) are developed and tested against the **requirements** in a **design basis**.

Modern2020 Screening Methodology	The Modern2020 Screening Methodology is a diagram and associated guidance that provides an overview of the steps that a waste management organisation (WMO) may take in identifying and managing a list of parameters, linked to processes, and repository monitoring strategies and technologies. The list of parameters will form a basis for repository monitoring system design at each stage of an iterative repository monitoring programme that evolves through the implementation of geological disposal.
Monitoring	Defined in the MoDeRn Project as "Continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/ characteristics, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment – and thus to support decision making during the disposal process and to enhance confidence in the disposal process." In this report, it can be assumed that the term "monitoring is being used as shorthand for "repository monitoring" where there is no indication otherwise.
Monitoring strategy	A high-level approach to repository monitoring, including consideration of *what* will be monitored (e.g. waste, **dummy packages**, specific **EBS components**), *where* monitoring will be undertaken (e.g. in a **pilot facility** or in the main repository, with or without retrieval), and *when* monitoring will be undertaken (e.g. during commissioning, at first waste emplacement, after closure).
Normal evolution	See **Scenario**.
Observation	Term used by some WMOs (for example Andra) to refer to monitoring for the purpose of continuous improvement of knowledge, as distinct from monitoring for regulatory purposes, which is termed **surveillance** by Andra. Observation monitoring will be used to underpin engineering and programme decisions and **optimisation** of the design.
Operational safety monitoring	Monitoring which takes place in the repository for the purpose of ensuring operational safety, i.e. the safety of personnel and equipment during operations, including any monitoring for the purpose of demonstrating **compliance** with operational safety regulations. It does not include monitoring undertaken during operations for the purpose of making **programme decisions** or building confidence in the post-closure safety case, which is termed **repository monitoring**, although some of the monitoring undertaken may overlap with repository monitoring.
Optimisation	In a general sense, a process whereby design and/or procedures are improved as a result of previous experience (including monitoring) to better meet the various requirements on them, usually involving balancing safety requirements with cost, effort and efficiency. However, the principle of optimisation is defined by the International Commission on Radiological Protection "*as the source-related process to keep the magnitude of individual doses, the number of people exposed, and the likelihood of potential exposure as low as reasonably achievable below the appropriate dose constraints, with economic and social factors being taken into account*" (ICRP, 2006). To prevent confusion, use of the term "optimisation" in its general sense is avoided where possible in this report.
Parameter	A numerical indicator of properties.

Performance assessment	Analysis of the evolution of the repository system, with the aim of developing confidence that the system will (or can be designed to) perform within acceptable bounds. Usually includes, but is not limited to, a range of quantitative analyses of radionuclide release from, and migration through, individual system **components**.
Performance target	Term used by Posiva to describe a measurable or assessable characteristic through which the maintenance of a **safety function** can be quantitatively evaluated over the entire assessment period. It is equivalent to the term safety function indicator used by SKB and others.
Pilot facility	A representative region of an underground repository, separate from the main emplacement area, in which a small but representative fraction of waste can be emplaced and monitored to provide information on the behaviour of the barrier system and check predictive models. Pilot facilities are distinct from **URLs** in that the sole activity undertaken in them is the emplacement and long-term monitoring of waste. URLs are used for a wider range of experiments but waste is not emplaced in them. URLs are considered to be part of the wider science programme, whereas a pilot facility is considered to be a **monitoring strategy**. Requirements for and on pilot facilities vary between programmes. A pilot facility is required by the Swiss safety authority, and in the Swiss programme is considered to be a direct analogue of the real repository, although there must be no significant thermal-hydro-mechanical-chemical (THMC) interactions between them. Monitoring in the pilot facility will take place in parallel with repository operations. Waste is not expected to be retrieved from the pilot facility and so it must fulfil the same safety requirements as the repository. A pilot facility is also part of the Dutch concept. Such a facility will be heavily monitored and will provide important evidence for completion of the **safety case**, and for **programme decisions** such as starting and ending waste emplacement elsewhere in the repository.
Post-closure monitoring	**Repository monitoring** that takes place once the entire underground repository has been sealed and is no longer accessible.
Post-closure safety	See **Long-term safety**.
Post-closure safety case	The post-closure safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that a disposal facility will be safe after closure and beyond the time when active control of the facility can be relied on. It is an integrated methodology using multiple lines of reasoning. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages. It will be updated periodically throughout the lifetime of a repository, including both before and after an operational licence is granted. A post-closure safety case includes the findings of a **safety assessment** and a statement of confidence in these findings.
Post-emplacement monitoring	**Repository monitoring** that takes place after the emplacement of waste, with or without some EBS materials, but while underground areas of the repository are still accessible to workers.

Process identification	The activities that lead to the identification of possible **processes** that could be monitored to meet specific objectives or sub-objectives. This could be done, for example, through an analysis of **safety functions**, **performance targets**, **FEPs**, **performance assessment** parameters etc., or through an analysis of the **design basis** for particular repository components. Following process identification, a process of **screening** should be undertaken to identify the actual parameters to be monitored.
Programme decision	Significant decision related to the overall programme of geological disposal, such as a decision to start or end waste emplacement, close part or all of a facility, retrieve waste etc. Such decisions are likely to involve multiple stakeholders and careful consideration of repository monitoring data.
Qualification	Process of determining whether a system or component is suitable for operational use, generally performed in the context of a specific set of qualification requirements.
Quality control	Process intended to verify that structures, systems and components correspond to predetermined requirements, applied at the point of their construction and/or emplacement. Also referred to as "quality assurance", but in this report quality control is used throughout for consistency. DBE uses the term "product control" to describe a similar process planned to be used to obtain information about the waste packages instead of continuous monitoring activities.
Redundancy	A feature of a monitoring programme or system where duplicate information is obtained via more than one method, with the aim of increasing the reliability of the information. Redundancy can be applied on different levels, for example: different types of sensor monitoring the same parameter in the same component; monitoring different parameters to obtain equivalent information about a process; and monitoring of equivalent components in different parts of the repository.
Reference scenario	See **Scenario**.
Repository monitoring	In this report, repository monitoring is used to refer to monitoring of the underground repository system for any purpose. The term is used to distinguish between monitoring of the underground repository system and other types of monitoring that could be undertaken during implementation of geological disposal, for example monitoring of societal attitudes.
Requirement	A need taken into account during design.
Retrievability	An overarching term used to refer to removal of radioactive waste from a repository after it has been emplaced.
Reversibility	Term used in many countries to describe the ability to reverse **programme decisions** taken as part of a phased decision-making process during the progressive implementation of a disposal system. It is sometimes used more specifically to refer to the retrieval of waste by reversing the original emplacement process (for example in the UK programme).
Safety analysis	A documented process for the study of safety, consisting of the identification of potential hazards associated with the operation of a facility or conduct of an activity. Safety analysis is part of **safety assessment**.
Safety assessment	Process of evaluating long-term safety, **compliance** with acceptance guidelines and confidence in the safety indicated by the assessment results. **Performance assessment** is a necessary input to safety assessment.

Safety envelope The boundaries within which, at the start of the post-closure phase, the state of the disposal system (i.e. the parameters expressing the safety functions important for post-closure safety) must fall in order to deliver the post-closure safety functions.

Safety function A purpose fulfilled by a repository system or sub-system (e.g. a particular barrier) that contributes to the overall goal of safe disposal, for example by contributing to isolating the waste from the surface environment or containing radionuclides.

Scenario A potential evolution of the repository system, arising from a postulated or assumed set of conditions and/or events. Two types of scenario are generally considered:

- **Reference scenario**, representing a hypothetical or probable evolution of the repository system.
- **Alternative scenario**, representing a possible but less likely evolution of the repository system compared to the reference scenario, and which results from alternative assumptions about future events and processes. A number of alternative scenarios may be considered to explore different sets of alternative assumptions.

Screening The process whereby each **process** or **parameter** is assessed in terms of its relevance to the post-closure **safety case** (and **retrievability**, if applicable), its ability to provide valuable information that is not available through any other means, and whether it is technically feasible to monitor it. At each of these stages a parameter can be "parked" if the assessment indicates it should not be included in the monitoring programme at the present time. By this means a list of parameters to be monitored in an implementable and logical repository monitoring programme is developed.

Site characterisation Detailed surface and subsurface investigations and activities at a site to determine its characteristics and conditions, for example in order to assess its suitability to host a repository, enable detailed design, and evaluate the long-term performance or a repository constructed at the site.

Stakeholder An actor (person, group, organisation etc.) with an interest in monitoring in relation to geological disposal of radioactive waste. Can include, but is not limited to, members of a WMO, government agencies, regulatory organisations, advisory bodies, and members of the public and/or their representative bodies. Referred to by the IAEA as an "interested party".

In this report, "stakeholder" is most commonly used as part of the term "local public stakeholder" when referring to people living in the vicinity of an existing or planned disposal facility.

Stepwise management The pre-closure management of a repository, consisting of a series of progressive steps which can be taken (or reversed) by means of **programme decisions**.

Surveillance Term used by Andra to refer to monitoring with regulatory purpose, as distinct from monitoring for the purpose of continuous improvement of knowledge, which is termed **observation**. According to Andra, surveillance is a legal requirement and is used to check that specified parameters remain within specified ranges defined in the safety analysis.

The term surveillance is also used in the Dutch programme and is closely related to monitoring in that monitoring is used as a means of surveillance once waste has been emplaced. In the Dutch programme, surveillance and monitoring are considered to be important activities for ensuring **retrievability**.

Surveillance structure	In the French programme, it is planned that monitoring will be undertaken using a system of cells with different levels of monitoring. Surveillance structures will be heavily instrumented cells that act as "witness structures" for less instrumented cells. They will be among the first structures to be built.
Technical design requirement	Term used by Posiva and SKB to describe a property that the barrier shall fulfil (at the latest) at the time of installation.
Trigger value	A pre-determined result from a monitoring programme that leads to a requirement for further action.
Underground Research Laboratory (URL)	A facility developed for the purpose of research and testing related to geological disposal. URLs may be generic (developed at sites that will not be used for waste disposal, but provide information that may support disposal elsewhere), or site-specific (developed at a site that is a potential site for waste disposal and may be a precursor to or the initial stage of developing a repository at the site).
Underground Rock Characterisation Facility (URCF)	A facility developed for the purpose of characterising a geological formation that is intended to host a repository. Posiva's ONKALO facility is an example of a URCF.

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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 jointly funded by the Euratom research and training programme 2014-2018 and European nuclear waste management organisations (WMOs). The Project is running over the period June 2015 to May 2019, and a total of 28 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, 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. An assessment and synthesis of a number of other tests and demonstrators will also be undertaken, and this will include consideration of the reliability of monitoring results.
- WP5: Effectively engaging local citizen stakeholders in research and development (R&D) and 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.

This report is Deliverable D2.1 of the Modern2020 Project and is the summary report for Task 2.1 (WP2.1), the first of three tasks in WP2. WP2.1 aimed to evaluate monitoring strategies, consider decisions requiring support from monitoring data, and develop methodologies for screening monitoring parameter lists. These approaches will be considered and tested further in Task 2.2, which will evaluate safety cases for repositories in France, Switzerland, Finland, Sweden, Germany, the Netherlands, and the Czech Republic, to identify potential monitoring parameters. Task 2.3 aims to develop decision-making methods, tools and workflows for responding to monitoring information, and to develop collective opinions on performance measures and response planning.

1.2 Objectives of this Report

This report addresses the following objectives of WP2:

- Evaluate the role of monitoring within the post-closure safety case.
- Evaluate high-level monitoring strategies.
- Consider the range of decisions to be made during repository implementation that will require information from monitoring.
- Develop screening methodologies used to develop monitoring parameter lists for different national monitoring contexts.

Of these objectives, the primary purpose of this document is the last objective, i.e. to develop and present a methodology for screening monitoring parameters. The methodology is referred to as the Modern2020 Screening Methodology. Application of the Methodology will be tested in Task 2.2 of the Modern2020 Project. The other objectives contribute to the development of the Methodology and the principles that underpin it.

1.3 Scope of this Report

Monitoring is a broad term that is applied in many contexts. Monitoring was defined in the MoDeRn Project (MoDeRn, 2013a), as:

> *"Continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/characteristics, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment - and thus to support decision making during the disposal process and to enhance confidence in the disposal process."*

The Modern2020 Project (and therefore this report) focuses on monitoring during the operational period to support decision making and to build further confidence in the post-closure safety case. Such monitoring relates to relatively slow, long-term processes and is undertaken in parallel with other monitoring that WMOs might include in a holistic monitoring programme. Examples of other monitoring objectives include ((MoDeRn, 2013a):

- To support operational safety.
- To support environmental protection/assessment.
- To support nuclear safeguards.
- To support repository programme governance and stakeholder engagement.

It is recognised that there are overlaps in the parameters monitored in response to these different objectives. As programmes become more advanced, it is anticipated that such overlaps would be identified, consolidated and managed as part of a holistic and coherent monitoring programme. The Modern2020 Project is focusing on monitoring during the operational period to support decision making and to build further confidence in the post-closure safety case, as this is where the greatest challenges lie in terms of strategy and technology, and where the greatest gains can be made through international collaboration. Throughout this report, it can be assumed that the term "monitoring" is being used as shorthand for "monitoring during the operational period to support decision making and to build further confidence in the post-closure safety case" where there is no indication otherwise.

Modern2020 aims to allow disposal programmes close to licensing to design monitoring systems suitable for deployment in the next decade, and supports programmes less close to licensing and other stakeholders by illustrating how the national context can be taken into account in designing repository monitoring programmes. Therefore, this report presents generic approaches and methodologies, illustrated using examples from specific disposal programmes, and focuses on themes relevant to Modern2020 partners.

1.4 Approach

In order to collate initial information about specific monitoring strategies being adopted by WMOs, and the decisions they expect monitoring information to underpin, a questionnaire was developed and distributed to the WMO partners of Modern2020. The responses were used as a direct input to this report, and were also used as the basis for follow-up discussions with individual WMOs to evaluate open questions.

In parallel, a literature review of existing monitoring programmes was undertaken. These programmes were selected to provide varied case studies illustrating the role of monitoring in repository implementation (such as decision making), and ways in which monitoring parameters have been screened.

The preliminary findings from the questionnaire and literature review were discussed at a workshop held in December 2015 (Smith and White, 2016a), and these discussions were also used as an input into this report. At the workshop, initial ideas for screening parameter lists were discussed. These were subsequently developed into a screening methodology, referred to as the Modern2020 Screening Methodology, which underwent iterative testing with three case studies, broadly representing end member monitoring programmes in terms of their objectives and strategies.

The outcomes of this task were presented at a final workshop held in June 2016 (Smith and White, 2016b), after which the Screening Methodology was further revised. Feedback from that workshop has also been incorporated into this report.

1.5 Report Structure

The remainder of this report is set out as follows:

- Section 2 (Understanding Prior to the Modern2020 Project and Key Remaining Issues) summarises previous international work on repository monitoring as a starting point for common understanding of monitoring strategies and parameter selection, and sets out the need for specific further work in Modern2020.
- Section 3 (Repository Monitoring and the Post-closure Safety Case) discusses the components of a post-closure safety case, methods for addressing uncertainty and demonstrating compliance in a post-closure safety case, the role of monitoring in a post-closure safety case, and the influence that a post-closure safety case can have on the design of a monitoring programme.
- Section 4 (High-level Monitoring Strategies) discusses high-level strategy elements including where and when monitoring takes place, and what is monitored. End member monitoring strategies (such as those being considered by the Modern2020 Project partners) are presented together with their strengths and weaknesses and the safety case drivers for adopting different strategies.
- Section 5 (Decision-making Requirements on Monitoring) identifies the main programme decisions that could be underpinned by monitoring data in different national contexts and discusses the requirements such decisions place on monitoring programmes. Types and examples of engineering decisions that might be made on the basis of monitoring results are also discussed.
- Section 6 (The Modern2020 Screening Methodology) discusses generic approaches to developing parameter lists, and presents the Modern2020 Screening Methodology.
- Section 7 (Conclusions) presents the main conclusions of WP2.1, in the form of (i) a series of common themes between programmes that can be considered as a set of "good practice guidelines", (ii) a discussion of the main differences between programmes and the reasons for them, and (iii) a recap of the Screening Methodology.
- Section 8 (References) presents a list of references cited in this report.

- Appendix A: Modern2020 Task 2.1 Questionnaire presents the questionnaire that was distributed to Modern2020 WMO partners at the start of WP2.1 in order to obtain country-specific inputs.
- Appendix B: Review of Existing Monitoring Programmes presents a review of existing monitoring programmes at the Waste Isolation Pilot Plant (WIPP) in the United States (US), the near-surface New Low-level Disposal Facilities (NLLWF) at Dounreay in the United Kingdom (UK), and the ONKALO underground research facility at Olkiluoto in Finland. These act as examples of how such programmes were devised with reference to the post-closure safety case, and of how monitoring results have been used in the stepwise management of such facilities.

A detailed glossary of key technical terms used in this report is provided at the start of the report.

2 Understanding Prior to the Modern2020 Project and Key Remaining Issues

In this section, previous international collaborative work on monitoring strategies and parameter selection is summarised. This provides the context for the further development of these topics in the Modern2020 Project. Three aspects are discussed: international work on monitoring undertaken prior to the Modern2020 Project (Section 2.1); experience from site-specific monitoring programmes developed for particularly radioactive waste disposal facilities (Section 2.2); and the need for further work on strategies and parameter selection in the Modern2020 Project (Section 2.3).

2.1 Prior International Work on Monitoring

Significant work on the reasons for, and principles of, repository monitoring has been carried out by international organisations and in international collaborative projects over the past two decades. International guidance on monitoring in the context of radioactive waste disposal facilities has been prepared by the International Atomic Energy Agency (IAEA) (Section 2.1.1 and Section 2.1.2) and the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD) (Section 2.1.3). In addition, the EC has addressed monitoring as part of a European Thematic Network (ETN) (Section 2.1.4) and within the MoDeRn Project (Section 2.1.5), which was the precursor to the Modern2020 Project.

This work collectively constitutes the shared knowledge and understanding of the international community regarding monitoring strategies and parameter selection ahead of the Modern2020 Project. The purpose of this section is to provide a summary of this baseline as the starting point for the work undertaken in the Modern2020 Project.

2.1.1 IAEA Safety Standards

The IAEA establishes and adopts standards for the protection of health, and minimisation of danger to life and property. These safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The IAEA Specific Safety Requirements SSR-5 (IAEA, 2011a) establish the requirements relating to the disposal of radioactive waste, and Specific Safety Guide 14 (SSG-14) (IAEA, 2011b) provides guidance on these requirements.

SSR-5 contains requirements concerning monitoring programmes in Requirement 21 (Monitoring programmes at a disposal facility), the text of which states:

> *"A programme of monitoring shall be carried out prior to, and during, the construction and operation of a disposal facility and after its closure, if this is part of the safety case. This programme shall be designed to collect and update information necessary for the purposes of protection and safety. Information shall be obtained to confirm the conditions necessary for the safety of workers and members of the public and protection of the environment during the period of operation of the facility. Monitoring shall also be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure.*
>
> *Monitoring has to be carried out at each step in the development and in the operation of a disposal facility. The purposes of the monitoring programme include:*
>
> *(a) Obtaining information for subsequent assessments;*
>
> *(b) Assurance of operational safety;*
>
> *(c) Assurance that conditions at the facility for operation are consistent with the safety assessment;*
>
> *(d) Confirmation that conditions are consistent with safety after closure.*

> *Monitoring programmes have to be designed and implemented so as not to reduce the overall level of safety of the facility after closure."*

With the presentation of these safety requirements, monitoring is explicitly recognised by the IAEA as playing an integral part in assuring the safety of a geological repository. However, SSR-5 does not distinguish between monitoring to build further confidence in the post-closure safety case and monitoring for other reasons (e.g. to support operational safety). Some of the requirements, for example the role of monitoring *to collect and update information necessary for the purposes of protection and safety*, are more focused on supporting operational safety than on building further confidence in the post-closure safety case. In addition, the scope of SSR-5 is the disposal of all radioactive waste, including disposal of this material to different types of facilities, e.g. landfills, near-surface facilities, repositories (referred to as geological disposal facilities), and disposal in boreholes. The monitoring required to build further confidence in the post-closure safety case and to make management decisions during stepwise implementation can be different for each type of facility.

Nonetheless, SSR-5 provides important guidance for repository monitoring associated with building further confidence in the post-closure safety case. For example, it notes that plans for monitoring with the aim of providing assurance of safety after closure have to be drawn up before the construction of a repository to indicate possible monitoring strategies. However, plans have to remain flexible and, if necessary, they will have to be revised and updated during the development and operation of the facility.

SSG-14, the scope of which is specific to underground disposal facilities, provides additional details regarding the expectations of a monitoring programme, especially the need for monitoring to provide an input into safety assessments and continuing assurance of operational safety:

> *"...performance monitoring should be used to provide confirmation of assumptions made in the safety case"* [Paragraph 6.2]
>
> *"A programme of monitoring should be included as part of the safety case and should be refined with each revision of the safety case. During the operational period, the monitoring programme should be used to demonstrate compliance with the regulatory requirements and licence conditions for operation, including compliance with safety requirements for environmental and radiation protection."* [Paragraph 6.62]

Specifically, SSG-14 also states that a programme of monitoring should be included as part of the safety case, and should be refined with each revision of the safety case. Within the Modern2020 Project, this is interpreted to require that monitoring data will be used as an input to periodic updates of the post-closure safety case. However, the extent to which such monitoring is focused on the far-field or on the near-field (engineered barrier system (EBS) and near-field rock, i.e. the focus of the Modern2020 Project), is an open question. The link between monitoring and periodic update of the post-closure safety case is discussed further in Section 0.

Additionally, SSG-23 (IAEA, 2012) sets out expectations relating to the development of safety cases and safety assessments for geological disposal (the emphasis of which is on the performance of the disposal facility and the assessment of its impact after closure), and states in relation to monitoring:

> *"The safety case and supporting assessment should also be used to establish a monitoring and surveillance programme for the site and the surrounding area that is appropriate for the specific disposal facility and for subsequent review of the programme. Surveillance and monitoring programmes should be developed and implemented to provide evidence for a certain period of time that the disposal facility is performing as predicted and that the components are able to fulfil their safety functions."* [Paragraph 4.74]

All IAEA guidance on repository monitoring includes the principle that a repository should be designed to be intrinsically and passively safe, with no further actions required from future generations following closure, and in particular, that long-term safety should not rely on monitoring after closure (IAEA, 2012). However, the IAEA has also recognised the importance of monitoring through all steps in repository development, reflecting the significance that many WMOs place on monitoring within their programmes. These documents also emphasise the importance of baseline monitoring and contingency plans to address system behaviour outside of the performance bounds addressed in the safety case. The latter of these topics is addressed in Task 2.3 of the Modern2020 Project.

2.1.2 IAEA TECDOC

In 2001, the IAEA published a Technical Document (TECDOC) entitled "Monitoring of Geological Repositories for High Level Radioactive Waste" (IAEA, 2001). This document is a key underpinning reference to requirements on monitoring in the Safety Standards discussed in Section 2.1. The TECDOC considers the purposes of monitoring, noting that no increase in surface radioactivity as a result of disposal of radioactive waste in a repository could be detected during any monitoring period, but that many other objectives could be met. The five key purposes of monitoring were concluded to be:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure.
- To strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects.
- To provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence - for as long as society requires - that the repository is having no undesirable impacts on human health and the environment.
- To accumulate an environmental database on the repository site and its surroundings that may be of use to future decision makers.
- To address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste.

The report also notes that routine operational monitoring would be required, in common with all nuclear facilities and industrial plants.

The report includes a discussion of potential detriments that may result from monitoring, including:

- Radiation doses to personnel.
- Degradation of materials resulting from delay while monitoring is carried out.
- Formation of pathways for radionuclide migration.
- Increased likelihood of human intrusion or adverse impacts by natural processes.
- Interference with other repository operations.

The report also discusses the importance of baseline monitoring as part of site characterisation. The use of monitoring results to meet the above-mentioned objectives is covered in detail, and a suggested monitoring methodology is outlined. This methodology included brief discussion of the key issues and typical parameters that might be included in a monitoring programme (Table 2.1), quality assurance of the monitoring activities, reliability of monitoring results and preservation of records and reporting.

The IAEA Monitoring TECDOC provides a good discussion on the various issues associated with monitoring to build further confidence in the post-closure safety case, noting that endorsement of the early programme steps must be based on having sufficient confidence in post-closure safety.

The TECDOC provides examples of the aspects of a safety case that can be tested further on the basis of protracted monitoring during the post-closure period. However, the impact on the passive safety of monitoring the parameters that are listed in the TECDOC is not discussed, the parameters are not linked to a monitoring strategy or to a safety case driver, and technical feasibility of collecting data on the proposed monitoring parameters is also not evaluated. Therefore, further elaboration of the principles introduced in the TECDOC is required to identify EBS parameters that can be monitored to provide build further confidence in the post-closure safety case. Further work is also required to provide a method that includes justification of the selection of these parameters for specific programmes in order to define needs driven repository monitoring programmes.

Table 2.1: Typical parameters and possible measurement methods recognised in the IAEA Monitoring TECDOC. From IAEA (2001).

Category/Purpose of Monitoring	Typical Parameters	Access Method	Typical Measurement Methods
DEGRADATION OF REPOSITORY STRUCTURES Monitoring of repository structures/structural stability of openings	Rock temperatures Deformation of openings (orientations and apertures, propagation rates) Rock stress changes close to repository Water infiltration rate Condition of rock supports Repository temperatures, humidity Resaturation of backfill and seal materials	Within repository monitoring including access from boreholes drilled from the repository. Could include the use of devices that are installed *in situ* but with radio signals or earth currents for transmission of data. *In situ*/remote monitoring of backfilled openings	Thermocouples etc. Displacement detectors Strain/load sensors Volume measurements Strain/load measurements Various techniques Pressure sensors, moisture detectors, geophysical techniques (seismic wave transmission)
BEHAVIOUR OF WASTE PACKAGES AND BUFFER MATERIALS Monitoring the condition of emplaced waste packages/condition of buffer	Strain, corrosion current Package temperature, humidity close to packages Radioactivity in drainage water Waste-derived gases in repository air Resaturation/swelling pressure in buffer	*In situ* /remote monitoring of waste packages *In situ* /remote monitoring of environment close to the package Radioactivity monitoring of repository effluent water Monitoring of radioactive and other gases in repository air *In situ*/remote monitoring of environment close to the package	Strain gauge, current meter Many techniques available Various e.g. gamma detection Gas analyser Pressure sensors, moisture detectors

Category/Purpose of Monitoring	Typical Parameters	Access Method	Typical Measurement Methods
NEAR FIELD CHEMICAL INTERACTIONS Chemical condition of backfill and seals/behaviour of engineered barriers/integrity of concrete structures/changes in near field environment/surface properties of tunnel walls/repository resaturation behaviour	Repository temperature, humidity Mineral, chemical, biological changes on repository surfaces Changes to water content, pressure, chemistry in the near field when dewatering ceases (i.e. following sealing)	Within repository monitoring Periodic sampling within repository Periodic sampling or continuous measurements from within repository	Temperature, moisture (e.g. electrical conductivity), pressure Various analytical techniques Various techniques based on sampling or continuous measurements
CHANGES TO THE GEOSPHERE Changes in surrounding geosphere/interactions between engineered barriers and rock-groundwater system/influence of alkaline plume	Changes in groundwater pressures and pathways Changes in groundwater chemistry e.g. pH, Eh, dissolved solids, radioactivity, microbial activity Changes in mechanical behaviour of important structures in the rock Changes in mineralogy Thermal field Stress field Monitoring of, and response to, seismic events	Access from new or existing boreholes plus remote (for microseismic) In-repository, surface and boreholes	Pressure monitoring devices, e.g. piezometers in saturated zone, tensiometers in unsaturated zone Various techniques; borehole sampling, gamma ray detection Electro-mechanical gauges, acoustic emission monitors Sampling Borehole logging Strain/load sensors plus microseismic techniques Seismic wave detectors

2.1.3 NEA

In 2014, the NEA published a report entitled "Monitoring of Geological Disposal Facilities: Technical and Societal Aspects" (NEA, 2014a) as part of a wider project on the preservation of records, knowledge and memory across generations. This report summarises general objectives, practices and approaches to monitoring of radioactive waste disposal facilities, covering both technical aspects of interest to technical specialists and societal aspects related to the expectations of local communities and the need for records, knowledge and memory preservation following the closure of such facilities.

The report provides an important focus on preparing for the implementation of repository monitoring programmes with respect to parameter selection:

> *"The current, and justifiable, tendency is to measure as many parameters as possible so as to contribute in the most comprehensive way towards both the compilation of a complex description of the disposal system and the understanding of its performance under real conditions. With the transition from the repository development stage to implementation, it becomes necessary to optimise the selection of the parameters to be*

monitored which is motivated by practical reasons since it would be difficult to install and operate such a large number of monitoring systems over long time periods in the final disposal system. Thus, the identification of those parameters which would sufficiently demonstrate the attainment or approach to the passive safety status of the disposal system would be of substantial benefit."

Identification of such "optimised" parameter lists is a key focus for the Modern2020 Project, and will be specifically addressed within the Modern2020 Screening Methodology (Section 6), and within safety case test cases undertaken in Task 2.2.

The Reversibility and Retrievability Project was an NEA project that ran from 2007 to 2010, with implications for monitoring (NEA, 2011). A major outcome of this work was a generic Retrievability Scale (R-scale) (Figure 2.1), adaptable to most national programmes and illustrating stages in the life cycle of waste, with changing degree of retrievability, cost of retrieval and passive versus active controls. The potential for reversibility and retrievability are likely to feature in response plans prepared by some WMOs to respond to system behaviour outside of the performance bounds addressed in the safety case (many other responses are possible and these will be identified and discussed with Task 2.3 of the Modern2020 Project). Reversibility is mandated in law in France (Loi, 2015), and, therefore, is one driver for Andra's repository monitoring programme. In addition, the R-scale illustrates lifecycle stages in the implementation of disposal, and provides a useful conceptualisation for consideration of stepwise monitoring during the repository operation and closure.

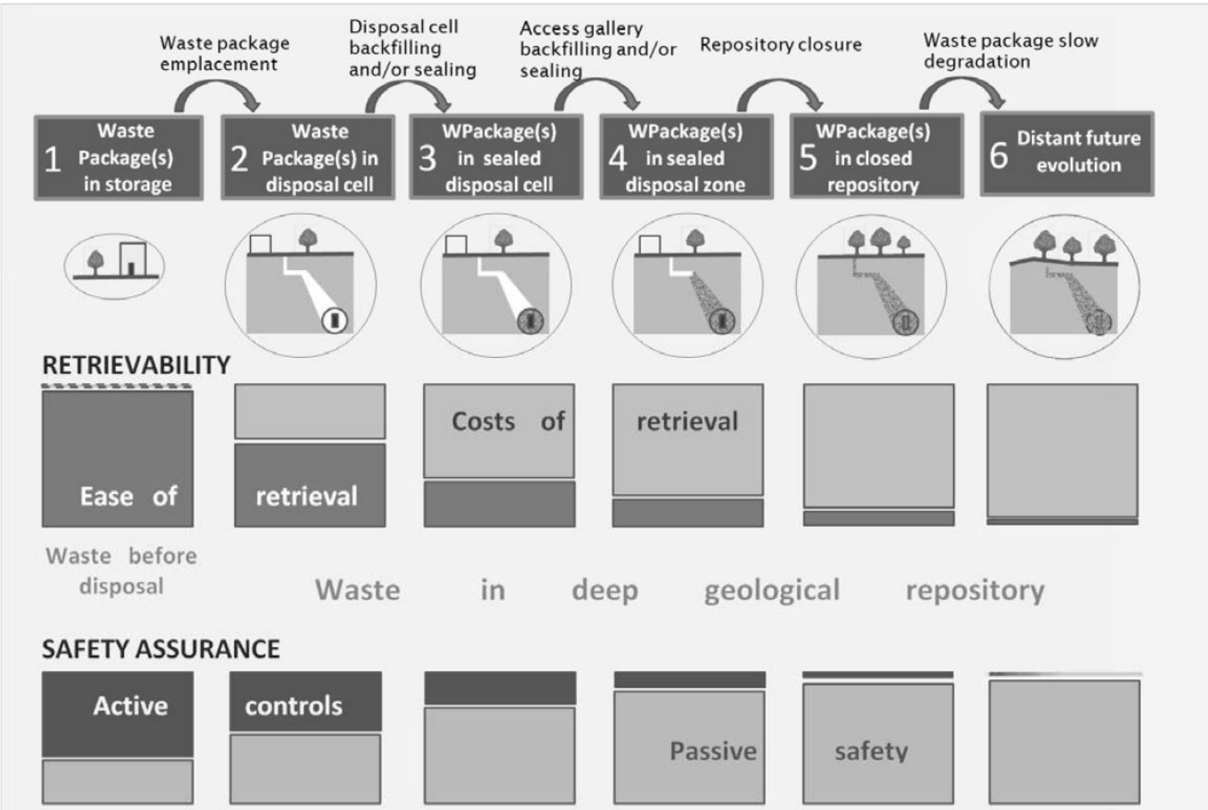

Figure 2.1: Graphical description of the R-scale (from NEA, 2011). The figure illustrates the changing degree of retrievability, and passive versus active controls on the waste for the lifecycle stages of a waste package. During the operational phase, not all waste packages in the facility will be at the same lifecycle stage.

2.1.4 European Thematic Network

Prior to the NEA Reversibility and Retrievability Project, the importance of monitoring in supporting decisions on waste retrieval was evaluated during an EC Concerted Action on the retrievability of long-lived radioactive waste in deep underground repositories (EC, 2000), and repository monitoring was identified as a subject requiring further work. Partly in response to this, a European Thematic Network (ETN) on the role of monitoring in a phased approach to geological disposal of radioactive waste was established (EC, 2004). The ETN was a collaborative effort between twelve organisations from within the European Union and Associated Countries, and built on guidance developed in the IAEA TECDOC (IAEA, 2001; see Section 2.1.2). It aimed to improve understanding of the options for, and role of, monitoring during phased geological disposal, and identify how monitoring can contribute to decision making, operational and post-closure safety and confidence in repository behaviour.

The following reasons for monitoring that relate to the stepwise implementation of a geological repository were identified:

- Monitoring as part of the scientific and technical investigation programme, including environmental monitoring.
- Monitoring of the acceptable operation of facilities.
- Confirmation of key assumptions of the disposal concept.
- Maintaining the confidence of future generations.
- Nuclear material safeguards.

The ETN explored the issues involved in monitoring by discussing four cross-cutting and overlapping "topics": baseline monitoring, monitoring for compliance, monitoring to support assessments of repository performance, and broader aspects of monitoring, including general scientific and technological development and the experience of other countries. The ETN also considered strategic aspects of monitoring, general requirements and constraints, and methods and techniques. A major conclusion was that, while existing and developing technologies give good prospects for a level of monitoring appropriate for assisting in stepwise repository implementation, national programmes would have to determine the actual extent of monitoring to be implemented. The use of underground research laboratories (URLs) for research and development (R&D) relating to monitoring relevant to a repository environment was emphasised. The report also included country annexes describing the plans for monitoring in each of the participating countries.

The ETN noted, however, that the extent of monitoring that is appropriate or useful to implement depends on implementation strategies, and stressed that there is a range of approaches to monitoring adopted by WMOs. No common method for determining the extent of monitoring, i.e. selecting the parameters to be monitored, was developed within the ETN.

2.1.5 MoDeRn Project

The MoDeRn Project was a four-year collaborative research project that ran from 2009 to 2013, with the overall aim to further develop collective understanding of the role of monitoring in the staged implementation of geological disposal and to provide examples, guidance and recommendations that may be useful to WMOs.

The outcomes of the Project were summarised in a synthesis report (MoDeRn, 2013a) and can be grouped into four sections: monitoring objectives and strategies, monitoring technologies, illustrative monitoring programme case studies, and stakeholder involvement. A summary of the findings for each of these topics is given below.

Monitoring objectives and strategies

In addition to defining and setting out the main objectives for monitoring (Figure 2.2), one of the principal outputs from the work on objectives and strategies was the development of the MoDeRn Monitoring Workflow (Figure 2.3), a generic structured approach to developing and implementing a repository monitoring programme, which has been recognised as a useful tool in developing a monitoring programme. It outlines a step-by-step process for identifying monitoring requirements and developing these into a defined programme through analysis of the disposal system.

The MoDeRn Monitoring Workflow envisaged three key stages to this process:

- Objectives and Parameters: Identification of main objectives and sub-objectives, and using these to develop a preliminary parameter list. Parameters may be identified through a number of means, including analysis of the safety case (e.g. consideration of safety functions and features, events and processes (FEPs)) or to address key programme requirements such as an ability to retrieve waste.
- Monitoring Programme Design: Analysis of monitoring system performance requirements, available technologies and redundancy/overlaps to screen the parameter list to facilitate the programme design. This will define how, where and when data will be collected, and specify performance levels, trigger values and action to be taken in response to these. This stage includes conducting further R&D if required.
- Implementation and Governance: Conducting a monitoring programme and using the results to inform decision making, including continuous and periodic evaluation of monitoring results within periodic safety case revision and other aspects of a disposal programme.

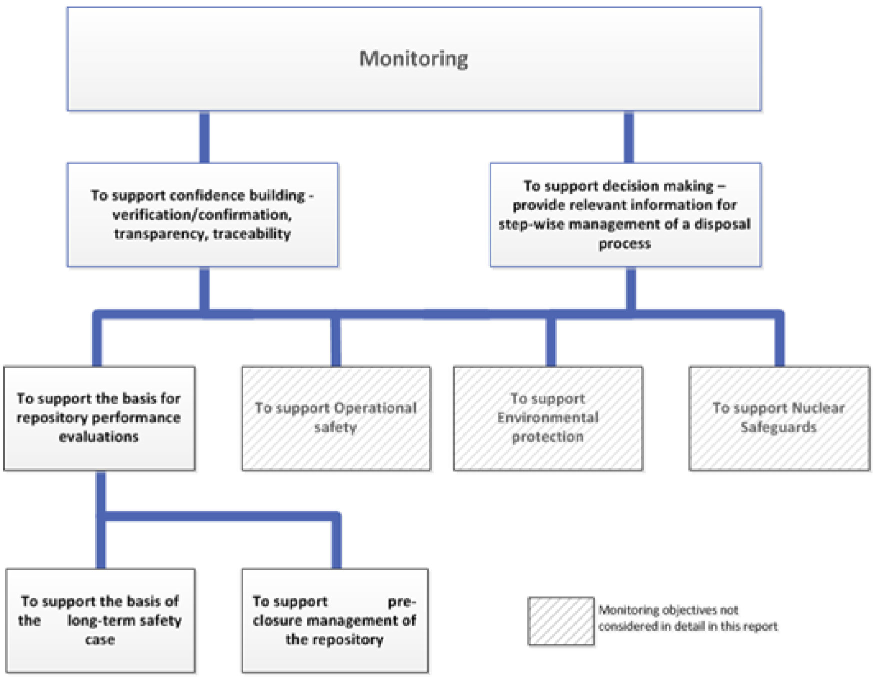

Figure 2.2: Overarching goals and main objectives for monitoring. From MoDeRn (2013a).

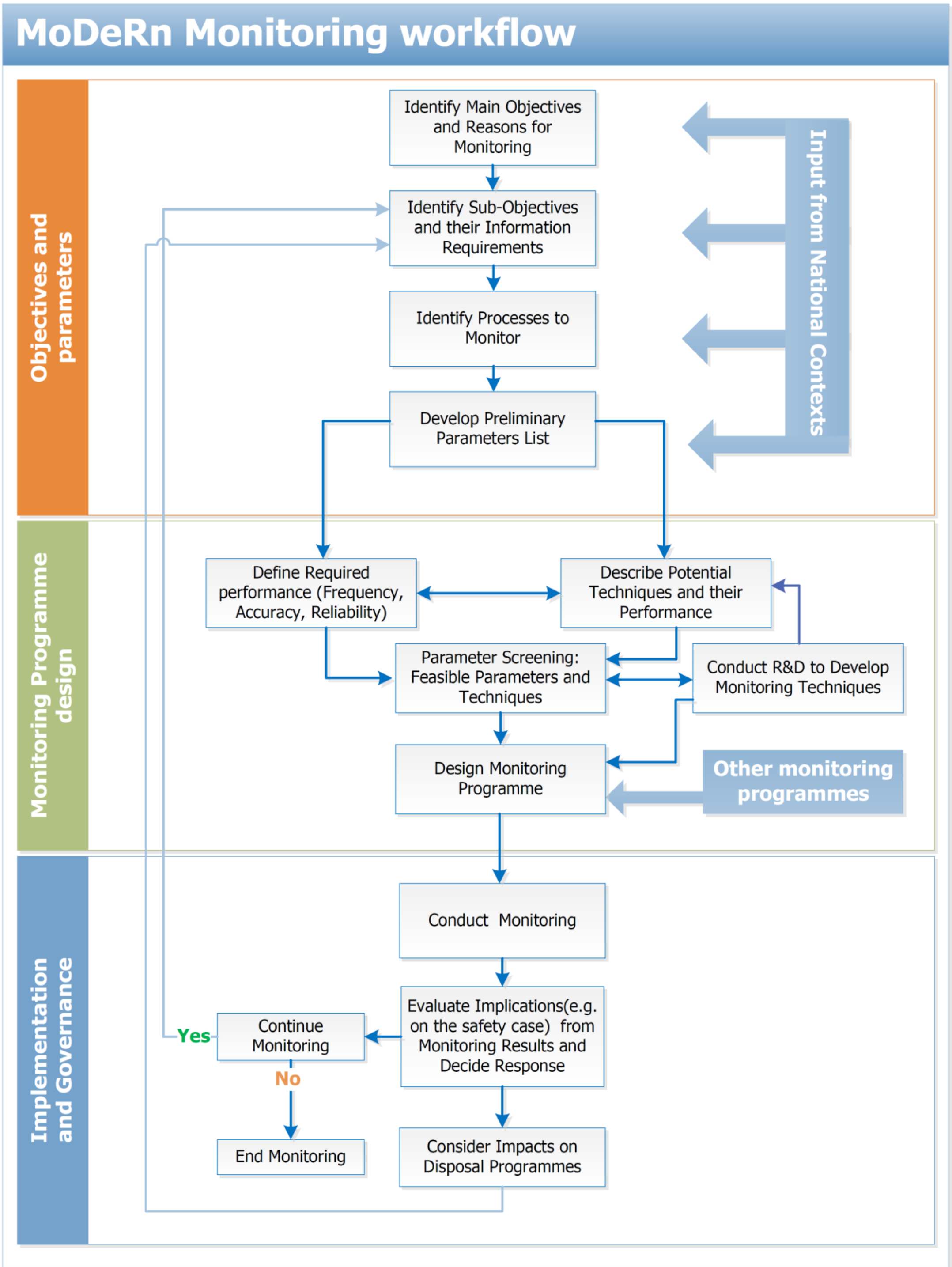

Figure 2.3: The MoDeRn Monitoring Workflow. From MoDeRn (2013a).

Monitoring technologies

Technical R&D in the MoDeRn Project focused on innovative EBS monitoring technologies in order to address the specific difficulties of monitoring in a repository environment. The work was captured in a state-of-the-art report on repository monitoring that provides a compendium of monitoring technologies (MoDeRn, 2013b). Within the project, R&D was carried out at several European URLs. Specific developments were made in technologies including seismic tomography, microseismic monitoring of the excavation damaged zone, wireless sensors and high- and low-frequency data transmission, fibre-optic sensors, digital image correlation and technologies for measurement of *in situ* corrosion rates. However, the

Project did not assess to what extent these technologies could actually monitor specific parameters during the operational period for specific repository designs.

Illustrative monitoring programme case studies

Three case studies focused on repository concepts constructed in salt (Germany), clay (France) and granite (KBS-3V). The case studies developed illustrative monitoring programmes using approaches based on the MoDeRn Monitoring Workflow (Figure 2.1). They consisted of both theoretical considerations and practical demonstrations, and included the use of a variety of monitoring strategies to avoid compromising the passive safety of emplaced waste.

Stakeholder involvement

Research was also undertaken on public stakeholder involvement in relation to repository monitoring. This took the form of interviews with specialists, workshops with stakeholders and public representatives from nuclear facility host communities; URL site visits with a subset of the public representatives; and discussions on the role of stakeholder involvement in repository monitoring programmes at an end-of-project international conference on monitoring in the geological disposal of radioactive waste. The main conclusions were:

- Many stakeholders believe that monitoring should not be viewed and designed as a confirmatory process, but rather as a comprehensive check of repository performance with no prior assumptions that it will behave as expected. Furthermore, they believe that this checking should be linked to an overall science programme including further R&D on disposal and repository monitoring techniques.
- Some stakeholders have expectations regarding post-closure monitoring with respect to preparation for and response to unanticipated events or evolutions.
- Monitoring can be characterised as a socio-technical activity and could contribute to building public confidence in the safety of a particular repository project. Monitoring can contribute to successful repository governance if it is expressed as a practical commitment to maintain a watch over repository performance and can address stakeholder expectations through clear communication of scientific understanding and the safety case.

Summary of MoDeRn Project Outcomes

The partners in the MoDeRn Project undertook a wide-ranging work programme that developed a better understanding of repository monitoring, provided developments in the technologies that can be used to monitor the repository near field, and provided a reference framework against which national programmes can be developed. However, the work was generic or illustrative in nature, and further work was therefore required to allow the collective understanding developed in the MoDeRn Project to be transferable to specific monitoring programmes.

2.2 Existing Monitoring Programmes

In addition to the theoretical and experimental work described above, important lessons can be learned from reviewing the development, implementation and management of monitoring programmes for existing radioactive waste disposal facilities. Three such examples are reviewed in Appendix B:

- The Waste Isolation Pilot Plant (WIPP), a repository for transuranic waste constructed in bedded salt in New Mexico, USA. The WIPP monitoring programme was designed to address the US concept of performance confirmation, and a multi-stage process resulted in the reduction of possible monitoring parameters to a relatively small list of compliance monitoring parameters.
- The NLLWF, a surface disposal facility for low-level waste developed at Dounreay, UK, under a similar regulatory regime as a geological repository would be developed.

The NLLWF monitoring programme demonstrates a strong link to the safety case prepared against similar requirements for authorisation as will be used for geological repositories, and also illustrates how a consolidated monitoring programme can be developed and managed starting from the consideration of a number of different monitoring objectives. There are strong parallels between the NLLWF and a geological repository in terms of the safety assessment approach, the nature of the post-closure safety case, and the role of monitoring within it.

- The ONKALO Underground Rock Characterisation Facility (URCF), developed in crystalline rock at Olkiluoto, Finland, as the first step in the construction of a geological repository for spent fuel. The preliminary identification of EBS monitoring parameters considers objectives, processes and parameters identified through an analysis of FEPs following by screening against various criteria.

2.3 Need for Further Work in Modern2020

The preceding discussion has illustrated that a significant body of work has been undertaken by the international community and in specific waste disposal programmes on repository monitoring. This existing work has defined the general principles and defined the role of monitoring within a geological disposal programme. Illustrations of how monitoring might be implemented have been developed and the overall reference framework for monitoring established.

However, the preceding discussion has also highlighted remaining generic issues for repository monitoring. The first step in further development of generic monitoring guidance is explicit consideration of the safety case and how monitoring can be integrated with other methods to build confidence and demonstrate safety. Such considerations need to be clearly set out, along with other themes common to all repository monitoring programmes, as good practice guidelines that WMOs can use to guide further development of monitoring plans. Such guidelines must consider the requirement to ensure that monitoring systems do not affect the passive safety of the repository, and this can be done by developing generic strategic approaches to monitoring in the context of specific concepts and safety cases.

The IAEA Safety Standards provide a clear requirement for monitoring of the repository during the operational phase, but the monitoring that is required is not necessarily EBS or near-field monitoring in support of building further confidence in the post-closure safety case. In theory, EBS monitoring could contribute to meeting the requirements of the IAEA (should these requirements be adopted into national regulations). However, the feasibility of EBS monitoring in support of building further confidence in the post-closure safety case depends to a large extent on the high-level strategy adopted in the monitoring programme, and also in further developments in monitoring technology (as addressed in WP3 of the Modern2020 Project). There is a need to choose parameters that will contribute to the periodic update of the post-closure safety case during the operational period, but, at the same time, such monitoring will have to have no significant impact on the post-closure safety case, i.e. such monitoring will have to avoid affecting the passive safety of the repository.

Although previous work has concluded that monitoring supports decision making, it has not explicitly described how this might occur. Therefore, it would be helpful if the pre-closure management decisions into which repository monitoring data might play a role (e.g. a supporting role through providing information that feeds into a periodic update to the safety case) were more clearly set out, including both high-level decisions that all WMOs will need to take, and examples of country- and concept-specific decisions. Such work is planned for Task 2.3 of the Modern2020 Project.

Finally, although the MoDeRn Monitoring Workflow has been used by several WMOs (e.g. Posiva, 2012 and RWM, 2014) in progressing monitoring plans, it is in need of thorough testing in different national contexts, particularly its more detailed aspects. Furthermore, the MoDeRn Project case studies focused on developing preliminary parameter lists and no screening against the post-closure safety case was applied. In order to develop and implement effective and efficient monitoring programmes, as identified by the NEA (2014a), more detailed and structured process descriptions for screening approaches must be developed.

The following sections of this report address several of these questions:

- Section 3 considers the role of monitoring within the safety case.
- Section 4 discusses high-level monitoring strategies.
- Section 5 considers the decisions that could be underpinned by monitoring.
- Section 6 provides generic methods for developing lists of monitoring parameters.

3 Repository Monitoring and the Post-closure Safety Case

This section presents a high-level overview of the relationship of repository monitoring to the post-closure safety case. This includes discussion of the scope and purpose of a safety case, and the role of safety assessment and performance assessment within it (Section 3.1); definitions of, and methods used to account for, uncertainties in the safety case; and the role of quality control and the wider science programme in checking compliance with the safety case (Section 3.2); and conclusions regarding the role of repository monitoring in a post-closure safety case (Section 3.3).

The discussion of the post-closure safety case in this section is high-level, the information does not present a detailed review of safety case approaches. More detail can be found in, for example, the guidance documents produced by the IAEA that are discussed in Section 2, and project and workshop reports produced by the NEA, such as:

- Summary of the state-of-the-art in the safety case for deep geological disposal of radioactive waste (NEA, 2014b).
- Overview of methods for safety assessment of geological disposal facilities for radioactive waste (MeSA Initiative) (NEA, 2012).
- Post-closure safety case for geological repositories (NEA, 2004a).
- Management of uncertainty in safety cases and the role of risk (NEA, 2004b).
- Establishing and communicating confidence in the safety of deep geological disposal (NEA, 2002a).
- The handling of timescales in assessing post-closure safety of deep geological Disposal (NEA, 2002b).
- Development and communication of confidence in the long-term safety of deep geological repositories (NEA, 1999).
- History and achievements of the Probabilistic System Assessment Group (NEA, 1997a).
- Lessons learnt from ten performance assessment studies (NEA, 1997b).

Further information on programme-specific approaches can be found in the major feasibility studies, safety assessments, post-closure safety cases and licence applications that have been produced by waste management organisations over the last four decades.

3.1 Scope and Purpose of a Post-closure Safety Case

A post-closure safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that a disposal facility will be safe after closure and beyond the time when active control of the facility can be relied on. It is an integrated methodology using multiple lines of reasoning, including both qualitative arguments and scientific evidence, and quantitative arguments based on safety assessment and performance assessment. The safety case includes a statement of confidence in these arguments. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages. It will be updated periodically throughout the lifetime of a repository, including both before and after an operational licence is granted.

The main components of a generic safety case are shown in Figure 3.1. These components are:

- The safety case context: The safety case context provides the scope and purpose of the safety case.
- The safety strategy: The approach that will be taken in site selection and facility design to comply with the safety objectives, principles and criteria, to comply with

regulatory requirements and to ensure that good engineering practice has been adopted and that safety and protection are optimised.

- The facility description: The facility description is a record of all of the information and knowledge about the disposal system and provides the basis on which safety assessment is carried out.
- Safety assessment: Post-closure safety assessment is the overall process of performing quantitative assessments of the radiological impact of the facility for the period after closure. Within the safety case, the performance of the facility against the quantitative safety standards is evaluated using a performance assessment. For assessment of the post-closure performance of the facility, the performance assessment involves developing an understanding of how, and under what circumstances, radionuclides (and chemotoxic substances) might be released from the repository, and how likely such releases are.
- Limits, controls and conditions: The safety case is used to assist in the establishment of limits, controls and conditions to be applied to all work and activities that have an influence on the safety of a facility and to be applied to the waste that will be disposed of in a facility (see Section 3.2.3).
- Iteration and design optimisation: Iteration and design optimisation is the process of making decisions on design options. Optimisation is defined by the International Commission on Radiological Protection (ICRP) as "the source-related process to keep the magnitude of individual doses, the number of people exposed, and the likelihood of potential exposure as low as reasonably achievable below the appropriate dose constraints, with economic and social factors being taken into account" (ICRP, 2006).
- Uncertainty management: Uncertainties in the safety case are the result of incomplete knowledge of the repository system or how it will perform in the future. Uncertainty management within the safety case is, arguably, the most significant aspect in relation to repository monitoring during the operational period in support of building further confidence in post-closure safety. Uncertainties are defined in Section 3.2.1, management of uncertainties is discussed in Section 3.2.2.
- Integration of safety arguments: Integration of safety arguments is the activity that combines the available evidence, arguments and analyses to demonstrate that the repository will be safe.
- Involvement of interested parties and the regulatory body (or bodies): This activity relates to dialogue processes undertaken as part of building confidence in the safety of the disposal facility, and as part of gaining authorisations.
- Application of management systems: The regulatory body (or bodies) and the operator are required to put in place an appropriate management system to ensure the quality of all safety-related work and activities. Of particular relevance to repository monitoring is quality control during emplacement, backfilling and sealing (see Section 3.2.3).

A safety case can be regarded as a process that continually evolves through the implementation of geological disposal in a repository, rather than a product produced at a fixed point in time. Each safety case collates the state of knowledge at a particular stage of repository implementation, and includes the identification of uncertainties, unresolved issues and guidance on work to resolve these before the next stage of implementation. It is therefore an essential input to important decisions concerning the repository. Safety cases can be used, for example, to demonstrate the feasibility of geological disposal, to support siting, as part of a licence application, and to support continued operation and closure of a repository. The latter two uses are of relevance to the scope of the Modern2020 Project.

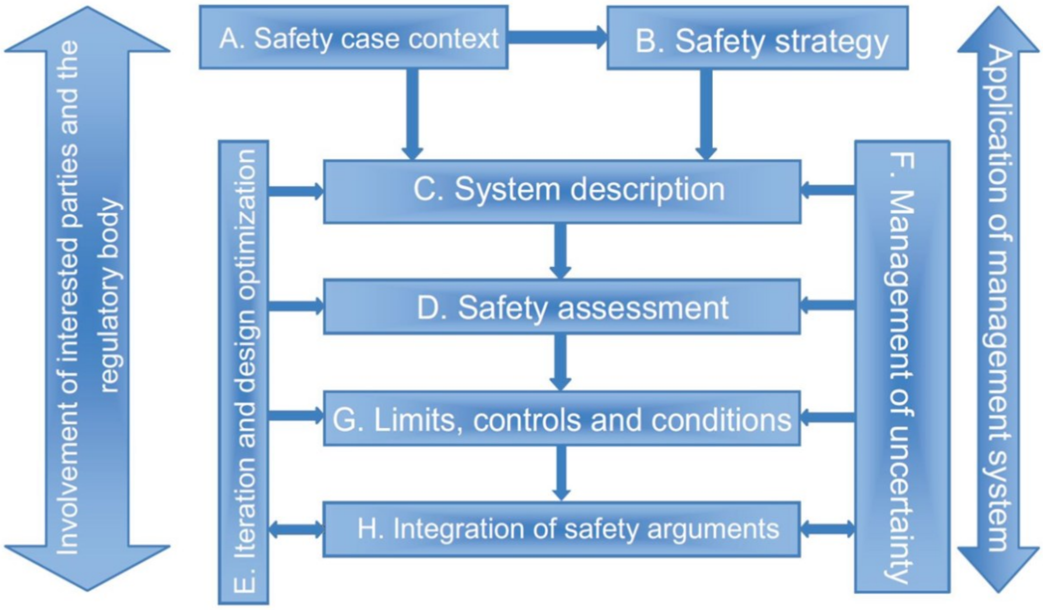

Figure 3.1: Components of a safety case. From IAEA (2012).

3.2 Accounting for Uncertainty in a Post-closure Safety Case

3.2.1 Types of Uncertainty in a Post-closure Safety Case

As noted in Section 3.1, a post-closure safety case presents arguments regarding safety of geological disposal over long periods. One of the key components of a post-closure safety case is uncertainty management, where uncertainty is incomplete knowledge of the system. This uncertainty can be identified and characterised, and there are many different methods of accounting for it such that it can be shown that the repository will operate safely despite this uncertainty, as long as the assumptions in the post-closure safety case hold true.

Two categories of uncertainty are widely recognised (see, for example, Wilmot, 2002):

- Epistemic uncertainty (subjective uncertainty) is knowledge-based uncertainty, for example data collected during site characterisation or laboratory experiments that may be used to define parameter values or probability density functions. Epistemic uncertainty may be reduced by the acquisition of more data, although this could be difficult and/or expensive.
- Aleatory uncertainty (stochastic uncertainty) is uncertainty that has a random or seemingly random element, such as prediction of specific tectonic events, climate change and future human activities. Additional study cannot provide additional quantitative information that will reduce aleatory uncertainty.

In the context of assessing the post-closure safety of a radioactive waste repository, the main types of uncertainty that will need to be addressed are:

- Uncertainty in the future evolution of the disposal system (scenario uncertainty).
- Uncertainty in the models used to represent this evolution.
- Uncertainty in the parameter values used in the modelling programme to evaluate the potential consequences of scenarios.

The first two are largely a consequence of aleatory uncertainty, while the third mainly represents epistemic uncertainty. However, different safety cases may classify epistemic and aleatory uncertainty in different ways, and, as a result, also address uncertainties using different methods. A more detailed discussion of uncertainty in the safety case is provided in PAMINA (2009).

The need for uncertainty management is not unique to geological disposal of radioactive waste, but geological disposal requires some specific considerations, for example, owing to the long timescales addressed in the post-closure safety case.

One particular example of timescale considerations is demonstration of the performance of the multi-barrier system with respect to the functions they are required to provide. Figure 3.2 illustrates the processes that contribute favourably to safety within the Swiss disposal concept for spent fuel, high-level waste (HLW) and intermediate-level waste (ILW), and the timescale over which these processes operate (Nagra, 2002). These processes are subject to uncertainty. For example, the exact value of the instant release fraction (IRF)[1] is difficult to determine, and, therefore, the radionuclide inventory that could be released soon after failure is uncertain (Johnson *et al.*, 2004). In systems that provide safety over much shorter periods, it may be possible to include monitoring of performance as part of an overall strategy to dealing with uncertainty; monitoring is part of the approach for demonstrating safety during repository operations. However, for post-closure safety, demonstration of safety cannot be undertaken by monitoring the processes illustrated in Figure 3.2. Instead, uncertainty must be addressed through a series of other methods. The types of approaches adopted in post-closure safety cases are briefly summarised in Section 3.2.2.

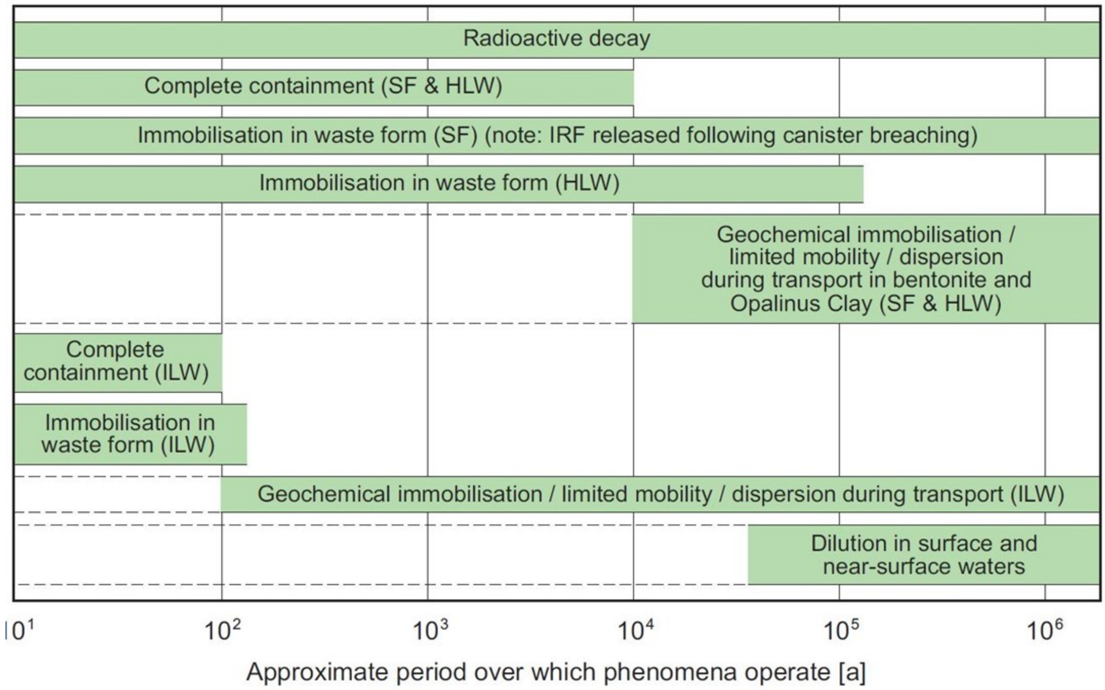

Figure 3.2: Key processes (phenomena) contributing positively to long-term safety, and the time frames over which they are expected to operate, in the Swiss concept for long-lived waste disposal in Opalinus Clay. From Nagra (2002).

[1] The IRF is the fraction of the inventory of more mobile radionuclides that is assumed to be readily released from HLW or spent fuel upon canister failure.

3.2.2 Managing Uncertainties and Building Confidence

Uncertainty can be managed in the safety case through a variety of methods, depending on the nature of the uncertainty and the context in which it needs to be accounted for. These methods broadly can be grouped into three categories:

- Uncertainty Reduction (Mitigation): This is the process of removing uncertainty at source.
- Qualitative Arguments: This is the process of using non-numerical strategies for uncertainty management.
- Quantitative Arguments (Assessment): The use of numerical methods to capture uncertainty and to evaluate the full range of impacts on safety.

Quality Control aiming at ensuring that barriers, installations and deposition chambers meet requirements is a key means of handling uncertainty. Mitigating or reducing uncertainty can also be achieved, for example, by better characterisation (e.g. of the waste or the repository site) through increased data collection or improved methods. For example, undertaking additional hydraulic tests may help to reduce the uncertainty in the spatial variability of parameters affecting groundwater flow (e.g. hydraulic conductivity). It is possible that additional information may increase the perceived uncertainty by revealing more complexity or variety than suggested by a less thorough characterisation, but in fact the uncertainty will be more fully understood than before and can therefore be more rigorously treated in the safety assessment and safety case. It may be possible to reduce the uncertainty at source – for example, siting a repository in a relatively homogeneous host rock will lead to less uncertainty concerning groundwater flow, and solute and radionuclide transport in the host rock, compared with a site in a complex geological environment.

If such mitigation is not possible, it may be appropriate to account for uncertainty through qualitative strategies. Several types of qualitative strategies may be employed. PAMINA (2009) recognises three examples: robust design; qualitative arguments and quality assurance. Robust design relates to the application of conservative engineering procedures. Examples include limiting the maximum temperature in the near-field to avoid complex coupled processes (e.g. avoiding steam generation) and use of disposal canisters with an additional corrosion allowance to account for any uncertainty in potential corrosion rates. The use of qualitative arguments relates to the use of alternative lines of reasoning to support demonstration of safety. These could include, for example, natural analogues, use of site-specific evidence such as paleo-hydrogeological information, and use of information from the RD&D programme to demonstrate that relevant features and events are well understood. Quality assurance includes a range of techniques to ensure appropriate methodologies are applied in the safety case. These include configuration control for all related computer files, documentation of changes and their impacts, verification and validation of models, use of formalised methods for assessing uncertainties subjectively, and peer review (including peer review of codes used for quantitative safety assessment calculations).

Quantitative arguments (assessment approach) can also be employed, in which the uncertainty is quantified or estimated and included in safety assessment through structured methods. Again, this encompasses a range of different techniques to ensure that the results of the safety assessment reflect (or bound) the full range of system behaviour that could reasonably be expected to occur during the assessment period. Methods include explicit consideration of parameter uncertainty, treatment of model uncertainty and treatment of scenario uncertainty. Parameter uncertainty could be addressed through use of, for example, probabilistic density functions for parameter values in a probabilistic safety assessment calculation. Model uncertainty could be addressed through consideration of, for example, alternative conceptual models, use of different mathematical models to represent a process, and use of different codes to implement the mathematical model. Scenario uncertainty could be addressed, for example, by defining several scenarios to account for specific uncertainties and demonstrating that repository performance is satisfactory in each case. Most programmes define a reference or normal evolution scenario, and identify alternative evolution scenarios through a structured process of scenario development. Both deterministic approaches (where the same end result is achieved given the same set of FEP assumptions) and probabilistic approaches (where a stochastic element means that the end result can be analysed statistically) can be used in scenario analysis.

3.2.3 Checking Compliance with Limits, Controls and Conditions

Management of uncertainty, for a given set of assumptions, contributes to a demonstration that the repository will perform safely. The assumptions include those related to the implementation of the design in the real-world. Such demonstration requires conversion of the assumptions into a set of design requirements that form the basis of detailed design of the repository. These design requirements will define the situation in which the initial state of the repository is compliant with the safety case. Compliance demonstration is based upon the limits, controls and conditions that are established and applied to all work and activities that have an influence on the safety of a facility.

Development of design requirements is a key component of a requirements management system (NEA, 2004c). In turn, design requirements are one part of the design basis for a repository, the design basis being defined as the set of requirements and conditions taken into account in design (see for example, SKB and Posiva, 2016). The design basis specifies the required performance of a repository and its sub-systems, and the conditions under which the required performance has to be provided. It includes requirements derived from regulations, and safety functions that the multi-barrier system has to fulfil as part of the overall safety objective of a disposal system. Requirements are statements on what the design has to do (the performance) and what it must be like (the characteristics), for example, the strength and the hydraulic conductivity of the materials used in an element of the EBS. Conditions are the loads and constraints imposed on the design, for example, the underground environment (dimensions, air temperature, humidity, etc.) or controls on the manner in which the design is implemented (e.g., the time available for construction).

The importance of design requirements in demonstrating compliance with the safety case is that requirements are translated into quality control checks that are made during the construction of repository facilities and installation of the EBS, and thereby act as a check that the as-built repository is consistent with safety case. A detailed example of such checking was provided by an evaluation of full-scale plug and seal experiments undertaken in the Demonstration of Plugs and Seals (DOPAS) Project (DOPAS, 2016). In this project, safety functions were linked to design specifications measured as the plugs and seals were installed. Examples of the parameters measured by quality control during installation of the DOPAS Project experiments were the curing temperature of concrete/shotcrete and the density of bentonite. Similar quality control checks, linked to design specifications will be made during the emplacement of waste packages and the EBS in a repository.

In addition to quality control, a wider science programme can be used to check compliance with limits, controls and conditions. This includes the application of laboratory experiments, upscaling of the results from these experiments to full-scale and to *in situ* conditions (e.g. using mock-ups or method tests), and the use of full-scale experiments in URLs and commissioning tests in repositories.

A good example is the compliance of concrete recipes with requirements. Concretes used in repositories are required to have several properties that are specified depending on the nature of their specific application. Properties include curing temperature, hydraulic conductivity, shrinkage characteristics, strength, water interaction (pH of pore water or leachate), durability, rheology/segregation characteristics and workability. Concrete recipes are first determined by laboratory tests supported by use of standards, including Eurocode standards, such as EN206, which is a European Standard that applies to concrete for structures cast *in situ*, precast structures, and structural precast products for buildings and civil engineering structures.

Standards provide ranges of constituents that can be used to develop concrete recipes that fulfil certain environmental exposure performance expectations, such as corrosion induced by chlorides from seawater, corrosion induced by carbonation and chemical attack from groundwater (chlorides and sulphates). Once the science programme has been used to develop and test a concrete recipe, the constituents of the recipe can be included in a design specification that can be tested during concrete mixing.

The principles of requirements management during emplacement of waste packages and the EBS in a repository have been considered in the IAEA International Intercomparison and Harmonisation Project on Demonstrating the Safety of Geological Disposal (the GEOSAF Project). In the GEOSAF Project, the principles have been expressed in terms of the relationship between a safety envelope, a design target and the as-built state (IAEA, 2016):

- Safety envelope: The safety envelope represents the boundaries within which, at the start of the post-closure phase, the state of the disposal system (i.e. the parameters expressing the safety functions important for post-closure safety) must fall in order to deliver the post-closure safety functions.
- Design target: The design target represents the boundaries within which, at the start of the post-closure phase, the state of the disposal system is designed to fall. The term design target is broadly synonymous with the term design requirement, although the use of "target" rather than "requirement" implies that the value specified does not necessarily have to be met, as long as it stays within the safety envelope.
- As-built state: The as-built state represents the real state of the disposal system at a given time (e.g., start of waste emplacement).

Preliminary conceptual thinking on the relationship between the safety envelope, the design target and the as-built state are illustrated for a single parameter in Figure 3.3 and for all parameters in Figure 3.4. Further development of these concepts would be required before they could be applied in specific waste management programmes.

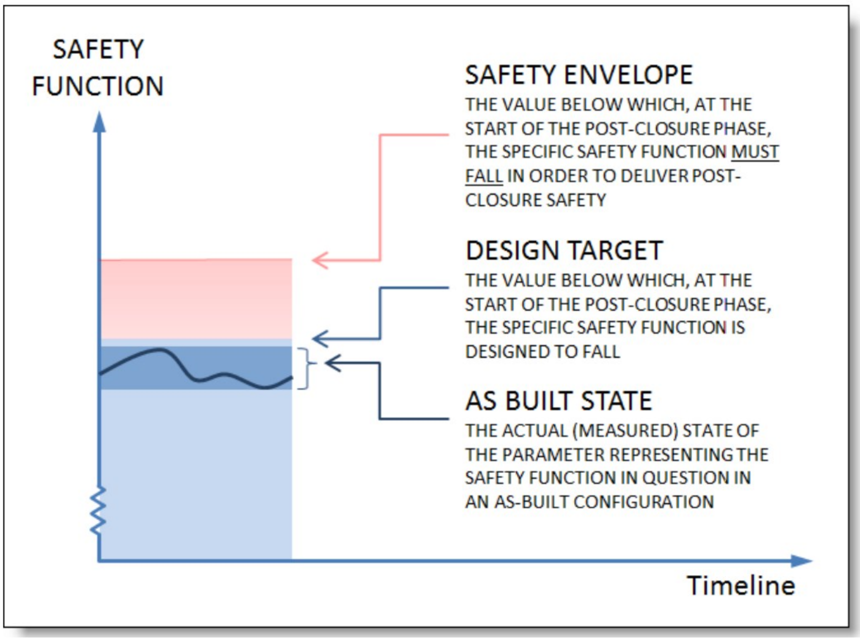

Figure 3.3: Visualisation of the general relationship between the safety envelope, the design target and the as-built state for one specific parameter. From IAEA (2016). References to values of safety functions in the figure, refer to values of a parameter representing a safety function.

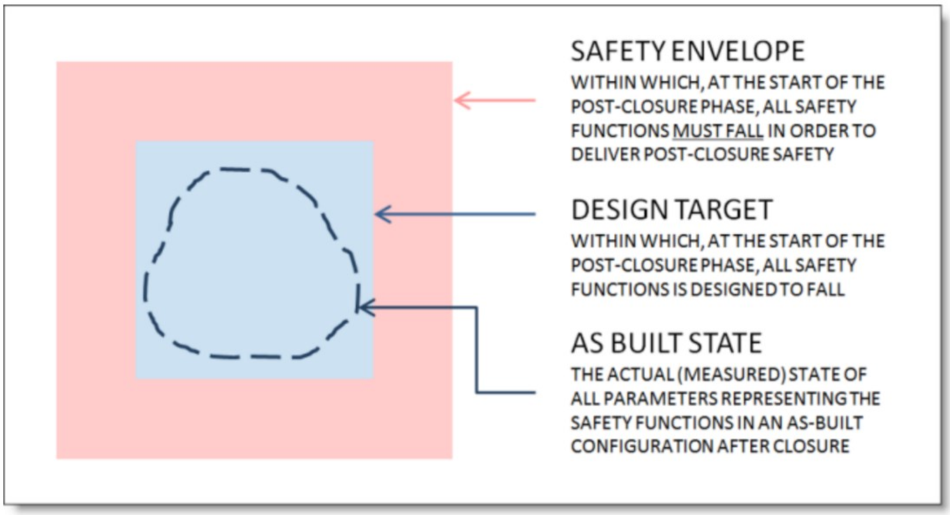

Figure 3.4: Visualisation of the general relationship between the safety envelope, the design target and the as-built state for all parameters. From IAEA (2016). References to values of safety functions in the figure, refer to values of a parameter representing a safety function.

3.3 Role of Repository Monitoring in a Safety Case

The discussion above has provided a high-level overview of the safety case and the use of the safety case to demonstrate safe performance of a repository for radioactive waste. This includes identification and treatment of uncertainty, and checking compliance of the as-built repository with requirements (design targets). None of the approaches outlined above rely on monitoring; demonstration of safety does not rely on monitoring.

However, the repository will be open and partially accessible for monitoring for several decades during the operational period and this provides an opportunity for gathering additional information on the performance of the disposal system following emplacement of the waste and the EBS. Such monitoring results can be compared with the arguments made in a safety case to check whether the repository system is evolving in a way that has already been demonstrated to be safe.

Indeed, this is consistent with IAEA Safety Guide SSG-14 (IAEA, 2011b; see Section 2.1.1), which makes clear that repository monitoring is an integral part of the safety case and the repository monitoring programme should be developed alongside development of the overall safety case, rather than being considered independently. In this respect, monitoring during the operation of the repository in support of building further confidence in the safety case should focus on providing information that can be used in periodic updates to the safety case. Indeed, such monitoring is likely to be a principal input to these periodic updates.

This monitoring can be described as monitoring to build further confidence in the safety case. To enter the operating phase, an operating licence must be awarded, and this entails regulatory scrutiny determining that any uncertainties remaining are not significant to safety. Therefore, for a repository to be licensed, sufficient confidence in safety must have been obtained.

Monitoring results must be used in the correct context. Safety assessment is founded on an understanding of the performance of the barriers with respect to the safety functions they are designed to meet, but does not predict the detailed evolution of the disposal system. In addition, safety assessment calculations are typically undertaken with conceptual and mathematical models that combine multiple processes, making pessimistic assumptions, which typically do not address all sub-system behaviour and hence are usually not good for comparing with monitoring results. Therefore, care is needed when comparing monitoring results with quantitative safety assessments. To demonstrate system understanding, and thereby to support further confidence building, a predictive model of the performance of the repository would be required. This predictive model must include parameters that are monitored during the operational period to ensure there is an expectation against which to compare the monitoring results.

Lessons can be drawn from the "history matching" approach adopted by oil and gas industry, in which models are developed that account for observed, measured data. Once they can reproduce historical data sufficiently accurately, these models can then be used for forecasting (see, for example, Gilman and Ozgen, 2013). History matching is a form of calibration, but its use over decades of production from oil and gas reservoirs, and requirement for analysis of large datasets, makes it analogous to the monitoring of the geological barrier during repository operation, which, for some disposal concepts, might be useful in building further confidence in the understanding of repository-derived impacts on the rock mass (e.g. recovery of groundwater pressures in response to backfilling). Although such monitoring might not impact on post-closure safety, it might provide an opportunity for a WMO to build further confidence in its capability to model phenomena over longer periods, and thereby also to demonstrate organisational competency.

Monitoring might also be undertaken as part of verifying compliance with design requirements, especially where the engineered barriers are accessible and there is an expectation that something might change over the monitoring period. Accessibility may be owing to the staged closure of repositories or the result of a specific strategy employed (e.g. monitoring in a pilot facility) – see Section 4 for a discussion of monitoring strategies. For example, the deposition tunnel plug in a KBS-3V has to confine the deposition tunnel backfill, and to do so must have a water flow across it (leakage rate) of less than 0.1 l/min. As the deposition tunnel plug is accessible for a period after its emplacement monitoring can be undertaken to demonstrate compliance with this requirement.

Therefore, monitoring can be used to check certain features of the repository evolution to provide additional confidence in performance. However, the IAEA principle that monitoring should not significantly affect system performance must always be considered when selecting monitoring parameters. Monitoring could affect the performance of the repository multi-barrier system. An outstanding issue is whether an argument can be made that it is better to know what is happening, and accept a decrease in the performance of the barrier, than to maintain fully intact barriers and not know what is happening. The extent to which monitoring affects performance is, in part, addressed by the high-level strategy that a WMO takes to monitoring. High-level strategies are discussed in Section 4.

In addition to monitoring to build further confidence in the post-closure safety case, repository monitoring may be required to address regulator and other stakeholder concerns. At this early stage in the development of repository monitoring programmes it is not possible to define these concerns, but potential examples can be identified. For example, treatment of uncertainty in the safety case may be difficult to communicate to some stakeholders, and there may be a concern that the safety case has missed a FEP (or made an error) that is significant to safety. There may be a concern that the disposal system is not implemented as assumed in the safety case, for example because quality control is not comprehensive enough to be sure that no elements are faulty and nothing unexpected has happened during implementation. For some disposal concepts, if these concerns arise, they will have to dealt with through other parts of the safety case as no amount of repository monitoring during the operational period would be able to demonstrate safety. This is the case where changes to barriers providing safety functions will only occur over much longer periods and/or relevant components will not be accessible without disturbing the EBS. However, it is possible that, for some elements of the disposal system, in some disposal concepts and some monitoring strategies (as discussed in Section 4) such concerns may be more readily resolved through monitoring than additional dialogue, explanation, calculation and/or RD&D (see for example, Table 5.1 in Section 5). However, such concerns need to be explicitly and specifically stated to allow an adequate response to be formulated.

Overall, deciding what to monitor is largely a process of expert judgement that will involve comparing and contrasting the benefits and disbenefits of any proposed monitoring activity, and considering the potential benefits to the safety case, especially the periodic update of the safety case during the operational period and in support of closure. Monitoring can be undertaken to increase confidence in the safety case further and to check concerns of third parties (award of an operational licence requires confidence in repository safety on behalf of both the implementer and the regulator). The expert judgement involved in deciding on monitoring parameters is a central theme of the Modern2020 Screening Methodology that is presented later in the report (Section 6).

4 High-level Monitoring Strategies

In this section, high-level strategic approaches to monitoring during the operational period in support of decision making and building further confidence in the post-closure safety case are reviewed. The information is based on the responses provide by WMOs to the Task 2.1 questionnaire (Appendix A), and discussion at the Task 2.1 workshops (Smith and White, 2016a and 2016b). Two aspects are discussed:

- The different elements of a "high-level" monitoring strategy, and the relative strengths and weaknesses of the different elements (Section 4.1).
- Examples of how these elements can be combined into programme-specific high-level monitoring strategies (Section 0).

4.1 Strategy Elements

A strategy is a method or plan for successfully achieving a specified objective. In the context of repository monitoring, there is a continuum between high-level strategy and detailed design. At each point on the continuum, consideration can be made of *what* will be monitored, and *where*, *when* and *how* monitoring will take place, at increasing levels of detail. A high-level strategy describes the overall manner in which these elements are combined in order to describe the main aspects of any specific monitoring programme.

For each of these aspects, a number of generic high-level strategy elements have been identified through review and analysis of the Task 2.1 questionnaire responses related to the strategies currently being considered by WMOs participating in WP2. These are set out in Table 4.1.

Table 4.1: High-level strategy elements.

Aspect	High-level strategy elements
Where	• Monitoring *in situ* in the main repository, without retrieval of monitored components at the end of the monitoring period • Monitoring *in situ,* with monitored components retrieved or decommissioned at the end of the monitoring period (and, if waste, re-disposed) • Monitoring in a pilot facility • Monitoring in an on-site URCF
What	• Waste packages (and surrounding EBS and near-field rock) • Dummy packages (and surrounding EBS and near-field rock) • Specific elements of the EBS (e.g. small-scale batch tests) • Geological barrier (near-field rock and far-field rock) • Biosphere
When	• Before repository operation or during commissioning • During the period of waste emplacement • After closure of the repository
How	*Not considered in detail in WP2*

Each of these strategy elements has inherent strengths and weaknesses, although it would be possible to combine them in ways that minimise or eliminate many of their weaknesses. These potential strengths and weaknesses are summarised in Table 4.2 (*where* elements), Table 4.3 (*what* elements) and Table 4.4 (*when* elements).

Table 4.2: Potential strengths and weaknesses of high-level strategy elements relating to where monitoring would take place.

Strategy element	Potential strengths	Potential weaknesses
In situ without retrieval	• Reflects real repository conditions • Avoids safety risk involved in package retrieval • Duration of monitoring only limited by lifetime of monitoring equipment	• Potential detrimental effect on EBS (although the impact on safety case would have to be insignificant) • Limited parameters can be monitored • Reliability of monitoring results could be questioned • Developing suitable equipment may be time-consuming and expensive
In situ with retrieval	• Reflects real repository conditions • No detrimental effect on final EBS • Can use wired systems and monitor more parameters	• Safety risk involved in retrieval of packages • Wired systems (if used) may affect processes being monitored • Duration of monitoring limited by need to retrieve before repository closure
Pilot facility	• Option for waste to be retrieved and redisposed (no detrimental effect on EBS; can use wired systems and monitor more parameters) • Potentially easier access for maintenance / investigation	• Rock must be homogeneous or may not reflect repository conditions • Safety risk if packages retrieved • Wired systems (if used) may affect processes being monitored
On-site URCF	• Can be operated for a period corresponding to repository operation • Relatively easy access	• Rock must be homogeneous or may not reflect repository conditions • Emplaced waste (and surrounding EBS) cannot be monitored in a URCF

Table 4.3: Potential strengths and weaknesses of high-level strategy elements relating to what would be monitored.

Strategy element	Potential strengths	Potential weaknesses
Waste ± EBS	• Reflects real waste and enables monitoring of whole system including radiological effects	• Potential radiological safety risk involved in maintaining equipment / investigating unexpected results

Strategy element	Potential strengths	Potential weaknesses
Dummy packages ± EBS	• Monitoring sensors can be placed inside packages • No radiological risk in the event of EBS failure • No radiological risk involved in maintenance / investigation	• May not reflect all important characteristics of waste (most thermal-hydro-mechanical-chemical (THMC) and biological characteristics can be reflected, but not radiological) • Creates additional (non-radioactive) waste and uses additional underground space
Specific EBS elements	• Flexible – can be tailored to suit needs and does not require extensive planning • No radiological risks involved • Easily accessible for maintenance and investigation	• Does not test whole system, e.g. radiological effects and coupled interactions may be missed • Need to demonstrate representativeness
Geological barrier	• Can potentially be monitored remotely (not from within repository) and could therefore be monitored after repository closure	• Does not test whole system • First signs of unexpected behaviour unlikely to occur in geological barrier

Table 4.4: Potential strengths and weaknesses of high-level strategy elements relating to when monitoring would take place.

Strategy element	Potential strengths	Potential weaknesses
Before operation / during commissioning	• Allows learning to feed into design / emplacement activities • Greatest flexibility and accessibility	• May not accurately reflect evolving conditions throughout operations • Short timeframe for monitoring processes
During waste emplacement	• Provides longest duration for monitoring processes, and potential for monitoring widest range of parameters	• Difficult to feed learning back to design
After closure	• Provides continuing confidence in expected performance once emplaced wastes and near-field are no longer accessible	• Technical feasibility for some parameters uncertain • Responding to results challenging (equipment not accessible) • Limited timeframe possible compared with whole post-closure period

4.2 End Member Strategies

The strategy elements identified and discussed in Section 4.1 can be combined in different ways to form bespoke high-level monitoring strategies that respond to specific national programme drivers (e.g. deriving from geology, concept, or legislation). Strategies that have been considered in WMO programmes include:

- Monitoring of emplaced waste packages/EBS *in situ* in the main repository, with no intention to retrieve.
- Monitoring of waste packages/EBS *in situ* in the main repository, with the intention to retrieve and redispose them after the monitoring period.
- Monitoring of waste packages/EBS in a pilot facility.
- Monitoring of dummy packages/EBS in specified parts of the main repository.
- Monitoring of various elements during repository commissioning tests (both active and non-active).
- Long term *in situ* monitoring of specific EBS elements and volumes at various locations within the repository.

Note that these strategies do not have to be employed in isolation; several of them can be used in a single monitoring programme.

A number of comprehensive high-level monitoring strategies envisaged by WP2 partner WMOs are presented and discussed in the sub-sections below. These are considered to represent "end members" of the strategies likely to be employed in monitoring geological repositories for radioactive waste. All of these specific strategies have the following common features:

- Regardless of the location of monitoring and nature of the target (real / dummy), all the high-level strategies described allow monitoring of both EBS elements (including wasteform / container) and surrounding rock. Which specific elements will be monitored in any particular location will be considered within Task 2.2 of the Modern2020 Project.
- All examples described focus on monitoring during (or before) the early stages of repository operation, allowing information to be gathered and used for optimisation and decision making during subsequent stages of operation.
- All examples described propose some form of selective monitoring; that is, not every waste package / disposal cell in a repository is planned to be monitored for all parameters for a prolonged duration. This is widely accepted to be a necessity for practical reasons and to ensure that monitoring does not adversely affect the long-term safety of the repository.

4.2.1 *In situ* monitoring of relatively broad scope: Andra

Andra is currently planning a monitoring programme of relatively broad scope, including monitoring of some emplaced waste cells and EBS elements. This is driven by the need to verify regulatory compliance (including conditions of retrievability during the operating period, i.e. for a maximum period of approximately 100 years), and to increase confidence in the understanding of repository evolution through observation of the disposal process.

Andra plans to make use of an industrial pilot phase at the beginning of repository operation. This is a preliminary phase of repository operation, lasting approximately ten years, in particular to test the operating processes and to verify that the parameters of the repository system are evolving within the domain applied in the safety case.

During the main phase of repository operation (waste emplacement), Andra intends to use a system of different levels of monitored cells within the repository, including:

- *Surveillance structures*. These heavily instrumented cells will be monitored for a wide range of parameters, acting as "witness structures" for less instrumented cells. Waste will not be routinely retrieved from such structures, so any monitoring equipment must not adversely affect the EBS.
- *Current structures*. These disposal cells will have minimal instrumentation; their performance will be calibrated against results from surveillance structures using key parameters.
- *Standard disposal cells* will generally not be instrumented. They will contain only essential equipment for operational safety and will be subject to occasional visual inspection.

This system is designed to balance the need for monitoring with the constraints of implementation, and the associated costs of monitoring equipment. As the number of embedded sensors decreases in the different types of structure, more emphasis would be placed on visual inspections and non-destructive tests. The similarity between the structures would allow the evolution of less instrumented current structures to be inferred from "witness" surveillance structures.

The number and location of surveillance and current structures would be determined by the expected heterogeneity of the processes being monitored, and could be amended over time as the monitoring programme evolves. They would be distributed throughout the repository and would be among the first cells to be filled, maximising the period available for the collection of monitoring data. The design and placement of the hierarchy of monitored cells would be finalised during the industrial pilot phase.

4.2.2 Limited monitoring focused on EBS elements / dummy packages: KBS-3V

Preservation of the bentonite barrier is key to the KBS-3V concept, and there is therefore a strong driver for monitoring activities not to disrupt this barrier. As a result, neither Posiva nor SKB plans to monitor emplaced waste directly, and the overall extent of planned monitoring is significantly more limited than in Andra's programme. Both Posiva and SKB consider quality control (rather than monitoring) to be the primary means of ensuring that the design has been implemented as planned (i.e. technical design requirements have been met), and thus building confidence in the post-closure safety case.

Posiva and SKB intend to monitor some EBS elements throughout the repository; for example, installed disposal tunnel plugs will be monitored from the central access tunnels while they are still accessible during the operational phase. In addition, host rock monitoring, which also constitutes indirect monitoring of the EBS will be undertaken in open disposal areas. Such monitoring may continue to some extent after closure.

A full-scale *in situ* test, using heated dummy canisters and the same buffer and backfill arrangements as for waste canisters, will be monitored during the operational phase of the repository. The test will be located in the ONKALO URCF (which will form part of the repository construction, such that the distance from the full-scale test to the nearest deposition tunnel will be ~30 m), to ensure accessibility throughout the operational period. The dummy canisters will be recovered to collect additional data (e.g. on corrosion) at the end of the test. Process-specific *in situ* tests may also be undertaken, possibly at smaller scale if this can be shown to be representative. Samples taken after the dismantling of such tests would provide information on the evolution of relevant processes without endangering safety.

Long-term, full-scale *in situ* tests are also likely to form part of SKB's monitoring strategy. Although the details of any such tests are not yet decided, they would likely be located in a drift in the same part of the host rock as the active deposition tunnels, and could include monitoring of materials relevant to canister evolution (e.g. copper).

SKB also plans to make use of non-active "batch tests". These small-volume process- or element-specific *in situ* experiments would be located in the repository but away from emplaced waste (e.g. between two deposition holes) and could be monitored to provide information on some aspects of the evolution of the EBS.

Monitoring of the full EBS, i.e. canister, buffer and backfill, is not envisaged for finally disposed waste in SKB's programme, as emplacement of instrumentation and the necessary cable leads to sensors is considered likely to impair the safety functions of the engineered barriers. However, the reviewers of SKB's licence application have questioned the position that there should be no monitoring of the EBS (SKB, 2015).

This statement recognises that knowledge of the repository site, as well as quality management and control of the production of repository engineered barriers, is central to assessing post-closure safety of the repository, and that monitoring the development of the repository barriers after waste emplacement and repository closure can further enhance this knowledge. However, appropriate methodologies and technologies would need to be developed, and limitations on what can be achieved and the potential consequences of erroneous signals would need to be considered, before such monitoring could take place.

4.2.3 Monitoring in a pilot facility: Nagra

Nagra has based its monitoring strategy on the use of a pilot facility. A pilot facility is a representative region of a repository, separate from the main emplacement area, in which a small but representative fraction of waste can be emplaced and monitored to provide information on the behaviour of the barrier system and check predictive models.

In Switzerland, a pilot facility is required by the Swiss safety authority (ENSI, 2009), following the finding of a group of experts (EKRA, 2000). The pilot facility is considered to be a direct analogue of the main repository, although there must be no THMC interaction between them. Monitoring to provide information on the behaviour of the waste, backfill and host rock will take place in the pilot facility in parallel with repository operations. Waste is not expected to be retrieved from the pilot facility (although it could be) and so it must fulfil the same safety requirements as the repository. Hence, it is not expected to be heavily wired or otherwise instrumented, although some specific parameters may be monitored using wired sensors if the effect on the EBS can be shown to be negligible. All monitoring activities would end with the closure of the access tunnel and shaft.

Nagra also plans to construct a URCF at the site of the repository, which would not deal with active waste but provide a location where monitoring of some other elements could be undertaken. For example, monitoring of geological and hydrological processes could provide information about likely conditions within the repository.

4.3 Summary

This section has highlighted the many varied ways in which repository monitoring may be undertaken during the operational period in support of decision making and developing further confidence in the post-closure safety case. Repository monitoring is not implemented by monitoring of emplaced waste, engineered barriers and the host rock only, but can be undertaken through a range of complementary approaches. Each of these approaches has different strengths and weaknesses, which must be considered when combining the different elements of where monitoring will be undertaken, what will be monitored and when monitoring will be undertaken. WMOs have already established various high-level strategies through which monitoring will be undertaken, and these strategies provide the context for considering the selection of monitoring parameters to undertake monitoring to feed into programme-specific needs driven work.

5 Decision-making Requirements on Monitoring

This section focuses on the requirements on monitoring to support decision making and the stepwise management of the disposal process. A key factor in such decision making is utilisation of monitoring information as part of periodic updates to the safety case, but decision making is likely to bring in much wider considerations. The discussion of decision making in Task 2.1 is preliminary and focuses on identification of the main aspects of decision making; a greater and more thorough examination of decision making will be undertaken within Task 2.3. The purpose of this preliminary analysis in Task 2.1 (and this report) is to:

- Introduce a broad understanding of the types of decisions that may be supported by analysis of monitoring information.
- Consider what programme decisions may be supported by analysis of monitoring information.
- Consider what other types of decisions might be supported by analysis of monitoring information.

This consideration provides basic supporting context for the development of the Modern2020 Screening Methodology in Section 6, and also the basic information on which work in Task 2.3 will be undertaken.

5.1 Monitoring in Support of Management Decisions

The IAEA TECDOC (IAEA, 2001) discusses monitoring in the context of supporting management decisions in a staged programme of repository development. The main principle of the approach advocated is the accumulation of information to allow the design to be checked, refined and, where necessary, modified. This accumulation of information progressively enhances confidence in the design concept, which allows both programme and engineering decisions to be made, and thus allows subsequent steps to take place. The TECDOC states:

> *"During the potentially long period prior to repository closure, both future operators and other sectors of future society will need to make critical decisions about how, when and if to implement various steps in the management of the repository system. The primary objective of monitoring is to provide information to assist in making those decisions."*

As reported in the sections below, Task 2.1 focuses on identifying the generic programme decisions and types of engineering decision that would be underpinned by monitoring data and therefore what requirements this might place on a monitoring programme. In contrast, Task 2.3 (Decision making, performance measures and response planning) addresses *how* monitoring data are used in making such decisions.

5.2 Programme Decisions

The main stages in the lifecycle of a repository, and therefore the programme decisions needed to move between phases, are similar for all programmes. These stages have been identified and defined in the NEA Reversibility and Retrievability Project (NEA, 2011) (Figure 5.1). It is noted that there may be differences in the major stages between programmes; for example, there is not always an observation phase between waste emplacement and repository closure (or the observation phase may run in parallel with waste emplacement rather than sequentially as shown in Figure 5.1). Licensing approaches also differ between programmes, and differences in the permits required prior to waste emplacement can have a significant effect on information requirements during the early stages of disposal implementation. Detailed aspects of the phases (for example, the nature and duration of commissioning or pilot phases within the pre-operational phase) do differ between programmes, and the objectives of such subphases may have implications for the requirements on monitoring to provide a support to decision making.

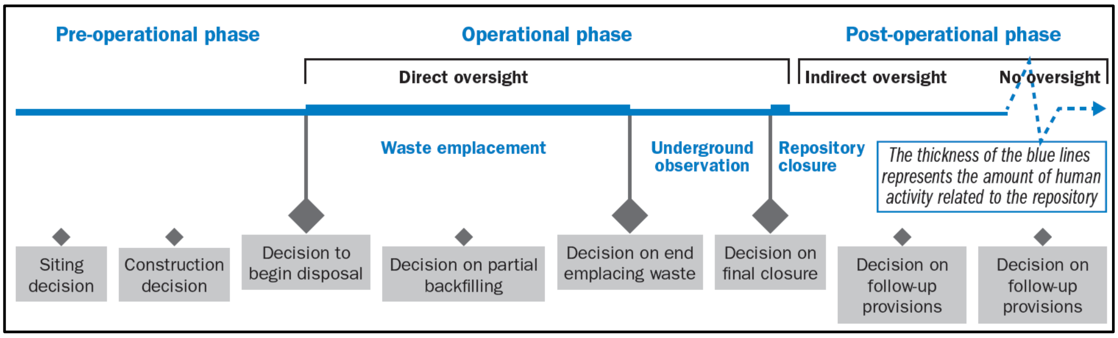

Figure 5.1: Generic Repository lifecycle phases and major decision points (NEA, 2012).

In addition, for programmes that include a requirement for reversibility or retrievability, any decision to reverse the disposal process for any reason would need to be underpinned by monitoring data (e.g. provision of information on the condition of the waste package in support of developing a safety case for the reversal operations). This could include information about the condition of emplaced waste packages, repository structures such as excavations and underground openings, and backfills and seals, which would be required to help prepare for retrieval operations. Some WMOs, such as Andra, may be required to commit to retrieving a number of packages to demonstrate that such retrieval is feasible, and this would be reflected in the setting of monitoring objectives and subsequent identification of processes and parameters to monitor.

Any programme decision would not be made solely on the basis of monitoring data, and no single parameter or monitoring result would form the technical input to such a decision. Rather, such decisions are likely to take account of a holistic review of all monitoring data collected as part of the repository monitoring programme and this aspect of monitoring is considered in Task 2.3 of the Modern Project. Therefore, specific parameters to support programme decisions are not considered in this report.

5.3 Engineering Decisions

5.3.1 General Discussion of use of Monitoring Information in Engineering Decision Making

The IAEA TECDOC (IAEA, 2001) includes a range of examples of engineering decisions in which monitoring data is likely to play a key role:

> *"The operators of a repository must make numerous decisions during its construction and operational life. Some of these will be made early, in response to site characterisation information, others will be made much later, after all construction has ceased and the repository has been operational for decades. Monitoring information is likely to play a key role in the latter. Setting aside the major 'political' decisions associated with repository closure, the operators may typically need to consider matters such as:*
>
> - *Adjusting the later stages of repository layout or design in response to long term monitoring of rock stresses and groundwater flow.*
> - *Modifying waste handling and emplacement procedures, EBS design or material properties in response to monitoring of the behaviour of waste emplacements.*

- *Postponing the final design of seals and selection of backfill materials for the various stages of repository closure, basing them on observation of rock stress response, the movement and chemistry of water in the EDZ or the creep behaviour of plastic formations.*
- *Deciding when to emplace certain types of buffer material based on monitoring package degradation behaviour, gas production and variations of surface physical and chemical properties of tunnel and vault walls, such as the growth of new mineral phases or biofilms, or oxidation or spalling of the rock which may affect seal bonding.*
- *The optimum time to backfill and seal disposal regions, in the context of long-term stability of openings.*
- *Whether to carry out repairs or remedial engineering work to excavation support systems, based on monitoring of rock movements, rock stresses and the degradation of rock bolts and other support materials.*
- *Adjustments to the repository de-watering scheme to account for variable resaturation of different completed regions and consequent long term changes in the groundwater flow pattern or in groundwater chemistry."*

Some WMOs have identified specific engineering decisions for which specific monitoring data would be useful. If this is done, relevant processes and parameters, linked to the objective of supporting a specific decision, can then be incorporated into a justified monitoring programme. For example, Posiva anticipates that continuous monitoring of the host rock might influence the precise location of deposition holes, and Andra has identified the following potential future design enhancements:

- The diameter of ILW disposal cell tunnels could be enlarged from 8 to 10 metres, according to changes in requirements on stability after construction and operation of the first disposal cells.
- The distance between adjacent HLW cells would be reduced if it can be shown that the uncertainty margins on thermal and thermo-hydraulic parameters, such as clay mechanical failure under thermal loading, may be reduced.

In addition, the results of monitoring during Andra's industrial pilot phase will contribute to optimisation of the design of the repository that will be implemented during the main phase of repository operation.

For some WMOs, providing information to input to engineering decision making is not a major stated objective of monitoring. For SKB, much of the expected engineering decision making will be underpinned by information obtained through the quality control programme, and monitoring is expected to have minimal impact on such decisions. However, SKB's quality control programme includes measurements of outflow at deposition tunnel plugs over a timeframe longer than a few days, which could be considered as monitoring. Findings from monitoring not directly related to the quality control programme (such as monitoring of hydrogeology and geochemistry) will be used periodically as input to revised safety assessments.

5.3.2 Example of the Role of Monitoring in Engineering Decision Making: German Clay Concept

The German repository concept for disposal of spent fuel, HLW and ILW in a clay host rock consists of a series of sequentially-filled emplacement fields, each consisting of a number of emplacement drifts and access drifts (Figure 5.2). Emplacement drifts will be continuously backfilled; that is, the overlying portion of the tunnel will be backfilled immediately after the filling of each deposition hole. This concept requires continuous decision making as to whether it is appropriate to move onto the next borehole, drift or emplacement field, since early-filled parts of the repository cannot be easily accessed subsequently.

It is expected that monitoring and quality control will both provide important information inputs to these decisions: quality control directly after emplacement (over a period of a few days) to determine if emplacement has been implemented as planned, and monitoring for a longer period after emplacement to check that elements are performing as intended.

Table 5.1 lists specific examples of such decisions and summarises the anticipated role of monitoring in providing information to feed into them.

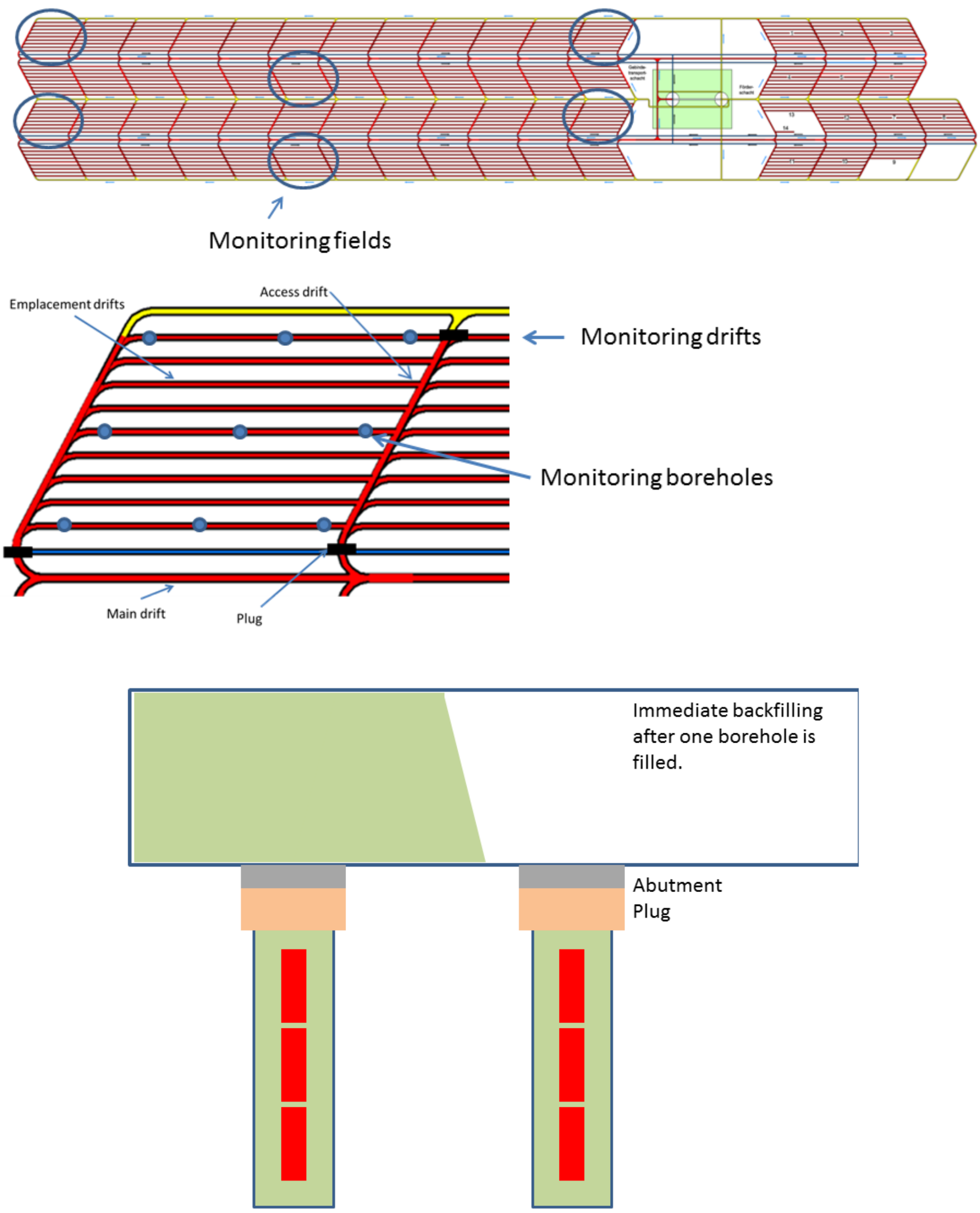

Figure 5.2: German clay concept, showing general layout and features, locations where monitoring is expected to take place, and illustration of continuous backfilling. Monitoring drifts are emplacement drifts in which monitoring boreholes (indicated by blue circles) are located.

Table 5.1: Decisions associated with the implementation of the German clay concept and the role of monitoring in supporting them.

Decision	Role of monitoring
Accept borehole for waste emplacement	None – information on borehole suitability obtained from quality control programme.
Backfill and seal borehole	Short-term feedback on quality of borehole backfill and seal emplacement largely obtained from quality control programme, but monitoring sensors will be placed in selected boreholes to provide time-series measurements beyond those collected through quality control.
Move to next emplacement drift	In order to move to the next emplacement drift, information is needed on whether the performance of borehole seals, thermal and mechanical performance of the host rock, and THMC evolution in the current drift are as expected. This information will be obtained through monitoring of temperature and pressure using wireless systems.
Backfill and seal access drift	Short-term feedback on quality of drift backfill and seal emplacement largely obtained from quality control programme, but monitoring sensors will be placed in selected drifts to provide time-series measurements beyond those collected through quality control.
Accept seal and move to next emplacement field	In order to move to the next emplacement field, information is needed on whether the performance of drift seals, thermal and mechanical performance of the host rock, and THMC evolution in the current field are as expected. This information will be obtained through monitoring of temperature and pressure using wireless systems.
Check seal: regular decision milestones	Performance of seals to closed parts of the repository will continue to be periodically checked throughout the operational phase. THMC evolution will continue to be monitored to provide input to these checks and associated decisions.
Backfill and seal main drifts from the underground services area to the disposal tunnels	Prior to filling the underground services area with high porous gravel all eight accesses from that area to the emplacement areas will be sealed by large drift seals. Short-term feedback is needed on quality of seal emplacement largely obtained from the quality control programme, but monitoring sensors will be placed in the seals to provide time-series measurements beyond those collected through quality control.
Backfill the underground services area and start building the shaft seals	Short-term feedback is needed on quality of seal emplacement largely obtained from the quality control programme, but monitoring sensors will be placed in the seals to provide time-series measurements beyond those collected through quality control.

5.4 Summary

Information from monitoring activities will feed into a wide range of decisions taken during the stepwise implementation of geological disposal of radioactive waste in repositories. This includes both major programme decisions, which will need to respond to integrated analyses of significant volumes of monitoring information, and engineering decisions and on-going optimisation of the repository, which may be undertaken on a more continual basis as disposal operations progress. Both types of decisions will need to be considered during Task 2.3 work within the Modern2020 Project. The information needs for some decisions can be identified in advance of the monitoring programme commencing, and will feed into the early part of the MoDeRn Monitoring Workflow, for example, the box labelled "Identify Sub-objectives and their Information Requirements" (see Figure 2.3).

6 The Modern2020 Screening Methodology

This section sets out a generic methodology, the Modern2020 Screening Methodology, for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. The Methodology is presented in two parts:

- Section 6.1 presents the approach to, and context for, the Methodology.
- Section 6.2 presents the Methodology, describes each step in it, and provides supplementary guidance on specific steps.

6.1 Approach to, and Context for the Modern2020 Screening Methodology

The Modern2020 Screening Methodology is based on the principles and context provided by the wider discussion of monitoring during the operational period in support of decision making and to provide further confidence in the post-closure safety case.

The Methodology was developed in collaboration with WP2 partners. As discussed in Section 1.4, initial development of the Methodology was based on the discussions at a workshop in December 2015, including review of the questionnaire responses provided by WMOs (Appendix A). The first draft of the Methodology was then tested through application using existing lists of parameters related to KBS-3V, Andra's HLW disposal cell design and a list of potential parameters for monitoring of a shaft in salt host rocks developed in the MoDeRn Project (MoDeRn, 2013a). The test cases were discussed at meetings with DBE TEC, Posiva and SKB, and used to provide some revisions to the Methodology ahead of the final Task 2.1 workshop, where further changes were identified. The Methodology presented in this report is the version that resulted from the discussions at that workshop. It might be further updated following testing in Task 2.2 of the Modern2020 Project.

The development of the Modern2020 Screening Methodology is motivated by a desire to develop a justified and needs-driven monitoring programme. As noted in the previous international collaborations on repository monitoring discussed in Section 2, in particular the NEA guidance related to the need to "optimise" the selection of parameters to be monitored (NEA, 2014a, see Section 2.1.3), repository monitoring has the potential to affect passive safety and will impact repository operations, and it is therefore important that all monitoring activities are carefully considered and their need justified.

The Modern2020 Screening Methodology builds on previous work represented by the middle part of the MoDeRn Monitoring Workflow (Figure 2.3). At a high level, the identification of parameters to monitor could be visualised as three steps (Figure 6.1). However, parameters must be considered in the context of both the process(es) they provide information about and other parameters proposed to be monitored. Therefore, a single iterative "Screening Methodology" is presented that guides users through all of these steps, from identifying processes that could be monitored to a list of parameters to be taken forward to the monitoring programme design stage.

6.2 The Modern2020 Screening Methodology

6.2.1 Methodology Summary and Supporting Diagrams

The Modern2020 Screening Methodology (Figure 6.2) provides an overview of the steps that a WMO may take in identifying and managing a list of parameters, linked to processes, and repository monitoring strategies and technologies. The list of parameters will form a basis for repository monitoring system design at each stage of an iterative repository monitoring programme that evolves through the implementation of geological disposal. The Methodology is supported by a diagram showing its iterative implementation (Figure 6.3) and a revised version of the MoDeRn Monitoring Workflow (Figure 6.4), which illustrates how the

Methodology relates to the Workflow. Additional guidance is also provided on the issues that a WMO may consider at specific steps in the process (6.2.3).

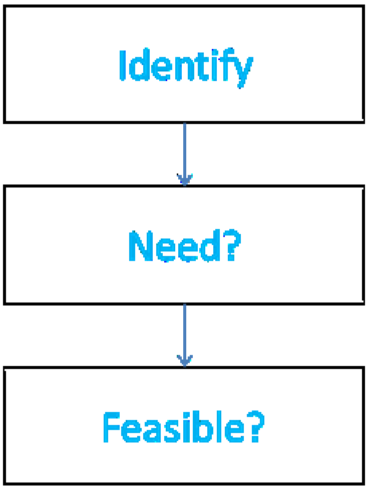

Figure 6.1: The three basic steps in developing a parameter list.

The Modern2020 Screening Methodology is organised into three columns that take into account the interplay between processes, parameters, and technologies (monitoring programme strategies are considered in parallel). These elements are fundamentally linked and are considered together for the purposes of screening. The description below provides an explanation of each step in the Methodology, with each step designated as follows:

- "PRO" designates steps that apply to each process under consideration.
- "PAR" designates steps that apply to each parameter under consideration.
- "TEC" designates steps that apply to each technology under consideration.

Interactions with regulators and other stakeholders are envisaged to take place in a manner consistent with the regulatory process and with the WMO stakeholder engagement plan, and this will be for each WMO programme to decide. In principle, dialogue can be undertaken at each step in the Methodology, or at key decision points. However, in the Modern2020 Project, it is envisaged that dialogue will be undertaken following application of the Methodology by a WMO so that there is a starting point to focus the dialogue.

One illustration of how interaction with stakeholders and regulators may proceed is shown in Figure 6.3. Figure 6.3 shows that the parameter screening methodology is intended to be iterated multiple times; the parameter list after one iteration as shown in Flowchart 1 is not final and can be revised (through a subsequent iteration of the methodology following engagement with stakeholders) periodically or at any time there is a trigger, such as a periodic update or change to the post-closure safety case or significant developments in technology.

The relationship of the Modern2020 Screening Methodology to the MoDeRn Monitoring Workflow is illustrated in Figure 6.4. In this figure, the MoDeRn Monitoring Workflow has been slightly updated to reflect the terminology used in the Modern2020 Screening Methodology and to account for the process of evaluating the implications of monitoring data on the monitoring programme itself, but is fundamentally unchanged from the version published in the MoDeRn Synthesis Report and reproduced in Figure 2.3 of this report.

This Modern2020 Screening Methodology is intended to be indicative and flexible rather than prescriptive, and can be regarded as a template that can be adapted by individual WMOs to suit particular needs. Each step in the Methodology is described in Section 6.2.2.

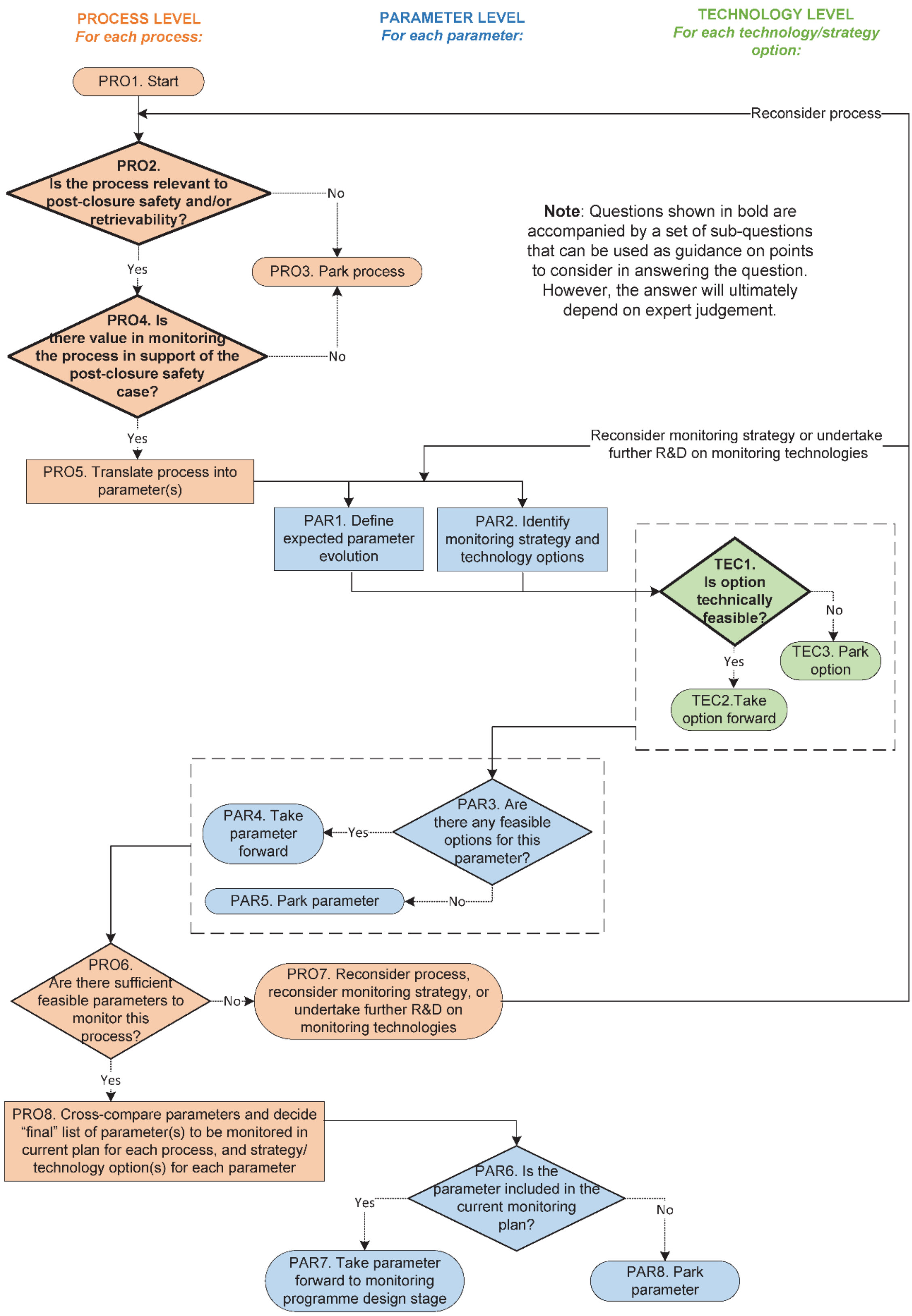

Figure 6.2: The Modern2020 Screening Methodology.

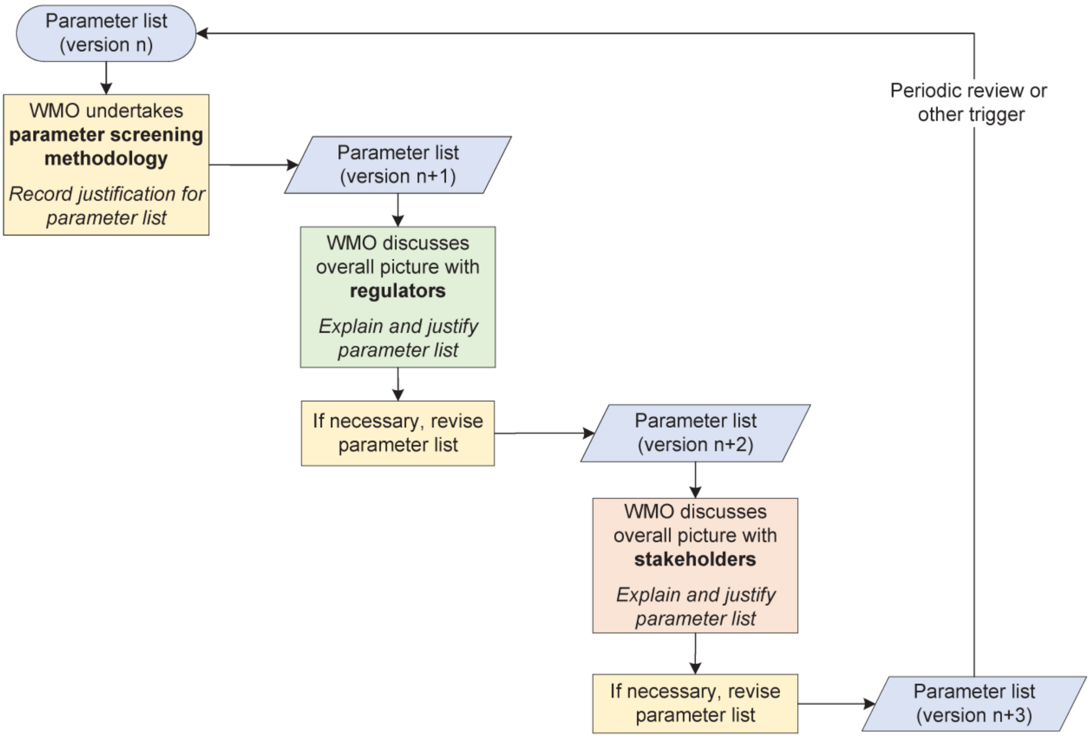

Figure 6.3: Illustration of a possible iterative implementation of the Modern2020 Screening Methodology, showing the situation in which a WMO engages with regulators following the first iteration and public stakeholders following the second iteration. There are multiple ways in which such iteration and dialogue could be undertaken: the order in which dialogue could be undertaken with public stakeholders and regulators is subject to the particular national strategies for dialogue and could also occur in parallel.

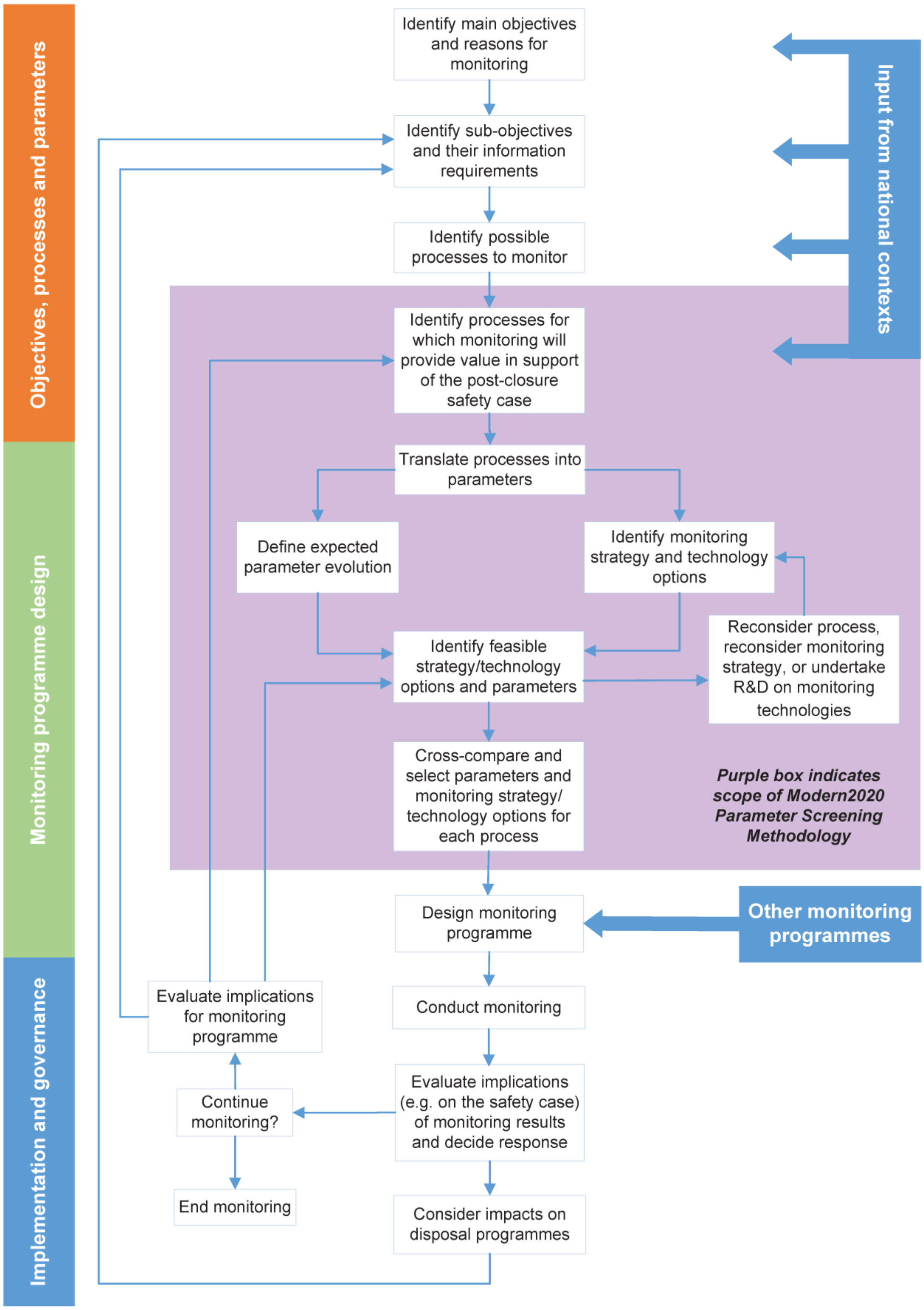

Figure 6.4: Revised MoDeRn Monitoring Workflow, illustrating the relationship of the Workflow to the Modern2020 Screening Methodology. In addition to an elaboration of the middle part of the Workflow, changes from the published version include an amendment of the box originally reading "Identify processes to monitor" to read "Identify possible processes to monitor", the addition of a feedback loop to evaluate the implications of monitoring data on the monitoring programme itself, and the addition of a question mark to the box "Continue monitoring" to clarify that this is a question rather than a statement.

6.2.2 Explanation of Steps

Each step in the Modern2020 Screening Methodology is explained in the order that it would be reached working through a single iteration of the flowchart. Titles of the steps are colour-coded (as per Figure 6.2) according to whether they relate to processes, parameters or technologies, for easy reference.

PRO1. Start

The Modern2020 Screening Methodology fits into the MoDeRn Monitoring Workflow between the steps "Identify Possible Processes to Monitor" and "Design Monitoring Programme". The starting point is therefore a process that a WMO is considering monitoring. In most cases, WMOs will have an existing list of processes that they are considering addressing in the repository monitoring programme, based on an analysis of the post-closure safety case. A process may also come into consideration by other means, for example through discussion with regulators or public stakeholders.

An alternative starting point could be a proposal for monitoring of a parameter (for example, by engineers designing a specific repository component, or by regulators). In this case, before it can be decided whether the parameter should be monitored, the parameter must first be related to a process or processes that it provides information about. The methodology is then followed in the same way.

PRO2. Is the process relevant to post-closure safety and/or retrievability? (SEE SUPPLEMENTARY GUIDANCE QUESTIONS in Section 6.2.3)

The recent NEA guidance states that it is important to select a limited number of parameters (and hence processes to be monitored) through identification of those which would sufficiently demonstrate the attainment or approach to the passive safety status of the disposal system. In line with this guidance, this question ensures that there is a justified reason (within the scope of the Modern2020 Project) to monitor the process under consideration, by assessing its relevance to post-closure safety and/or retrievability.

A set of supplementary guidance questions has been developed for this step, which can be considered as a list of points for consideration in determining an overall answer to PRO2. Recording detailed responses to these sub-questions can also form (part of) the justification for monitoring a parameter to provide information on a process and the parameters that represent it.

PRO3. Park process

If it is determined (through consideration of the list of PRO2 sub-questions or otherwise) that the process under consideration is not relevant to post-closure safety or retrievability, then it should be "parked". This means that it should not be included in a list of processes to be monitored in the current monitoring plan for the purpose of building confidence in the post-closure safety case. It may of course be included in monitoring plans for other purposes, but that is outside the scope of Modern2020.

It is important to note that this is not a final decision and can be reviewed at any time, but rather ensures that the remainder of the Screening Methodology is only undertaken for relevant processes that are currently planned to be monitored. The parked processes remain within the system, with a record of the justification for their status to provide transparency and allow future review.

PRO4. Is there value in monitoring the process in support of the post-closure safety case? (SEE SUPPLEMENTARY GUIDANCE QUESTIONS in Section 6.2.3)

This question addresses the extent of the value to be gained by monitoring a safety-relevant process. It is needed because there may be processes that are relevant to safety but for which monitoring would not provide valuable information/understanding additional to the information/understanding that is available through other elements of the post-closure safety case. Some WMOs may consider that the benefit of monitoring such processes is limited, and use this as a justification for not including the process in current monitoring plans. Conversely, some WMOs may feel that there is value in monitoring such processes in any case, for example because it would provide additional confidence.

Deciding if there is value in monitoring a process will depend on expert judgement and the national context. As with PRO2, a set of supplementary guidance questions has been developed to help WMOs answer this question, and to provide a framework for recording a justification.

PRO5. Translate process into parameter(s)

Each process will have one or more associated parameters that can be monitored to provide information about it. These can be identified through expert knowledge (e.g. from an understanding of the operation of the process within a repository setting) and previous experience (e.g. from research into the process within the repository RD&D programme).

PAR1. Define expected parameter evolution

Once parameter(s) associated with the process under consideration have been identified, it is necessary to model the performance of each parameter over the planned monitoring period to develop a prediction of the parameter values over the monitoring period and determine the requirements on proposed systems for monitoring the parameter. This is needed in order to evaluate whether the potential options for monitoring it are suitable, e.g. to understand if techniques are available with sufficient precision, accuracy and reliability to monitor the scale of potential changes over the monitoring period. Note that predictions will, in most cases, require presentation with uncertainties quantified to ensure that responses to monitoring data account for the expected performance of the facility.

This step is undertaken in parallel with PAR2 and should be done for each parameter identified in PRO5.

PAR2. Identify monitoring strategy and technology options

In this step, options for monitoring the parameter in question are identified. Each option will consist of a high-level monitoring strategy (e.g. whether the parameter will be monitored *in situ* or in a pilot facility, and which repository elements will be monitored) and a technology (a physical method of measuring the parameter). The choice of monitoring strategy will reflect the safety strategy under which the monitoring programme is being developed.

It is expected that, at this stage, a set of preferred strategy options would be identified and evaluated, rather than all possible options.

This step is undertaken in parallel with PAR1 and should be done for each parameter identified in PRO5.

TEC1. Is option technically feasible? (SEE SUPPLEMENTARY GUIDANCE QUESTIONS in Section 6.2.3)

This step evaluates whether each strategy and technology option identified in PAR2 is technically feasible, against the expected parameter evolution defined in PAR1. A set of supplementary guidance questions has been developed for this step to assist with this and provide a framework for recording the results.

TEC2. Take option forward

If option is considered to be technically feasible (based on the answers to the sub-questions in TEC1 or otherwise), the option should be carried forward to the next stage in the Modern2020 Screening Methodology.

TEC3. Park option

If an option is considered not to be technically feasible (based on the answers to the sub-questions in TEC1 or otherwise), the option should be parked. This means that it should not be included in the options to be considered for monitoring the parameter in question in the current plan.

It is important to note that this is not a final decision and can be reviewed at any time. It ensures that the remainder of the Screening Methodology is only undertaken for technically feasible options. The parked options remain within the system, with a record of the justification for their status to provide transparency and allow future review (there is an opportunity later in the Methodology to identify the need for R&D on technology development if necessary – see PRO7).

PAR3. Are there any feasible options for this parameter?

Once all strategy and technology options identified in PAR2 have been evaluated for technical feasibility, it will be apparent whether any of the options identified for a particular parameter are feasible.

PAR4. Take parameter forward

If there is at least one technically feasible option, the parameter should be taken forward to the next stage of the screening methodology, together with the option(s) identified as technically feasible for monitoring it.

PAR5. Park parameter

If there are no technically feasible options for monitoring a parameter, the parameter should be parked. This means that it should not be included in the parameters to be considered for monitoring the process in question in the current plan.

It is important to note that this is not a final decision and can be reviewed at any time, but rather ensures that the remainder of the Screening Methodology is only undertaken for parameters that can feasibly be monitored. The parked parameters remain within the system, with a record of the justification for their status to provide transparency and allow future review.

PRO6. Are there sufficient feasible parameters to monitor this process?

This question reviews whether the process in question can be feasibly monitored. In many cases a single parameter will be sufficient to provide the desired level of information about a process. However, in other cases it is possible that multiple parameters may be needed.

PRO7. Reconsider process, monitoring strategy, or conduct further R&D on monitoring technologies

If there are not sufficient feasible parameters to monitor the process in question, it is necessary to reconsider:

- Monitoring of the process. If the process was identified as valuable in preceding steps, but there is no feasible technique for monitoring related parameters for the range of monitoring strategies under consideration, it may be necessary to reconsider the basis for the decision to monitor it. This could include re-evaluation of the process within the post-closure safety case. However, although monitoring can strengthen understanding of some aspects of system behaviour during the operational period, the safety case would typically not depend on monitoring during the operational period, but rather on scientific understanding (including assessment of any uncertainties) and quality control of manufacturing and installation. Inability to monitor a parameter would thus very rarely, if ever, result in a revision to the safety case.
- Whether a different high-level monitoring strategy could enable the desired parameter(s) to be monitored.

- Whether further R&D on monitoring technologies should be undertaken to develop promising options for monitoring the desired parameter(s) to a technically feasible level.

Indicative loops are shown on the flowchart to illustrate this reconsideration, but, in reality, users can revisit any part of the methodology at any time.

PRO8. Cross-compare parameters

This step considers the technically feasible parameters for each process, and strategy/technology options for each parameter, in a holistic manner. Its purpose is to ensure that the proposed parameter(s) for each process, and strategy/technology options for each parameter, are optimised – that is, sufficient to provide the desired information, with an appropriate (but not excessive) level of redundancy. Different WMOs will have different views and requirements on redundancy; therefore, no further guidance is provided.

Opportunities for “doubling up”, e.g. using the same strategy and/or technology to measure several parameters, can also be identified as part of this step.

The output of this holistic review should be an optimised list of parameters to be monitored (in the current monitoring plan) for the purpose of providing information about the process under consideration, together with optimised strategy/technology combinations by which these parameters will be monitored.

PAR6. Is the parameter included in the current monitoring plan?

This final question takes the parameter screening methodology to a logical conclusion, considering each parameter in turn.

PAR7. Carry parameter forward to monitoring programme design stage

Parameters to be included in the current plan following step PRO8 are carried forward to the design stage. As for previous endpoints, this is not a final decision and can be reviewed at any time.

PAR8. Park parameter

Parameters not included in the current plan following step PRO8 are not carried forward to the design stage. As for previous endpoints, this is not a final decision and can be reviewed at any time.

6.2.3 Supplementary Guidance Questions for PRO2, PRO4 and TEC1

Sets of supplementary guidance questions have been developed for three of the steps in the parameter screening methodology: PRO2, PRO4, and TEC1. These are intended to assist WMOs in developing an answer to the main question in each step, by acting as a list of relevant points to consider. It is recognised that the answers to these sub-questions are likely to be complex and that the overall answer will ultimately depend on expert judgement; therefore, there is no metric for relating sub-question answers to an overall answer.

It is envisaged that WMOs will record detailed responses to these sub-questions (including references where appropriate) as part of the justification for the parameters selected for monitoring through this methodology. This would provide long-term traceability and enable parameter justification to be efficiently reviewed and revised over time. However, each WMO is free to use these as they see fit: the sub-questions can be modified to suit particular needs, and they could be adapted into scored value assessments if a more detailed or numerical approach is required.

PRO2. Is the process relevant to post-closure safety and/or retrievability?

- Is the process related to one or more safety functions of any element of the repository system?

- Is the process related to any safety function indicator?
- Is the process linked to a parameter modelled in the safety assessment that has a significant impact on system performance (dose/risk)?
- Is the process related to system performance that could lead to a decision to retrieve waste or otherwise reverse the disposal process?

PRO4. Is there value in monitoring the process in support of the post-closure safety case?

- Could monitoring the process reduce uncertainty in repository performance over-and-above knowledge derived from research, development and demonstration (RD&D)? (Examples of RD&D are discussed in Section 3.2.3 and include materials science, procedure development, full-scale experiments, natural analogues and fundamental scientific understanding.)
- Could monitoring provide confidence that the repository system has been implemented as designed, additional to that gained in other ways (for example, through quality control)?
- Could the changes to the repository system resulting from the process be quantifiable during the monitoring period?
- Could any uncertainty that would be addressed by monitoring the process be more readily addressed by changes to the repository design?
- Could monitoring the process support repository design improvements?
- Could monitoring the process result in greater system understanding that would be incorporated in a periodic update to the post-closure safety case?

TEC1. Is the monitoring technology and strategy option technically feasible?

- Can the proposed technology meet sensitivity, accuracy and frequency requirements for monitoring the parameter over the monitoring period?
- Can the proposed technology meet reliability and durability requirements for monitoring the parameter over the monitoring period?
- Can the proposed technology function effectively under repository conditions for the monitoring period?
- Can the proposed technology be applied without significantly affecting the passive safety of the repository system?
- Are the radiological doses to workers that could result from the installation, data acquisition or maintenance of the technology acceptable?
- Are the non-radiological risks to workers that could result from the installation, data acquisition or maintenance of the technology acceptable?
- Is the likely impact of the installation and/or normal operation and/or maintenance of the technology on repository operations (i.e. in terms of interrupting or delaying waste emplacement) acceptable?
- Is the likely impact of the development, manufacture or deployment of the technology on the environment acceptable?

7 Conclusions

This section presents the conclusions of Task 2.1 of the Modern2020 Project in three sections. First, in Section 7.1, five common themes are identified; these are aspects and aspirations of repository monitoring that are shared by all programmes reviewed as part of this task, and can be considered as a set of good practice guidelines for WMOs developing an operational phase monitoring programme in support of decision making and in support of building further confidence in the post-closure safety case.

Second, in Section 7.2, a summary discussion of the differences in monitoring requirements and strategies between programmes, and the reasons for these, is presented.

Finally, in Section 7.3, a summary of the Modern2020 Screening Methodology, developed in WP2.1, is provided.

7.1 Common Themes

Monitoring should be integrated into the post-closure safety case alongside other methods of building confidence

Monitoring during the operational phase is one of many tools that can contribute to building further confidence in post-closure safety, but it is widely accepted that the long-term safety of a repository does not depend on monitoring.

In order to accurately reflect the contribution monitoring can provide to a post-closure safety case, a monitoring programme should be developed alongside and as part of the post-closure safety case, rather than as a separate project that is matched to the post-closure safety case retrospectively. The post-closure safety case should also discuss the relationship between monitoring and closely related activities, for example, quality control, site characterisation, and full-scale experiments.

Not everything should be monitored

No organisation is proposing to monitor all elements of a repository system during the operational period. Monitoring has significant impacts on operations and, if implemented inappropriately, could affect post-closure safety. Therefore, it is not feasible to monitor all possible parameters. Instead, programmes are seeking to reach an equilibrium between undertaking sufficient monitoring to meet the high-level objectives of building further confidence in the post-closure safety case and supporting decision making, and ensuring that monitoring is practically feasible, proportionate and justified in the context of a specific disposal system concept.

Many different approaches to monitoring are possible (e.g. pilot facilities, representative monitoring fields and specific monitoring cells), and these are summarised in Section 7.2.

Monitored parameters should provide information about processes relevant to safety, there should be demonstrable value in monitoring them, and monitoring them must be technically feasible. A generic process for identifying such parameters has been developed in Task 2.1, and is summarised in Section 7.3.

Processes that cannot be monitored (e.g. because the rate of change in related parameters is too slow) but are important to safety need to be considered in other ways (e.g. natural systems studies and sensitivity analyses undertaken as part of the safety assessment). Equally, processes that can be monitored will also be considered in the safety case by other methods and will not rely on monitoring alone for safety demonstration.

Monitoring should not impair barrier functions

There is a common understanding that monitoring should not impair the performance of any barrier safety functions. There are different ways in which preservation of barriers can be ensured, e.g. not emplacing any sensors behind or within barriers (reliance on quality control);

use of wireless sensors; and use of fully sealed wired sensors, but this overarching principle is widely accepted.

Engagement with public stakeholders and regulators should take place throughout monitoring programme development and iteration

It is widely recognised that early, continued interaction with stakeholders, including regular evaluation during repository planning, construction, operation and closure, is an effective way to build confidence among the wider community. Early interaction does not necessarily mean at the start of programme development: it is useful for WMOs to provide initial proposals regarding the monitoring strategy and list of parameters, which can then be iterated through open discussions with regulators and public stakeholders in the wider context of the post-closure safety case for geological disposal. Lists of parameters will be subject to developments and change as monitoring programmes are iterated throughout the operational phase.

Confidence building should happen in parallel with technical work, and not be seen as a separate process. Activities needed to make progress within the technical community or also relevant to broader society, including discussion and questioning, consensus and confidence building, and maintenance of dialogue.

Monitoring should be considered holistically

It is important to consider and discuss monitoring for the purpose of building further confidence in post-closure safety and supporting stepwise management of the repository in the context of a wider monitoring programme. All WMOs will also carry out monitoring for other purposes, such as construction/operational safety, environmental impact and security and safeguards. If monitoring plans for these other purposes are not clearly communicated when discussing repository monitoring more widely, there is a risk that stakeholders may assume that they are not being considered at all. Parameters relevant to one specific aspect of an overall monitoring programme may also be relevant to another aspect too. Similarly, although the focus of the Modern2020 Project is monitoring during the operational phase, such monitoring is also closely aligned with monitoring in other phases (baseline monitoring, monitoring during construction and monitoring following closure).

7.2 Programme Differences

Within the boundaries of the common themes identified in Section 7.1, differences exist between the current monitoring plans of different national programmes in both high-level strategy (i.e. what will be monitored, and where and when monitoring will take place) and more detailed aspects. These are largely a result of differences in national legislation and regulatory requirements, and differences in geological environment, which drive requirements on the disposal system (and, therefore, the selected disposal concept) and monitoring system, and lead to different monitoring concepts.

The main difference between programmes is the extent to which emplaced waste will be monitored directly. Many approaches are possible, combining strategy elements in different ways. However, it is possible to identify three “end member” monitoring concepts with contrasting strategies:

- ***In situ monitoring of relatively broad scope, represented by Andra’s monitoring programme.*** In this approach selected disposal cells within the main repository will be monitored at different levels following waste emplacement. These include; surveillance structures, which will be monitored for a wide range of parameters, and current structures, whose performance will be calibrated against surveillance structures using key parameters. Monitoring of the conditions of waste packages and other EBS elements in disposal cells is defined in Andra’s programme in order to verify conditions of retrievability.

- ***Limited monitoring focused on EBS elements/dummy packages, represented by the KBS-3V concept.*** A requirement to prevent disruption to the bentonite barrier means that only limited monitoring is envisaged by SKB and Posiva. These programmes have comprehensive quality control programmes (including some extended time-series measurements that could be considered to be monitoring) that will ensure emplacement of waste and EBS elements as planned. However, outflow from deposition tunnel plugs may be monitored, together will full-scale *in situ* tests using heated dummy packages, and small-scale "batch tests" focusing on specific volumes or elements of the EBS and/or specific processes, such as corrosion.
- ***Monitoring in a pilot facility, represented by Nagra's monitoring programme.*** In this approach, a fraction of waste emplaced in a separate facility (where conditions are representative of the main part of the repository) is monitored to provide information on the behaviour of the barrier system and check predictive models. The waste is not expected to be retrieved and redisposed, so it must fulfil the same safety requirements as the repository. A pilot facility is a requirement of the Swiss safety authority.

7.3 Screening Methodology

As noted in Section 7.1 and explained earlier in this report, it is widely recognised that it is necessary and desirable to identify parameters to monitor that:

- Provide information about processes relevant to post-closure safety.
- Offer value in support of the post-closure safety case, above that gained from other aspects of the wider science programme.
- Are technically feasible to monitor.
- Are appropriate in the context of other parameters proposed for monitoring.

The parameters that meet these criteria will be highly dependent on national context and repository concepts, and the resulting differences in monitoring requirements and strategy. Therefore, any generic guidance must recognise and accommodate the role of expert judgement, and be adaptable to suit specific needs.

The Modern2020 Screening Methodology sets out a generic approach for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. The Methodology takes account of the interplay between processes, parameters and technologies and addresses each of the steps listed above, providing more detailed guidance where appropriate. The Methodology is visualised through a diagram (Figure 6.2) and accompanied by a detailed explanation of each of the steps.

The Methodology is further supported by a diagram showing how it could fit into iterative processes of engagement with stakeholders and regulators (Figure 6.3). Such interactions are envisaged to take place at a higher level than within the Methodology (i.e. during programme-wide engagement programmes), allowing the parameter list to be discussed in the context of the post-closure safety case and other aspects of the disposal programme.

The Methodology is intended to be iterated multiple times; the parameter list derived after one iteration is not final and can be revised (through subsequent iteration) periodically or at any time there is a trigger, such as an update to the post-closure safety case, following significant developments in technology, or in response to specific monitoring results.

The Methodology is fully compatible with the MoDeRn Monitoring Workflow, fitting between the steps "Identify Processes to Monitor" and "Design Monitoring Programme". It constitutes an elaboration of the middle part of the Workflow (Figure 6.4).

Although the Modern2020 Screening Methodology has been reviewed and iterated by WP2 partners as part of this task, it will be tested during Task 2.2, and is expected to be revised to address feedback from this testing.

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Appendix A: Modern2020 Task 2.1 Questionnaire

Background

In WP2 of the Modern2020 Project a questionnaire was used to collate information on specific approaches being adopted by WMOs to repository monitoring. The information obtained through the questionnaire and the follow-up work fed into this report.

Scope

The questionnaire focused on monitoring of geological repository systems in relation to developing further understanding of, and building further confidence in, post-closure performance, and also to support management during the operational phase (e.g. possible decisions to retrieve or not retrieve the waste, on-going demonstration of compliance with the design basis, and on-going system optimisation). This may include direct monitoring of engineered barrier system (EBS) components and the host rock, as well as proxies, i.e. monitoring of other parameters that reflect EBS and/or host rock evolution. Such monitoring is expected to take place during the operational period and, potentially, during and after closure. Conventional monitoring, such as that for industrial health and safety purposes, was outside the scope of the questionnaire.

Monitoring of long-term commissioning tests, pilot facilities and dedicated monitoring galleries that are undertaken in the repository was included in the scope, as such monitoring may form aspects of strategies that can be used to obtain information about the actual repository system during operations. However, monitoring of generic underground research laboratory (URL) experiments or monitoring of other *in situ* experiments, the results of which mainly input to RD&D activities, is beyond the scope of the questionnaire, except in questions which specifically ask about such monitoring in relation to how it may inform repository monitoring programmes.

Questionnaire

The questionnaire contained specific questions grouped into four separate sections:

- Section WP2.0: The first section of the questionnaire was focused on gathering contextual information, and therefore has a broader scope than defined above. The purpose was to understand the disposal programme context under which information on the monitoring programme was provided.
- Section WP2.1: The second section was focused on the needs of the monitoring programme by focusing on the decisions that would be supported by monitoring information, and how monitoring information is expected to be used.
- Section WP2.2: The third section was focused on monitoring strategies and the process for identifying monitoring parameters.
- Section WP2.3: The fourth section was focused on monitoring techniques, in particular on *a priori* expectations regarding the monitoring techniques that would be used in the monitoring programme.

The questionnaire is provided on the following pages. For each question, both the question topic and supplemental questions used to provide guidance on the detail of the responses that were expected was included. The supplemental questions were provided in italics. The supplemental questions were intended to provide examples of the topics that should be covered in the detailed responses, and thus to facilitate the transfer of information.

Modern2020 Work Package 2 Questionnaire Monitoring Programme Design Basis, Decision Making and Monitoring Strategies	
Organisation	
Name	
Date of Completion	
Version	

WP2.0 Questions about national programme context. Questions in this section have a broader scope than that defined in the introduction.

Question WP2.0.1

Please provide a definition of monitoring as used in your national programme.

What is the scope of your monitoring programme?

What are the main reasons for undertaking repository monitoring in your disposal programme?

What are the principal objectives of repository monitoring in your disposal programme?

Question WP2.0.2

What wastes are considered in your geological repository design?

Is the repository for spent fuel, HLW, or for co-location of spent fuel and/or HLW with ILW?

Broadly, what are the fractions and amounts of these wastes?

Question WP2.0.3

Describe the overall disposal concept.

What is the geological environment in which the repository will be constructed (e.g. crystalline, clay or salt host rock)?

What are the geometrical arrangements of the EBS, for example disposal in tunnels / boreholes?

What type of buffers and backfills and other barriers are used?

Question WP2.0.4

What is the current repository programme status and how is this related to your consideration of monitoring?

Is the disposal programme in the generic, site-specific or implementation phase?

What impact does the current repository programme status have on considerations of monitoring, i.e. has monitoring been an important consideration in your programme previously, and do you expect consideration of monitoring to become more important as the repository programme moves towards operation?

Question WP2.0.5

What is the repository schedule?

When and for how long do you expect the repository to operate?

What are the key uncertainties in the repository operational schedule, e.g. waste availability?

What is the relative sequence of repository construction, operation (waste emplacement) and backfilling / engineered barrier emplacement?

How long will disposal areas be open prior to backfilling following waste emplacement?

In relation to this sequence, when will repository monitoring equipment and/or infrastructure be emplaced / constructed?

Question WP2.0.6

Will the waste packages and/or other parts of the near-field such as disposal vaults/tunnels be accessible to personnel (e.g. for the purpose of maintaining repository monitoring equipment) following emplacement?

How will the emplaced wastes be accessible and for how long?

Question WP2.0.7

Who is responsible for the waste and/or repository at different stages of the programme?

At what point in the process of waste generation, treatment and disposal does the WMO assume responsibility for the waste?

Does responsibility for the waste / repository transfer to the state or any other organisation at any point after closure, and what are the requirements for any such transfer?

Question WP2.0.8

What is the status of the regulatory context under which the repository will be licensed?

Have the regulations governing repository construction, operation and post-closure safety been established and, if so, what are the regulations (please provide a reference)?

Which organisations are responsible for regulation and licensing?

Question WP2.0.9

What are the national policy and regulatory requirements for repository monitoring?

Are there any specific regulatory requirements on monitoring in national regulations for geological disposal?

Are there any implications for monitoring that arise from national policy decisions or more general regulatory requirements in national regulations for geological disposal?

Are there any requirements on monitoring that arise from environmental regulations?

How will regulators assess the adequacy and safety of monitoring proposals?

At what stage in the repository development programme will these assessments be made?

Are the regulators undertaking any independent work on repository monitoring?

Are there any national/international standards that need to be followed regarding the overall repository monitoring programme?

WP2.1 Questions about decision-making requirements
Question WP2.1.1 With reference to the anticipated repository schedule (Question WP2.0.5), what are the main programmatic decisions and how will they be underpinned by repository monitoring results? *Examples of programme-level decisions include: decision to start emplacing waste, decision to close vault/deposition tunnel, decision to close underground facility and access ways, decision to close surface facilities, decision to transfer responsibility etc.* *How would programme decisions be made, and what is the expected input from repository monitoring to these decisions?* *Who has responsibility for or is involved in these decisions (e.g. operators, board members, regulators and/or local citizen stakeholders)?*
Question WP2.1.2 What contribution could repository monitoring make to a decision to reverse the disposal process or retrieve waste? *How would such decisions be made, and what is the expected input from repository monitoring to these decisions?* *Is there a monitoring result that would automatically lead to a reversal in the disposal process or retrieval of waste?* *What kind of monitoring information would underpin a reversal in the disposal process or retrieval of waste?* *Who has responsibility for or is involved in a decision to reverse the disposal process (e.g. operators, board members, regulators and/or local citizen stakeholders)?*
Question WP2.1.3 At a level below the programme level discussed in Question WP2.1.1 (i.e. on a more "engineering" basis), what operational / design decisions related to the wasteform, waste container and/or waste package are expected to be underpinned by monitoring results, and how? *How might repository monitoring information be used to inform detailed aspects of design and/or implementation related to the wasteform, waste container and/or waste package?* *What information on the wasteform, waste container and/or waste package performance and/or characteristics is required to underpin these decisions?* *Who has responsibility for or is involved in these decisions (e.g. operators, board members, regulators and/or local citizen stakeholders)?*
Question WP2.1.4 At a level below the programme level discussed in Question WP2.1.1 (i.e. on a more "engineering" basis), what operational / design decisions related to the buffer and/or backfill are expected to be underpinned by monitoring results, and how? *How might repository monitoring information be used to inform detailed aspects of design and/or implementation related to the buffer and/or backfill?* *What information on the buffer and/or backfill performance and/or characteristics is required to underpin these decisions?* *Who has responsibility for or is involved in these decisions (e.g. operators, board members, regulators and/or local citizen stakeholders)?*

Question WP2.1.5 At a level below the programme level discussed in Question WP2.1.1 (i.e. on a more "engineering" basis), what operational / design decisions related to plugs and seals are expected to be underpinned by monitoring results, and how? *How might repository monitoring information be used to inform detailed aspects of design and/or implementation related to plugs and seals?* *What information on plugs and seals performance and/or characteristics is required to underpin these decisions?* *Who has responsibility for or is involved in these decisions (e.g. operators, board members, regulators and/or local citizen stakeholders)?*
Question WP2.1.6 At a level below the programme level discussed in Question WP2.1.1 (i.e. on a more "engineering" basis), what operational / design decisions related to service areas and/or access routes (tunnels / shafts) are expected to be underpinned by monitoring results, and how? *How might repository monitoring information be used to inform detailed aspects of design and/or implementation related to the service areas and/or access routes (tunnels / shafts)?* *What information on the service areas and/or access routes (tunnels / shafts) performance and/or characteristics is required to underpin these decisions?* *Who has responsibility for or is involved in these decisions (e.g. operators, board members, regulators and/or local citizen stakeholders)?*
Question WP2.1.7 At a level below the programme level discussed in Question WP2.1.1 (i.e. on a more "engineering" basis), what operational / design decisions related to the near-field host rock are expected to be underpinned by monitoring results, and how? *How might repository monitoring information be used to inform detailed aspects of design and/or implementation related to the near-field host rock?* *What information on the near-field rock performance and/or characteristics is required to underpin these decisions?* *Who has responsibility for or is involved in these decisions (e.g. operators, board members, regulators and/or local citizen stakeholders)?*
Question WP2.1.8 In relation to decision-making requirements, how and on what basis would the repository monitoring system change / evolve over time? *On what basis would you increase or decrease the frequency, density and location of repository monitoring (for example to gather information needed for specific decisions)?* *On what basis would you end repository monitoring?* *Consider that this may differ for monitoring of different repository system components.*

WP2.2 Questions about repository monitoring strategies and the process for identifying parameters to be monitored
Question WP2.2.1 Have you developed a framework/process/approach to guide the development of a repository monitoring programme? *If yes, please described the framework/process/approach.* *Who is responsible for or is involved in the development and validation of the repository monitoring programme?* *How and how often do you plan to review the repository monitoring programme during operations to incorporate increased knowledge of the disposal system from monitoring data?*
Question WP2.2.2 What is your overall strategy for repository monitoring? *Do you plan to monitor emplaced waste and/or EBS components directly, and if so, will this be in the main repository or in a separate facility?* *If in the main repository, will the entire repository be monitored or only a part? Will there be different levels of monitoring in different parts of the repository?* *If in a separate facility, will waste remain* in situ *or be retrieved and re-emplaced in the main repository after the monitoring period?* *Do you plan to monitor dummy canisters, and in what setting?* *Do you plan to conduct full-scale tests as well as / as an alternative to monitoring?* *Are there any other elements to your monitoring strategy?*
Question WP2.2.3 What do you consider to be the strengths and weaknesses of different repository monitoring strategies? *What are the main reasons for selecting the strategy/strategies described in your response to Question WP2.2.2?* *What are the weaknesses of this strategy and how do you plan to mitigate them?* *Are there any repository monitoring strategies you have rejected? If so, why?*
Question WP2.2.4 How will locations for monitoring be selected, and what is their spatial distribution (general layout)? *Does your placement strategy consider representativeness, accessibility and/or redundancy (with respect to technical failures)?* *Will monitoring locations be evenly spread across the repository or clustered around certain elements?* *Consider that this may differ for monitoring of different repository system components, and/or for different techniques.*

Question WP2.2.5

How is repository monitoring linked to your safety case/safety assessment and/or licence application?

Is it appropriate to use monitoring to develop further understanding of the repository system during operations, or should sufficient confidence be demonstrated in the safety case submitted as part of the licence application?

What assumptions or assessments are made about the (potential) impacts of monitoring equipment on the performance of the repository system, and how is the acceptability of such impacts addressed within the safety case?

Is repository monitoring linked to a demonstration of safety function performance / safety function indicators?

Are repository monitoring parameters identified through an analysis of features, events and processes (FEPs)? If yes, how are FEPs screened and what reasoning would be used to screen parameters in/out of a monitoring programme?

Does there have to be a detectable response during a monitoring period for monitoring to be undertaken?

Does the repository monitoring programme explicitly address scenarios modelled in safety assessment sensitivity calculations? If yes, what is the reasoning for collecting additional data?

What added value is monitoring expected to provide beyond the safety assessments that are performed as part of the safety case?

How will monitoring data be evaluated against the safety assessments underlying the safety case?

Question WP2.2.6

How is repository monitoring linked to the conclusions from research, development and demonstration (RD&D) of the disposal system, construction procedures and quality control?

If research and/or the safety case demonstrates that the design of the disposal system is robust, does this mean that repository monitoring does not need to be undertaken, i.e. a non-monitoring option?

How do you extrapolate the conclusions from RD&D to the development of a repository monitoring programme?

Can construction procedures and quality control be used to provide a proxy for monitoring results by demonstrating that repository system components are emplaced to be compliant with the design basis, and, therefore, with the safety case?

Question WP2.2.7

How will your repository monitoring programme incorporate learning from monitoring of URL experiments?

Do you have any direct experience of monitoring in a URL (including monitoring of generic experiments?), and if so, how has this affected your plans for repository monitoring?

How does the difference between repository operation and URL operation impact the design of monitoring systems to be applied in the repository?

Question WP2.2.8

What process(es) is/are used to determine which parameters will be monitored?

Do you follow a stepwise procedure? If so, what steps are involved?

Is the process based on screening a preliminary parameter list?

If so, how is the preliminary parameter list drawn up, and what is the approach to screening it?

Are specific monitoring parameters linked to the safety case / safety assessment / performance assessment?

Are specific monitoring parameters linked to FEPs and/or safety functions?

Do you already have a definitive list of specific parameters to be monitored? If so, what are they and what is the justification?

Question WP2.2.9

Are there any parameters that you consider to be worth monitoring (or not worth monitoring), irrespective of the result of the screening process?

What is the justification for this position? (E.g. are the parameters significant for safety, will they provide information on specific processes, is there insufficient scientific understanding to interpret them?)

Would you consider monitoring any parameters for the purpose of providing reassurance or confidence to local citizen stakeholders, even if the screening process suggests there is no technical reason to monitor them?

Question WP2.2.10

What is the role of technology demonstration in full-scale tests in your national programme?

What demonstrations/tests will be/have been undertaken, and how do the results of these demonstration tests have any impact on the need for monitoring in the repository?

Do you expect results from full-scale demonstrations/tests to mean that less monitoring of the final repository will be needed? To what extent?

Question WP2.2.11

Over what timeframe do you expect monitoring to be carried out?

Please relate this to the schedule outlined in your response to Question WP2.0.5.

Will monitoring be carried out prior to/during/after construction and/or operations?

Will any monitoring be carried out after the closure of the underground facilities and if so, for how long?

WP2.3 Questions about monitoring techniques and technologies. These are intended to obtain a general understanding only, not a detailed description or analysis of monitoring plans.

Question WP2.3.1

Do you have a strategic RD&D programme on monitoring techniques and technologies?

Please describe how such RD&D is organised.

Question WP2.3.2

What techniques are under consideration for monitoring of the performance of the wasteform / waste container / waste package?

Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.

What is your experience with these techniques, and what are the prospects of achieving readiness in time for deployment in your repository monitoring programme?

Do you anticipate any issues / problems with these techniques?

If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?

Question WP2.3.3

What techniques are under consideration for monitoring of the performance of the buffer and/or backfill?

Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.

What is your experience with these techniques, and what are the prospects of achieving readiness in time for deployment in your repository monitoring programme?

Do you anticipate any issues / problems with these techniques?

If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?

Question WP2.3.4

What techniques are under consideration for monitoring of the performance of plugs and seals?

Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.

What is your experience with these techniques, and what are the prospects of achieving readiness in time for deployment in your repository monitoring programme?

Do you anticipate any issues / problems with these techniques?

If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?

Question WP2.3.5

What techniques are under consideration for monitoring of the service areas and access tunnels and shafts?

Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.

What is your experience with these techniques, and what are the prospects of achieving readiness in time for deployment in your repository monitoring programme?

Do you anticipate any issues / problems with these techniques?

If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?

Question WP2.3.6 What techniques are under consideration for monitoring of the near-field host rock? *Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.* *What is your experience with these techniques, and what are the prospects of achieving readiness in time for deployment in your repository monitoring programme?* *Do you anticipate any issues / problems with these techniques?* *If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?*
Question WP2.3.7 What techniques are under consideration for monitoring of the far-field host rock? *Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.* *What is your experience with these techniques, and what are the prospects of achieving readiness in time for deployment in your repository monitoring programme?* *Do you anticipate any issues / problems with these techniques?* *If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?*
Question WP2.3.8 Is there any other monitoring you will undertake in relation to the evolution of the repository system (including host rock) that is not covered in the questions above, e.g. monitoring of ground elevation as a proxy for thermal-mechanical evolution of the sub-surface? *What techniques are under consideration for such monitoring?* *Please describe each technique, the parameter(s) it will be used to monitor, and give an indication of its technology readiness level.* *Do you anticipate any issues / problems with these techniques?* *If more than one technique is under consideration for any one parameter, are they alternatives or will they be used together to add system redundancy?*

Question WP2.3.9

Do you envisage applying any of the technologies under investigation in WP3 of Modern2020 in your repository monitoring programme?

Note that this does not include use of these technologies in generic URL experiments.

Please indicate whether any of the following technologies could be of principal interest, and in what context:

- *Wireless data transmission systems:*
  - *High/medium frequency wireless data transmission systems*
  - *Low frequency wireless data transmission systems*
- *Alternative power supply sources:*
  - *Energy harvesting based on low thermal gradients*
  - *Energy storage devices*
  - *Wireless energy transmission*
  - *Miniaturized nuclear generators*
- *New sensors:*
  - *New generation optical fibre sensors based on quasi-distributed measurements based on cascaded fibre Bragg gratings*
  - *Optical fibre cable for distributed measurements of four parameters (temperature, strain, hydrogen and radiation)*
  - *New method to determine thermal conductivity, density and water content of the EBS based on distributed temperature sensing*
  - *New method to determine water pressure in boreholes based on distributed temperature sensing and distributed strain sensing*
  - *Thermocouple psychrometers for water content measurement*
  - *Techniques for non-contact displacement measurement*
  - *Chemical measurements (ion-selective electrodes for measuring ion activities)*
  - *Combined thermal-hydrological-mechanical-chemical smart sensors (small combined cells to measure total pressure, temperature, pore pressure and humidity)*
- *Geophysical methods:*
  - *Seismic full waveform inversion*
  - *Combined method based on electrical resistivity tomography and induced polarisation tomography*

Appendix B: Review of Existing Monitoring Programmes

This Appendix provides a review of monitoring parameter selection in three existing waste disposal programmes:

- The Waste Isolation Pilot Plant (WIPP) in the United States (US).
- The NLLWF at Dounreay in the United Kingdom (UK).
- The ONKALO underground research facility at Olkiluoto in Finland.

The first two of these are existing and authorised/licensed facilities for radioactive waste disposal, while the third is a URCF developed in the same host rock as Posiva's repository for spent fuel. The review is primarily concerned with the methods used initially to identify and screen monitoring parameter lists for these facilities, and the subsequent evolution of the monitoring programmes in response to monitoring data. As such, the review provides three illustrations of how the principles and approaches described within this report and captured within the Modern2020 Screening Methodology can be implemented in practice.

WIPP (US)

Regulatory context: Performance confirmation (PC)

Performance confirmation (PC) terminology was defined formally in the US Nuclear Regulatory Commission (NRC) licensing criteria for the high-level radioactive waste disposal programme at Yucca Mountain. However, the concepts behind PC are applicable to any disposal facility, and the terminology has been applied retrospectively in the US to the compliance monitoring programme developed at the WIPP. Therefore, this section starts with an explanation of the concepts behind PC and continues to explore how these have been met at the WIPP.

Subpart F of 10 CFR part 63, the NRC licensing criteria for Yucca Mountain, describes the required development of a PC programme. Section 63.131 of Subpart F (General Requirements) states the objectives of the PC programme and specifies that the programme be started during site characterisation and continue until permanent closure.

The objectives of the PC programme are stated as:

> *"the programme must provide data that indicate, where practicable, whether: (1) Actual subsurface conditions encountered and changes in those conditions during construction and waste emplacement operations are within the limits assumed in the licensing review; and (2) Natural and engineered systems and components required for repository operation, and that are designed or assumed to operate as barriers after permanent closure, are functioning as intended and anticipated."*

Section 63.132 of Subpart F (Confirmation of Geotechnical and Design Parameters) requires the US Department of Energy (DOE - the Yucca Mountain proponent) to monitor subsurface conditions during repository construction and operation to confirm original design assumptions and to ensure that performance of geologic and engineered features is within design limits. The DOE is also required to inform the NRC of any design changes needed to accommodate actual field conditions encountered.

Section 63.133 of Subpart F (Design Testing) requires the DOE to undertake a programme of testing of features, for example, borehole and shaft seals, backfill, drip shields, and the effects of thermal interaction between waste packages, backfill, rock, and groundwater.

Section 63.134 of Subpart F (Monitoring and Testing Waste Packages) requires the DOE to establish a programme for monitoring and testing waste packages at the geologic repository operations area that is to continue as long as practical up to the time of permanent closure.

Development of a PC Plan

The development of a PC plan at Yucca Mountain was divided into eight steps:

1. Identification of the PC factors.

2. Establishment of the PC database (site characterisation baseline) and prediction of performance.
3. Setting of tolerances and bounds (acceptable limits of deviation from predictions).
4. Determination of completion criteria, and setting of guidelines for corrective actions.
5. Planning and set up of the PC test and monitoring programme.
6. Monitoring, testing, and collection of data.
7. Analysis and evaluation of the data.
8. Recommendations and implementation of corrective actions if required.

The focus on this review is on the first step – the identification of the PC factors.

Identification of PC Factors

Factors that had to be addressed by the PC plan were identified from three sources:

- Principal factors important to repository performance.
- Requirements documents.
- Data and validation needs of the analysis and process models.

An initial PC plan was prepared in 2000, just before the Site Recommendation phase. A full range of up-to-date performance assessment (PA) sensitivity analyses was not available for the development of the initial PC plan. Therefore, the preliminary principal factors to the Repository Safety Strategy were used to identify the PC factors in the interim, with the commitment to make any necessary adjustments in the future as sensitivity studies and further model evaluation were conducted. The principal factors in the Repository Safety Strategy were determined by ranking factors potentially important to post-closure safety on a scale of 0 – 2 (highest) for importance to PA, and A to C (lowest) for technical understanding. For each of the principal factors ranked with a score of 2, a corresponding PC factor was identified, e.g., failure rate of drip shields, which was tested in laboratory experiments.

Further PC factors were identified from the specific testing requirements set out in 10 CFR part 63, such as those related to testing of backfill and evaluation of thermal responses. Finally, data needs for the future development of process models were identified through dialogue with the appropriate staff.

Following identification of PC factors, the underlying parameters were evaluated in order to establish what to monitor / measure. A three-step screening process was applied:

1. The parameter must be relevant – i.e., it must describe conditions, be affected by construction or emplacement, or be time-dependent.
2. The parameter must be clearly defined, and must be both measurable and predictable.
3. The parameter must be important to post-closure performance so that, when measured, it will reduce the uncertainty of the repository system.

WIPP Repository Description

The WIPP is operated by the US DOE for the disposal of transuranic (TRU) waste (roughly equivalent to long-lived low-level waste (LLW) and ILW) from its defence programs. Waste disposed at the WIPP is termed “mixed” waste because it contains both radioactive and hazardous constituents. In October 1996, the DOE submitted a compliance certification application (CCA) to the US Environmental Protection Agency (EPA) for a licence to dispose of radioactive waste. In May 1998, the EPA stated in its final certification decision that the WIPP will comply with the EPA’s radioactive waste disposal standards. The WIPP was also issued with a Hazardous Waste Facility Permit by the New Mexico Environment Department in 1999.

The WIPP facility is located 42 km east of the town of Carlsbad in south-eastern New Mexico. Geologically, the repository is located in the northern Delaware Basin, 655 m underground in the Permian-age Salado bedded salt formation. The design concept envisages the stacking of drums of contact-handled waste in panels, with remote-handled waste drums being emplaced horizontally, either singularly or in pairs, in boreholes in the walls of the panels. Waste panels consist of seven rooms. Each room has approximate dimensions of 90-m long, 10-m wide, and 4-m high. Magnesium oxide is packed in bags around and between the waste drums, to act as a chemical conditioner and to react with carbon dioxide gas after closure. All of the panels will be closed using concrete-based seals when full. The underground is connected to the surface by four vertical shafts, each of which will eventually be sealed.

Monitoring Drivers

The key regulatory driver for monitoring comes from the radioactive waste disposal regulations of the EPA. Requirements for disposal system monitoring are stated in 40 CFR § 191.14(b):

> *"Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardise the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring."*

Monitoring is one of several activities defined in the regulations as part of active institutional control (40 CFR § 191.12(f)).

In order to certify the DOE's compliance with the requirements of 40 CFR part 191, the EPA established certification criteria that the DOE must satisfy in its application for certification (EPA, 1996a). The criteria related to monitoring are stated in 40 CFR § 194.42:

"(a) The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for pre-closure and post-closure monitoring required pursuant to paragraphs (c) and (d) of this section. The disposal system parameters analysed shall include, at a minimum:

(1) properties of backfilled material, including porosity, permeability, and degree of compaction and reconsolidation;

(2) stresses and extent of deformation of the surrounding roof, walls, and floor of the waste disposal room;

(3) initiation or displacement of major brittle deformation features in the roof or surrounding rock;

(4) groundwater flow and other effects of human intrusion in the vicinity of the disposal system;

(5) brine quantity, flux, composition, and spatial distribution;

(6) gas quantity and composition; and

(7) temperature distribution.

(b) For all disposal system parameters analysed pursuant to paragraph (a) of this section, any compliance application shall document and substantiate the decision not to monitor a particular disposal system parameter because that parameter is considered to be insignificant to the containment of waste in the disposal system or to the verification of predictions about the future performance of the disposal system.

(c) Pre-closure monitoring. To the extent practicable, pre-closure monitoring shall be conducted of significant disposal system parameter(s) as identified by the analysis conducted pursuant to paragraph (a) of this section. A disposal system parameter shall be considered significant if it affects the system's ability to contain waste or the ability to verify predictions about the future performance of the disposal system. Such monitoring shall begin as soon as practicable; however, in no case shall waste be emplaced in the disposal system prior to the implementation of pre-closure monitoring. Pre-closure monitoring shall end at the time at which the shafts of the disposal system are backfilled and sealed.

(d) *Post-closure monitoring. The disposal system shall, to the extent practicable, be monitored as soon as practicable after the shafts of the disposal system are backfilled and sealed to detect substantial and detrimental deviations from expected performance and shall end when the Department can demonstrate to the satisfaction of the Administrator that there are no significant concerns to be addressed by further monitoring. Post-closure monitoring shall be complementary to monitoring required pursuant to applicable federal hazardous waste regulations at parts 264, 265, 268, and 270 of this chapter and shall be conducted with techniques that do not jeopardise the containment of waste in the disposal system.*

(e) *Any compliance application shall include detailed pre-closure and post-closure monitoring plans for monitoring the performance of the disposal system. At a minimum, such plans shall:*

(1) *identify the parameters that will be monitored and how baseline values will be determined;*

(2) *indicate how each parameter will be used to evaluate any deviations from the expected performance of the disposal system; and*

(3) *discuss the length of time over which each parameter will be monitored to detect deviations from expected performance."*

Therefore, the EPA criteria define the periods over which the DOE must address the need for monitoring: the pre-closure period and the post-closure period, with closure being defined as the time of shaft sealing. They also define a minimum set of parameters that must be considered by the DOE in its determination of what to monitor. These parameters are based on the EPA's consideration of what could affect the containment capability of the WIPP (EPA, 1996b).

Monitoring is also required under the terms and conditions of the Hazardous Waste Facility Permit. The New Mexico Environment Department requires the implementation of a Detection-Monitoring Program, Site Closure Plan and Site Post-Closure Plan, each of which contain requirements pertaining to monitoring.

Development of a Monitoring Plan

The DOE approached the development of its monitoring plan in the CCA by addressing the requirements of 40 CFR § 191.14(b) and criteria of 40 CFR § 194.42 (DOE 1996a). Accordingly, the plan needed to:

- Address significant disposal system parameters.
- Address important disposal system concerns.
- Obtain meaningful data in a relatively short period (stated in the supplementary information to 40 CFR part 191; EPA, 1993).
- Preserve disposal system integrity.
- Be complementary with programmes addressing hazardous waste regulations.

Significant Disposal System Parameters

The 40 CFR § 194.42 criteria state that the DOE is to base decisions regarding disposal system monitoring on "an analysis of the effects of disposal system parameters on the containment of waste in the disposal system". The DOE considered the major processes and models identified in the development of its PA, and the parameters set out in the 40 CFR § 194.42 criteria, and developed an initial list of potentially significant parameters. Parameters were screened for inclusion in the list based on the following criteria:

- The parameter represents one or more important aspects of a chemical or physical process or model.
- The parameter represents subjective uncertainty (such as spatial variability in a physical property or process).

- The parameter represents stochastic uncertainty (such as drilling rate).
- The parameter proved to be moderately to highly sensitive in terms of modelling results in previous preliminary performance assessments.
- In addition to the list of parameters/areas set out by the EPA in the 40 CFR § 194.42 criteria, other key areas covered in the analysis included:
  - Repository chemical conditions.
  - Shaft seal system.
  - Radionuclide transport and retardation.
  - Direct releases.
  - Mining.

The parameters included on the initial list were assigned high, medium, or low significance values. 40 CFR § 194.42(c) states "a disposal system parameter shall be considered significant if it affects the system's ability to contain waste or the ability to verify predictions about the future performance of the disposal system." A parameter's effect on "the system's ability to contain waste" was evaluated in terms of its potential effect on compliance with the regulatory release limits. A parameter's effect on "the ability to verify predictions about the performance of the disposal system" was evaluated in terms of verifying the assumptions used in modelling the system's performance. Those parameters that would significantly affect a release of radioactivity or that were important to modelling assumptions were assigned a high significance level. Parameters that influence a release or assumption were assigned a medium level. Parameters that are not significant (e.g., representing spatial variability or an uncertainty in a given value) were assigned a low significance level.

Important Disposal System Concerns

This consideration is closely tied with the first above in that, in the final analysis, the most significant parameters are generally related to important disposal system concerns. However, this step in the development of the monitoring plan was included separately to identify any other parameters that, while they are not significant in performance assessment, do describe important disposal system features. As an example, the creep of the host salt formation was considered an important feature of the disposal system, although the parameter analysis identified the creep properties of the salt as having a minor effect on the outcome of the analysis.

Meaningful Data in a Relatively Short Time

All of the potential monitoring parameters were assessed against two further qualifications. First, parameters needed to be amenable to measurement within the disposal system and, second, parameter changes expected to occur within the first 150 years (i.e. during the 50-year operational and 100-year active institutional control periods[2]) and affecting long-term disposal system performance needed to be predictable. For example, parameters such as the shape of pore spaces cannot be reasonably measured and, therefore, were not considered further as candidates for the monitoring programme. This part of the analysis greatly reduced the number of parameters determined as potentially suitable for monitoring.

Preservation of Disposal System Integrity

Disposal system integrity could be compromised by drill holes, conduits, or other entries that are left in place to allow access to monitoring equipment. The requirement to avoid such conditions leads to the conclusion that the only viable monitoring systems are those that can be managed directly during operations, those that can transmit information without cabling (i.e., telemetry), and those that can be

[2] The regulations state that post-closure monitoring will cease when no more meaningful data is being collected, but for planning purposes the post-closure monitoring period is taken to be the same period as the institutional control period, the length of which is specified separately in the regulations.

used to evaluate parameters using remote sensing / geophysical techniques. Concerns were raised regarding the latter two techniques:

- *Telemetry:* Although through-the-earth transmission of signals is feasible, any post-closure monitoring system that uses this type of telemetry must be self-contained and durable. For the WIPP, this would have required extending battery or portable generators beyond the tens of years that could be achieved for low-duty cycle systems when the monitoring programme was established. Components would have to withstand the harsh brine and gas environments that are predicted, as well as the effects of creep closure and repressurisation. Further, in addition to the equipment issues, there were concerns about interpreting results in an environment where interference, such as background electromagnetic noise, can only be, at best, poorly characterised. The DOE determined that, while these issues and concerns could be addressed with technology development programmes, it was considered doubtful that the high cost was justifiable for the limited amount of data that may be obtained from such systems.
- *Remote Sensing (i.e. Geophysics):* The DOE determined that, in general, the changes in the repository will be too small (in scale), too far from the surface, and too slow to be detectable using geophysics.

  However, the DOE did decide that, although no single technique could be used to fully assess the repository's condition, one remote technique could be used as an identifier to alert that a condition may exist. If such an alert was triggered, then other techniques could be used in unison to assess and validate the condition. From a review of survey techniques, the best current monitoring technology that could be used for a post-closure monitoring identifier was determined to be surveying for subsidence. This method was considered to be the most practical because it is a simple, repeatable, low-cost, low-maintenance, low-technology approach to monitoring the repository. In addition, the DOE committed to perform the following surveys one time after facility closure to establish baseline data:

  - Seismic survey over the waste panels.
  - Resistivity survey over the waste panels.
  - Electromagnetic survey over the waste panels.
  - Gravitational survey.
  - Obtain and archive core samples from previous core work.
  - Subsidence survey.

  Thereafter, periodic levelling surveys of the subsidence network will be undertaken, and compared to expected results. Should an unexpected condition be detected, then the other surveys might be repeated for comparison to the baseline.

Complementarity with hazardous waste regulations

The WIPP also contains hazardous wastes and must comply with hazardous waste regulations, as controlled under the statutes of the Resource Conservation and Recovery Act (RCRA). The DOE has specified three monitoring programmes in its RCRA hazardous waste permit: (1) a confirmatory volatile organic compound monitoring programme to demonstrate that the numerical predictions of volatile organic compound releases are reasonable; (2) a groundwater monitoring programme to verify knowledge regarding the characteristics of groundwater flow, including periodic testing for releases from the repository; and (3) a geomechanical monitoring programme to support decisions regarding operations and maintenance of underground openings. Where they have overlapping interests, the groundwater and geomechanical monitoring programmes have been designed to address the needs of both RCRA and 40 CFR part 194 commitments.

Final Compliance Monitoring Parameters

The result of the analysis in the CCA was the identification of ten Compliance Monitoring Parameters (COMPs – Table A1).

The CCA also describes a series of individual monitoring programmes:

- Groundwater monitoring programme (GWMP).
- Geotechnical monitoring programme (GTMP).
- Subsidence monitoring programme (SMP).
- Delaware basin drilling monitoring programme (DMP).
- Volatile organic compound confirmatory monitoring programme (VCMP).
- Environmental monitoring programme (EMP).

Table A-1: The ten compliance monitoring parameters identified in the CCA.

Monitored Parameter	Pre-closure	Post-closure
Culebra Member groundwater composition	X	X
Culebra Member change in groundwater flow	X	X
Probability of drilling intersecting a brine reservoir	X	X
Drilling rate (number of new boreholes per km^2)	X	X
Subsidence	X	X
Waste activity	X	
Creep closure and stresses	X	
Extent of deformation (around the excavations)	X	
Initiation of brittle deformation	X	
Displacement of deformation features	X	

Each of the monitoring programmes has several drivers (e.g., EPA regulations, RCRA regulations, formal agreements, and health and safety considerations). For example, the Environmental Monitoring Programme was developed in response to various DOE Orders in the early 1990s, specifically written to prevent environmental contamination at DOE sites during its pre-operational and operational life. Monitoring data collected under the Environmental Monitoring Programme are reported in an Annual Site Environmental Report.

The DOE's Monitoring Implementation Plan (DOE, 1999[3]) describes how information and data are extracted from the various WIPP monitoring programmes in order to derive the COMPs.

Management of Monitoring Results

Monitoring data and observations are used to derive "values" for the ten COMPs, which are then evaluated against performance expectations for the disposal system. The performance expectations are based on results from the WIPP PA, and its associated scenarios, models, and parameter values. The subsequent course of action is determined by the nature of the evaluation:

1. ***The COMP data indicate an unplanned and significant change from expected performance***. In this case, the DOE will notify the EPA rapidly (within 1 or 10 days, depending on whether the change indicates a possible exceedance of the containment requirements).

[3] DOE (1999), *40 CFR Parts 191 and 194 Compliance Monitoring Implementation Plan*. DOE/WIPP 99-3119, Carlsbad Area Office, Carlsbad, NM.

2. ***The COMP data do not indicate a significant change from performance expectations***. In this case, the monitoring results and evaluations will be reported to the EPA as part of the DOE's annual reporting commitment and 5-year recertification process.

Any anomalous monitoring data represent an unplanned potentially significant change. A COMP assessment plan (SNL, 2000[4]) recommended that trigger values be established for each COMP, and be used in the annual assessment as indicators of monitoring results that may invalidate or place serious question on one or more of the key assumptions or components of the CCA. The exceedance of a trigger value during the annual assessment does not mean that continued compliance is in jeopardy, but that further action, such as additional investigative studies, should be taken. For example, the trigger values established for the Culebra Member groundwater composition make use of statistical quantities (means and confidence intervals) derived from concentrations of major ions determined during the background or baseline water quality sampling. Specifically, the trigger values are defined as the composition for a major ion falling outside the 95% confidence interval for three consecutive sampling periods (DOE, 2003[5]).

Example

Groundwater monitoring at WIPP has been historically conducted through several programmes including the Site Characterization Program, the WIPP Water Quality Sampling Program, and most recently, the WIPP Groundwater Monitoring Program.

The principal goal of the data collection is the comparison of data arising to the equivalent baseline data to identify potentially significant deviations. The comparisons for the Culebra Member groundwater levels make use of water level measurements (and their errors) taken in 32 wells used to calibrate the Culebra Member transmissivity fields that defined, in part, the flow and transport conceptual models used in the CCA PA.

The PA initially assumed steady-state conditions in the WIPP groundwater model used for flow and transport calculations. Water levels in 17 of the 32 monitoring wells exceeded the range used in the PA for these wells, with time-series plots showing a long-term rise in water levels that suggested that the steady-state model was not accurately characterising reality. A four-year investigation into the potential cause and possible modelling corrections identified that the most likely cause was leakage from overlying units, due to poorly plugged boreholes. The investigation resulted in a refined WIPP groundwater conceptual model, which passed peer review and was duly approved by the EPA.

This example illustrates how the WIPP monitoring programme:

- Identified a condition outside PA expectations.
- Researched the cause and effects of the condition.
- Modified the modelling of the system to account for new information.

This performance confirmation action resulted in a more defensible and robust understanding of the disposal system, thus meeting the goal of the PC programme.

[4] SNL (Sandia National Laboratories) (2000), *An Analysis Plan for Annually Deriving Compliance Monitoring Parameters and their Assessments Against Performance Expectations to Meet the Requirements of 40 CFR 194.42.* SNL Analysis Plan AP-069, Carlsbad Programs Office.

[5] DOE (2003), *Strategic Plan for Groundwater Monitoring at the Waste Isolation Pilot Plant*. DOE/WIPP-03-3230, Carlsbad Area Office, Carlsbad, NM.

Dounreay NLLWF (UK)

Repository Description

A disposal facility for LLW – referred to as the New LLW Facilities (NLLWF) – has recently been licensed and constructed in the United Kingdom to support decommissioning and restoration of the Dounreay nuclear licensed site. The NLLWF are operated by Dounreay Site Restoration Limited (DSRL). The NLLWF were authorised in 2013 under the Radioactive Substances Act 1993 (RSA 93) by the Scottish Environment Protection Agency (SEPA) for the disposal of up to 175,000 m^3 of LLW with a total activity in the region of 1.3E+13 Bq beta/gamma activity and 1.1E+12 Bq alpha activity.

The NLLWF comprise two sets of vaults. One set of vaults will be used for disposal of LLW and a second set of vaults will be used for disposal of demolition wastes and soil with very low contents of radioactivity, a group of LLW streams termed Demolition LLW. The vaults essentially comprise concrete boxes constructed in excavations in the bedrock. During operation, the vaults will have roofs to keep the waste dry. Prior to disposal, the packages containing LLW will be filled with cement-based grout to remove voids and so form a stable cemented block of waste. The Demolition LLW will be disposed of in large nylon bags and emplaced in the vaults without the use of any grout, being backfilled with inert granular material such as sand or crushed rock. This, along with waste compaction, will help minimise voids and stabilise the waste. On closure, all of the vaults and the access roads will be covered by a cap containing an anti-intrusion layer over the vaults, and a low-permeability layer to isolate deep groundwater from the more active near-surface groundwater system.

Development of a Monitoring Plan

In preparation of an application for authorisation for disposal of radioactive waste, a high-level Monitoring Plan for the NLLWF was developed in 2007 and updated in 2010[6]. For the purposes of the Monitoring Plan, monitoring is defined as continuous or periodic observations and measurements of engineering, environmental or radiological parameters to help evaluate the behaviour of the disposal system or the impacts of the disposal facility and its operation on the environment. Therefore, the Monitoring Plan does not cover site investigation activities or one-off measurements, except insofar as such activities are used to define the baseline for monitoring. Such activities and measurements are covered under site characterisation planning. A site characterisation plan for the NLLWF was developed in conjunction with the Monitoring Plan to include the activities needed to establish the monitoring baseline for individual monitoring programmes.

The Monitoring Plan considers monitoring objectives in terms of four areas:

- Long-term safety case. A risk-based approach was adopted for selecting important monitoring concerns, as advocated by regulatory guidance. Results from the post-closure radiological safety assessment, which underlies the environmental safety case (ESC), were used to identify parameters significant to long-term performance and/or building confidence in long-term performance that are suitable for monitoring. It is highlighted that in identifying parameters that underpin the long-term safety case, there is no implication that there has to be a need to monitor them over a long period.
- Operational safety case. Following a risk-based approach, the Preliminary Safety Report and accompanying hazard and operability (HAZOP) study for the NLLWF were used to identify operational safety issues and associated monitoring parameters and requirements.
- Environmental impact assessment. The Environmental Impact Assessment of the facilities conducted for the planning application included a number of monitoring commitments to mitigate the potential environmental impacts of the planned facilities. These commitments were consolidated in the Monitoring Plan into monitoring programmes.

[6] DSRL (2010), *New Low Level Waste Facilities – Monitoring Plan 2010*. Galson Sciences Ltd report NLLWF/3/REP/GAL/0313/IS/02.

- Other objectives. Monitoring control of the facilities, waste management developments, the regulatory framework, and public reassurance were considered as additional objectives defining monitoring needs.

For each objective or set of objectives, the Monitoring Plan defined the information requirements in terms of monitoring parameters, with suggested techniques for undertaking the monitoring of the parameters. The monitoring parameters for each objective were then grouped into monitoring programmes, each concerned with a set of related parameters (e.g., groundwater monitoring covers hydrogeological parameters and groundwater chemistry parameters). The duration of each monitoring programme was defined in terms of the stages of development of the facilities, as set out in the GRA[7]:

- Pre-construction.
- Construction.
- Operations (which will run in parallel with phased construction).
- Closure (which will proceed in parallel with phased operations).
- Post-closure.

The Monitoring Plan was then derived by considering overlaps between the monitoring programmes, the associated lists of monitoring parameters, and the timescales for their determination for each objective. The final result was a consolidated list of 24 monitoring programmes.

Outlines of the procedures and techniques for collecting and assessing monitoring data for each monitoring programme / parameter in the Monitoring Plan were provided in the Monitoring Plan 2010. As necessary, monitoring programmes can be specified in more detail in separate implementation plans to provide measurement and evaluation details and schedules, performance measures, potential responsive actions, and reporting requirements. The Monitoring Plan and implementation plans together address the desired features of a monitoring and surveillance programme for near-surface disposal facilities, as identified by the IAEA.

Prior to the issue of the RSA 93 Authorisation, an annual review of all NLLWF monitoring activities was prepared by DSRL. Schedule 2.9 of the RSA 93 Authorisation concerns monitoring and paragraph 2.9.2 requires a programme of monitoring to confirm the assumptions of the ESC to be approved by SEPA. To address this paragraph and to form the basis for annual reporting of NLLWF environmental monitoring required specifically by SEPA under Schedule 2.9 of the RSA 93 Authorisation, DSRL has prepared an Environmental Monitoring Programme as part of the NLLWF Operational Environmental Management Plan which complements the earlier overall high level Monitoring Plan. The Environmental Monitoring Programme assesses monitoring activities solely in terms of compliance with the RSA 93 Authorisation. In turn, the Environmental Monitoring Programme supports the NLLWF Operational Management Plan. It is compliant with the requirement of the Authorisation to use Best Practicable Means (BPM) in the preparation of the monitoring programme, as is described in the NLLWF Operational BPM analysis.

Management of Monitoring Results

Baseline monitoring to establish pre-construction background levels, particularly for site groundwater, was undertaken. The baseline levels allowed the setting of performance measures for construction and operations. Figure B-1 shows the general procedure for undertaking the monitoring programmes. Following evaluation of the monitoring data against defined performance measures, the green route is followed where the data indicate compliance with expected performance. In this case, an assessment of the need to continue or modify the monitoring will be performed. The amber route is followed where the data do not comply with expected performance, but the non-compliance is not found to be significant with regard to risk of compliance of the facilities with requirements and expectations. In

[7] Environment Agency, Scottish Environment Protection Agency, Northern Ireland Environment Agency (2009), *Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*.

this case, the performance measures may be realigned to reflect the new data. The red route is followed where the data represent concerns with regard to the risk of continued compliance. In this case, actions to address the risk may be developed, and both the monitoring programme and the performance measures may be realigned to monitor the efficacy of the actions. Such a situation has not yet arisen for the NLLWF.

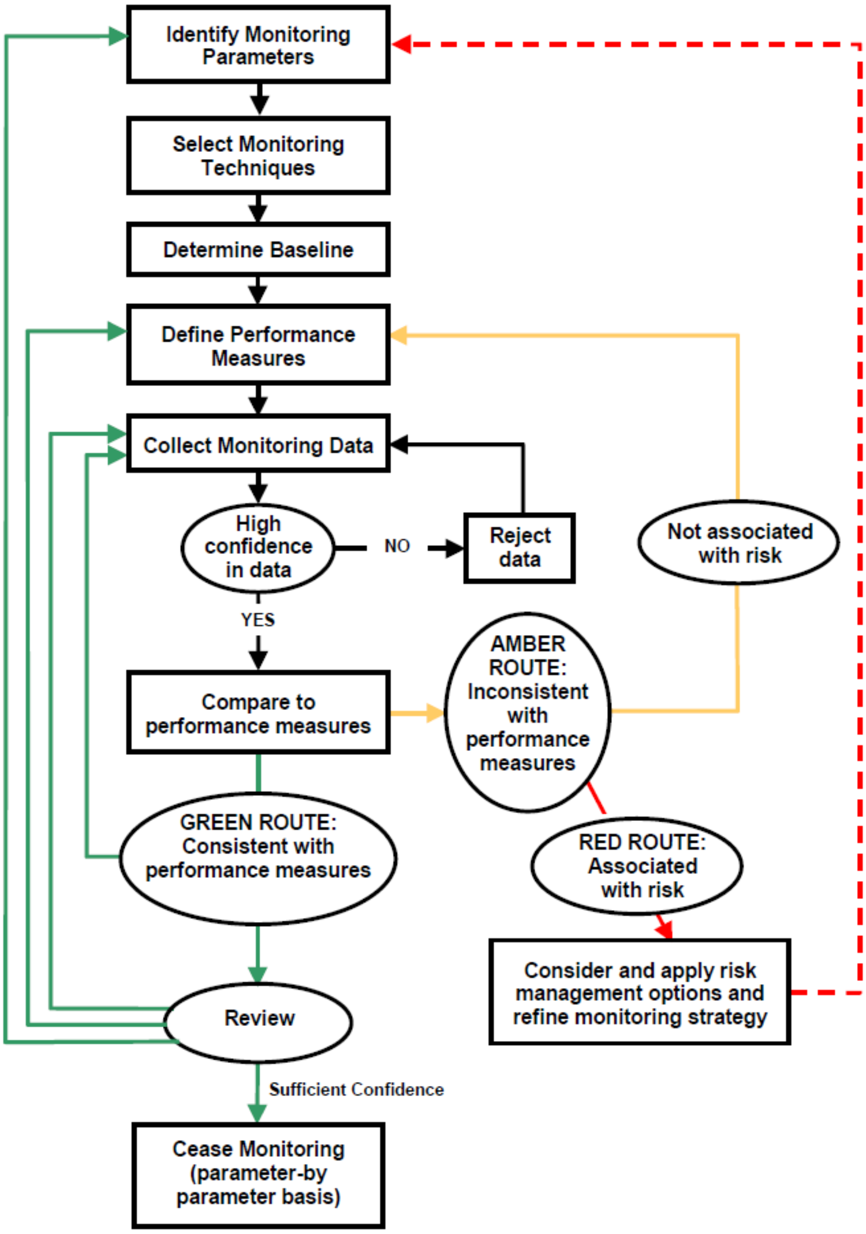

Figure B-1: Flowchart for undertaking monitoring and evaluation of monitoring data at the NLLWF.

Although not shown in Figure B-1, the monitoring parameters and programmes may also be reviewed and altered at any time through identification of new monitoring techniques and/or locations, and through changes in the assessed needs for monitoring data. In addition, each monitoring technique would be assessed to ensure that the monitoring itself does not compromise the ESC; this assessment is necessary to ensure compliance with the regulatory guidance (GRA [para. 6.4.32]). Each monitoring programme can be terminated when it has been assessed that there is no further need for the monitoring of the parameters in the programme (e.g., at the end of construction or operations), or where sufficient data have been collected to satisfy the relevant stakeholders (e.g., the operators, regulators) that the performance measures are being met for each parameter and there is no benefit from continuing the monitoring.

Example

By the end of 2011, DSRL had established the pre-construction baselines for site groundwater levels and site groundwater and surface water chemistries. The pre-construction baselines were obtained from twelve monitoring rounds during three years of monitoring in 2009, 2010 and 2011. Groundwater and surface water monitoring continued in 2012. By the end of 2012, the post-excavation groundwater levels had been measured for the period of Phase 1 construction. These levels reflect the perturbation of groundwater by the pumping necessary to keep the Phase 1 excavations dry. Figure B-2 shows contours of groundwater levels below ground surface in October 2012 that indicate a cone of depression from dewatering the Phase 1 excavations. The zone of influence from pumping is significant, with hydraulic gradients directed towards the sumps serving the pumped excavations (Figure B-2).

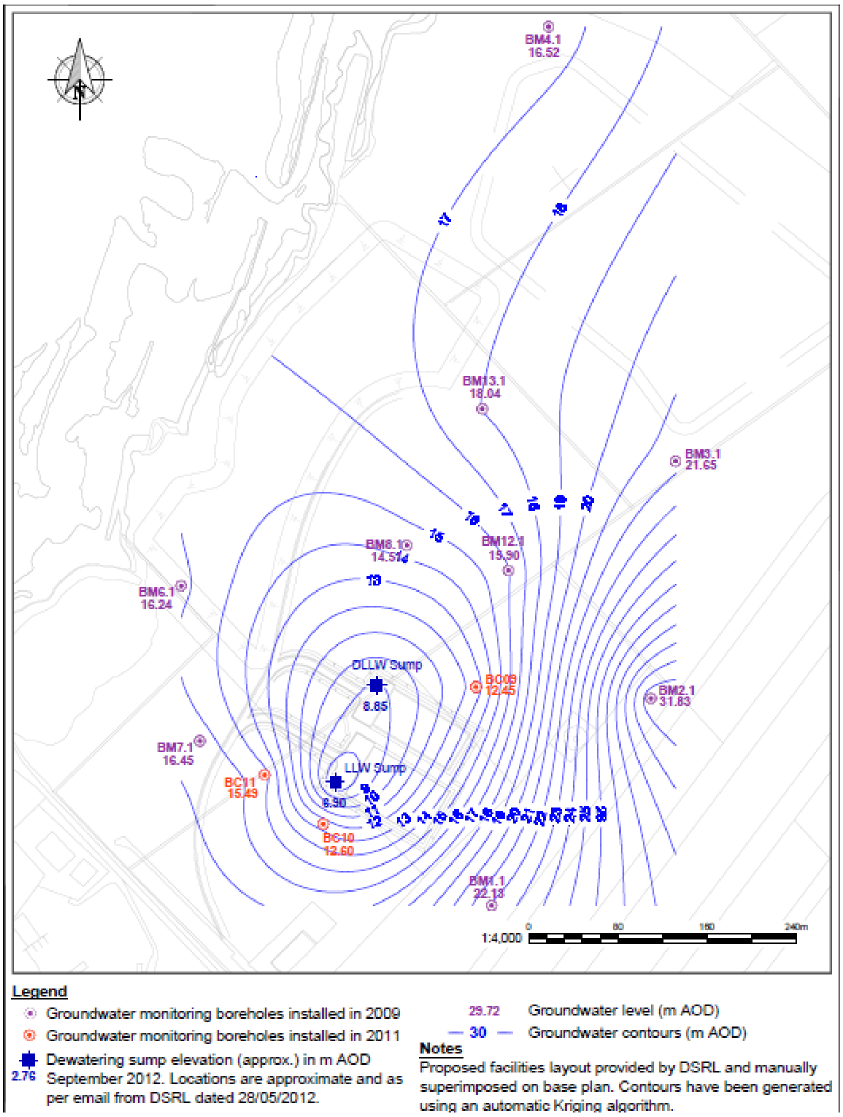

Figure B-2: Groundwater levels at the NLLWF site in October 2012, indicating a cone of depression from dewatering the Phase 1 excavations.

During operations, monitoring borehole heads will provide confirmation of groundwater drawdown in the vicinity of the excavations as a result of pumping to keep the vaults dry. The post-excavation groundwater levels established by late 2012 (Figure 2) and maintained during 2013 are unlikely to change significantly during the Phase 1 operations until any Phase 2 excavation works commence. Groundwater level monitoring during Phase 1 operations will, therefore, involve a continuation of quarterly rounds of manual dipping of the water levels in the NLLWF site boreholes together with pressure transducers installed in selected boreholes to provide automatic readings of groundwater levels. The number of boreholes being monitored does constitute a reduction in the monitoring programme compared to that undertaken during construction, due to a change in emphasis from investigating the baseline to monitoring the status quo. The modifications will be further reviewed after a period of waste disposal operations, and where the results show no change to the baseline as anticipated the monitoring programme will be altered accordingly. DSRL does, however, anticipate differences to occur in relation to the degassing of groundwater etc. as a result of the ongoing groundwater abstraction. The proposed monitoring also reflects the data requirements for further vault construction.

ONKALO (Finland)

Repository Description

Responsibility for disposal of spent nuclear fuel from the Olkiluoto and Loviisa reactors in Finland lies with Posiva. Posiva's plans for the disposal of spent fuel are based on the KBS-3 concept involving spent fuel placed in copper canisters with steel inserts, and disposed in vertical holes bored in the floor of a tunnel system. The disposal holes are backfilled with bentonite and the tunnels are also backfilled with a suitable material.

On 18 May 2001, the Finnish Parliament ratified a Decision-in-Principle (DiP) taken by the government that "construction of the disposal facility for spent nuclear fuel at Olkiluoto in the municipality of Eurajoki is in the overall interest of society". The first phase of the development of the spent fuel repository at Olkiluoto was the construction of an underground rock characterisation facility (URCF), referred to as ONKALO, comprising a system of exploratory tunnels accessed by a shaft and an access tunnel. Construction started in 2004 and was largely completed prior to submittal of a construction licence for the actual repository at the end of 2012 (which was granted in February 2015). ONKALO is located at a depth of 420 m, which is the intended repository depth. The bedrock consists of crystalline Svecofennian metasediments and plutonic rocks.

Posiva's monitoring programme has undergone several stages of iteration during the planning for, and construction and operation of, the ONKALO URCF. Further work on parameter identification in relation to the Olkiluoto repository will be undertaken in Task 2.2 of the Modern2020 Project. In this section, we summarise the early stages of development of the monitoring programme, to illustrate some of the parameter screening methods that have been applied. As such, some of the discussions in this section have been updated in Posiva's programme, but, nonetheless, the early development of Posiva's monitoring programme remains a useful example of benefit to the development of screening methodologies in the Modern2020 Project.

Development of a Monitoring Plan

Definition of Monitoring and Relevant Laws

The monitoring of the Finnish repository will be based on the monitoring network established for the monitoring of the impact of the construction of ONKALO and the presence of ONKALO itself on the state of the system (Posiva, 2003[8]). It is anticipated that the results of monitoring will lead to enhanced confidence in the site description, and will be used to specify the initial conditions for the site-specific safety assessment.

The general safety requirements for final disposal of spent fuel as laid down in the DiP state that "disposal shall be planned so that no monitoring of the disposal site is required for ensuring long-term safety and so that retrievability of the waste canisters is maintained to provide for such development of technology that makes it a preferred option". In addition, YVL Guide 8.4 (STUK, 2001[9]) states that "facilitation of retrievability or potential post-closure surveillance activities shall not impair the long-term safety".

Monitoring Strategy

A programme of monitoring was developed for the construction and operation of ONKALO[10], and has been implemented since 2004, using a network of monitoring stations (both at the surface and underground) that is intended to be used in expanded form in further development of the repository.

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[8] Posiva (2003), *ONKALO Underground Rock Characterisation Facility – Main Drawings Stage*. Posiva Working Report 2003-26.

[9] STUK (2001), *Long-term safety of disposal of spent nuclear fuel*. YVL-guide 8.4, Radiation and nuclear safety authority, Helsinki.

[10] Posiva (2003), *Programme of Monitoring at Olkiluoto During Construction and Operation of the ONKALO*. Posiva report 2003-05.

An updated monitoring programme, to be implemented from 2012 until the planned start of repository operations, was published in 2012[11].

The updated programme is divided into five discipline-based sub-programmes:

- Rock mechanics.
- Hydrology and hydrogeology.
- Geochemistry.
- Foreign materials.
- Environmental monitoring.

Each sub-programme is linked to one or more of six objectives of the monitoring programme:

1. **Long-term safety (site)**. Demonstrating that the conditions in the surroundings of the repository remain favourable for long-term safety despite repository construction and operation.
2. **Feedback to site characterisation and modelling**. Acquiring data that can be used to define and test various models of the surroundings of the repository, which increases understanding of the site and its evolution.
3. **Monitoring the environmental impact**.
4. Providing feedback for construction and design on the impact of construction on the geosphere and surface environment.
5. **EBS performance**. Monitoring the performance of the EBS to confirm the basis for expected/predicted behaviour.
6. **Compulsory radiological monitoring**. Conducting the mandatory monitoring of radiation and of releases of radioactive substances in the environment of the repository.

The 2012 update reflects new objectives to monitor EBS performance and radioactive releases into the environment, although plans for EBS monitoring are currently only developed to a preliminary stage. An operational monitoring programme has not yet been published. Objectives 1 and 5 are particularly relevant to the demonstration of long-term safety.

Identification of parameters

The determination of parameters to be included in the monitoring programme is based on the identification of specific processes affecting the long-term safety of the repository, which are linked to FEPs and safety functions.

In the study reported by Miller *et* al (2002)[12], two expert workshops were held with the purpose of comprehensively identifying the processes thought likely to occur in the subsurface. A list of processes was developed under a number of headings – physical, hydrogeological, geochemical and biological. In this case, international FEP lists were not used as a starting point because these do not provide detail on processes occurring during construction of underground facilities, and because such lists tend to be general and do not adequately characterise processes that are specific to local conditions. The significance of each process to site understanding and to repository performance was then assessed by expert judgement, and only processes considered to be highly significant to one or both of these areas were carried forward to the monitoring programme.

[11] Posiva (2012), *Monitoring at Olkiluoto – a Programme for the Period before Repository Operation*. Posiva report 2012-01.

[12] Miller B, Arthur J, Bruno J, Hooker P, Richardson P, Robinson C, Arcos D and West J (2002), *establishing baseline conditions and monitoring during construction of the Olkiluoto URCF access ramp*. Posiva report 2002-07.

Following this assessment, further parameters were screened out according to the following criteria:

- Not feasible to monitor.
- Not yet relevant.
- Related to human activity.
- Can be monitored indirectly by measuring another parameter.

Other approaches to examining potential perturbations and identifying parameters to be monitored have included closer alignment with safety assessment studies[13] and consideration of FEPs[13,14]. In the latter study, relevant FEPs were selected via a screening process from a comprehensive FEP database on the basis of their potential significance for the long-term safety of the repository. This was done for the following topics:

- Evolution of the EBS.
- Migration within the EBS.
- Geosphere (evolution of site and migration of radionuclides).
- Surface environment (evolution of site and migration of radionuclides).

Again, many of the relevant FEPs were not included in the monitoring programme for a variety of reasons, for example:

- They are so regular that it is not reasonable to monitor them specifically (e.g. radioactive decay).
- They can be monitored indirectly.
- They are better studied in the lab.
- They are too slow to measure (e.g. erosion) or only occur after several millennia (e.g. glacial processes).
- They are out of scope of the monitoring programme (e.g. human behaviour).

Such analysis has resulted in a provisional list of specific parameters to be monitored in relation to the EBS (Figure B-3). The EBS monitoring plan will become more focused and detailed on the basis of development work during the period 2012-2018.

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[13] Alexander W R and Neall F B (2007), *Assessment of Potential Perturbations to Posiva's SF Repository at Olkiluoto from the ONKALO facility*. Posiva Working Report 2007-35.

[14] Posiva (2012), *Features, events and processes (FEPs) for a KBS-3V type spent fuel repository at Olkiluoto.* Posiva Report 2012-07.

Objectives						Process	Targets
1: Long-term safety (site)	2: Site characterisation and modelling	3: Environmental impact	4: Feedback for constructors and design	5: EBS performance	6. Compulsory radiological monitoring		
Canister (monitoring possible in a mock-up)							
				X		Radiogenic heat production	Surface temperature
				X		Deformation of the copper overpack	Radial and axial strain
Buffer and backfill							
				X		Heat transfer	Temperature
				X		Water uptake	Moisture in buffer
				X		Swelling	Swelling pressure and pore pressure
				X		Mass redistribution	Buffer displacement and uplift
							Canister displacement
				X		Chemical changes in pore water	in situ pH (and other possible) measurements
Auxiliary components							
				X		Degradation of plugs and seals	Plug integrity
							Temperature, moisture, pressure

Figure B-3: Potential targets of EBS monitoring in Posiva's repository for spent fuel at Olkiluoto.