Contract Number: 622177

Deliverable D2.2:
Monitoring Parameter Screening: Test Cases

Work Package 2

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Contributor(s)	J. Farrow, M. White and Sally Scourfield (GSL); A. Chabiron (Andra); M. Jobmann and R. Gazul (DBETEC); B. Frieg (Nagra); J. Hart, E. Rosca-Bocancea and T. Schröder (NRG); A. Wildenborg (TNO); T. Karvonen (Saanio & Reikkola Oy); T. Pere and J. Hansen (Posiva Oy); H. Reijonen (Geological Survey of Finland); M. Morosini and D. Luterkort (SKB); A. Vokal (SURAO)
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Approved by:

This report has been approved by:

- Mansueto Morosini, Work Package 2 Leader, *15/04/2019*
- Johan Bertrand, the Modern2020 Project Co-ordinator (on behalf of the Modern2020 Project Executive Board), *08/05/2019*

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Executive Summary

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project is a European Commission project funded by the Euratom research and training programme 2014-2018. The Project is running over the period June 2015 to May 2019, and a total of 29 waste management organisations (WMOs), 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 monitoring programme during the operational phase, taking into account requirements of specific national programmes.

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

This report describes the outcomes from Task 2.2, in which seven test cases were undertaken, each one focused on identification of potential repository monitoring parameters through analysis of a recent safety case. These test cases were also used to test the application of the Modern2020 Screening Methodology. The Methodology was developed in Task 2.1 of the Modern2020 project, in which the relationship of repository monitoring to the post-closure safety case was investigated.

The Modern2020 Screening Methodology provides guidance on the steps that a WMO may take in identifying and managing a list of repository monitoring parameters, linked to processes, and repository monitoring strategies and technologies. The list of parameters is intended to form the basis for repository monitoring system design at each stage of a repository monitoring programme that evolves through the implementation of geological disposal. The context for the Screening Methodology is provided by the MoDeRn Monitoring Workflow, which was developed in a previous EC project on repository monitoring, and which describes the steps prior to screening (specification of monitoring objectives and identification of a preliminary list of monitoring processes) and those that come after parameter screening (design, operation and responding to monitoring results).

The test cases presented in this report are:

- Cigéo test case: The safety assessment for the planned repository for high-level waste (HLW) and long-lived intermediate-level waste (ILW-LL) in the Callovo-Oxfordian Clay in France.
- ANSICHT test case: The new safety assessment concept developed for a repository sited in clay in Germany.
- Opalinus Clay test case: The demonstration of disposal feasibility for spent fuel, HLW and ILW-LL in a clay host rock in Switzerland.
- OPERA test case: An evaluation of the technical feasibility and safety performance of a repository for low and intermediate-level waste (L/ILW) and HLW in the Boom Clay, in the Netherlands.
- TURVA 2012 test case: Posiva's 2012 safety case for disposal of spent fuel in crystalline rock in Olkiluoto, Finland.
- SR-Site test case: Long-term safety case for the final repository for spent nuclear fuel at Forsmark, Sweden.

- Reference Project 2011 test case: Update of the reference project of a deep geological repository in granite at a hypothetical locality, Czech Republic.

Note that, with the exception of the ANSICHT test case, the results from the test cases relate to this exercise only, and do not represent fully underpinned decisions on parameters that would or would not be monitored in monitoring programmes implemented by WMOs in the future. The ANISICHT test case represents a preliminary iteration of the monitoring programme that could be implemented in a geological repository programme in Germany.

The following conclusions can be drawn from the development and results of the test cases regarding identifying and screening repository monitoring parameters:

- Determining parameters to be monitored in an implementable and logical repository monitoring programme for the engineered barrier system (EBS) and near field is challenging but achievable. Finding a balance (appropriate to the national context and drivers) between monitoring everything possible and monitoring only what is valuable (when compared to the resources required to collect the data and the potential safety implications) is a key challenge. Consistent with IAEA and NEA guidance, a repository should be passively safe without relying on monitoring, and so it is important that all monitoring activities are carefully considered and their need justified.
- A parameter for monitoring may be justifiably selected for screening if 1) it is directly relevant to post-closure safety and/or retrievability, for example, through being directly linked to safety functions, or 2) it is indirectly related to post-closure safety; for example, monitoring during the operational phase can build further confidence in the safety case by demonstrating general thermal, hydraulic, mechanical, chemical and radiological (THMCR) understanding as well as validating performance (for some WMOs). This illustrates that a direct link to safety is not necessarily required for there to be value in monitoring a parameter.
- Further work on developing implementable monitoring programmes is ongoing for all WMOs. Activities undertaken in the test cases need to be extended to all relevant components of the underground repository system. There is also a need, in most programmes, to focus on more detailed aspects of monitoring programme design, such as selection of sensor type, number and locations. Detailed assessments of the impact of the monitoring system on the post-closure safety case (such as including sensors in models) will also need to be carried out.
- There is no common set of parameters that should be monitored in every repository monitoring programme. Instead, the parameters to be monitored in each programme will depend strongly on the specific drivers, constraints and objectives identified in the national and repository-specific context.
- To be useful and traceable in the future, the screening process and its results must be transparent and understandable to future generations and external stakeholders. Therefore, WMOs must give thought to both the format and the level of detail of how results and their underpinning justification will be presented.
- Decisions on parameter screening are more readily undertaken by programmes with detailed safety case approaches and repository performance models, and a more developed understanding of stakeholder expectations regarding monitoring. However, there are advantages to planning repository monitoring at an early stage, such as allowing sufficient time for technology development, ensuring design takes account of monitoring needs, building stakeholder confidence, and enabling some information/confidence requirements to be addressed through long-term experiments instead of or in addition to monitoring. Early thinking about monitoring also ensures that aspects of monitoring relevant to different stages (e.g. siting, construction, commissioning and operation) can be developed and implemented at the appropriate time.

The Modern2020 Screening Methodology was shown to be useful across the range of programmes involved in the task, is flexible and can be adapted to the needs of individual programmes. Its relative simplicity (although underpinned by detailed explanations) is appreciated, and, although the primary audience is technical monitoring specialists, may be helpful for engaging with external stakeholders on the topic of monitoring parameters.

A revised version of the Modern2020 Screening Methodology was developed in response to feedback from the test cases and is illustrated in Figure E.1. The figure shows how the Methodology is organised into three columns that take into account the interplay between processes, parameters, and technologies (monitoring strategies are considered in parallel with technologies).

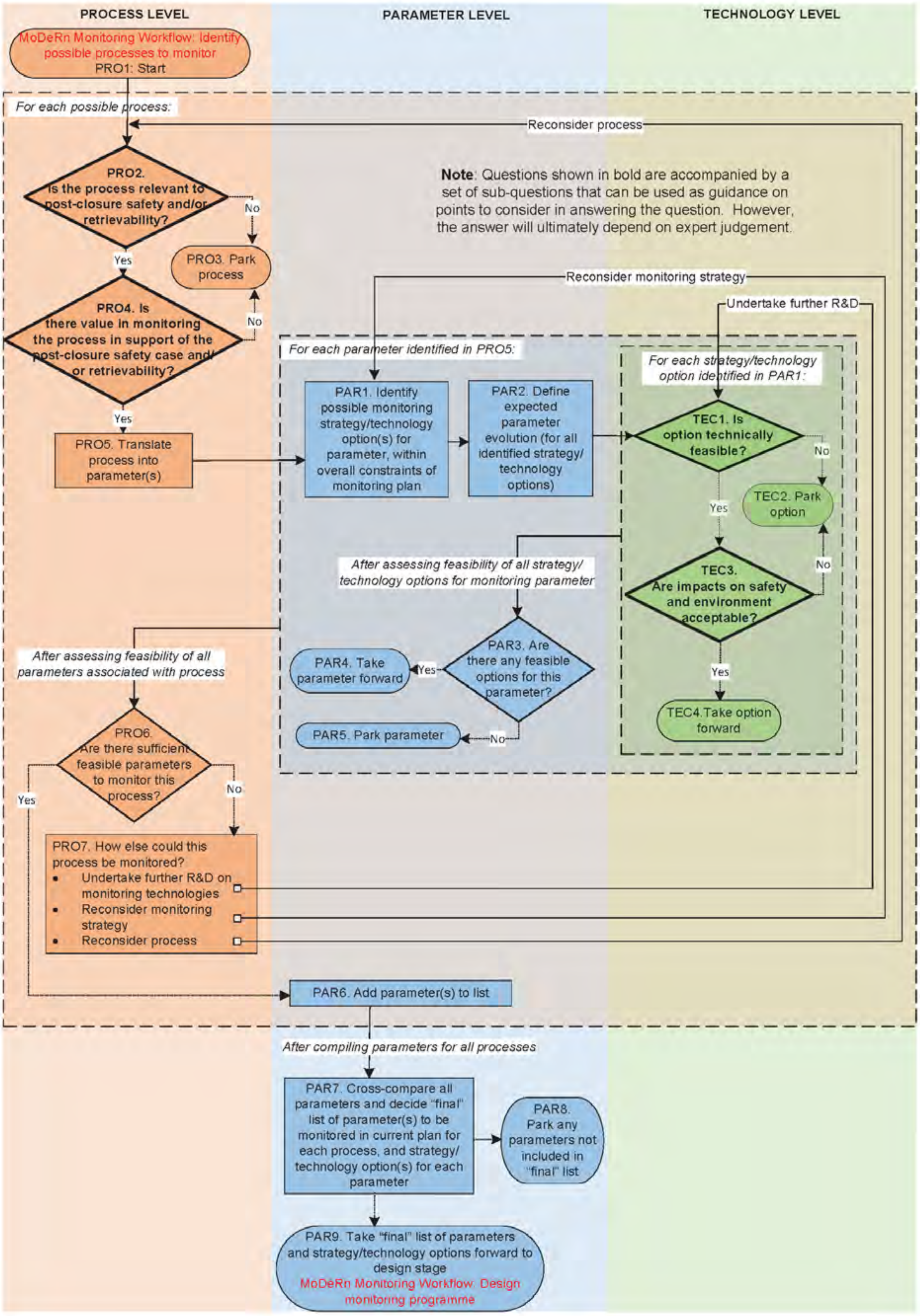

Figure E.1: Revised version of the Modern2020 Screening Methodology, following the test cases.

List of Acronyms

ADR:	Azimuthal deep resistivity
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation damage zone
FEPs:	Features, events and processes
HLW:	High-level waste
ILW:	Intermediate-level waste
ILW-LL	Long-lived intermediate-level waste
LiDAR:	Light Detection and Ranging
L/ILW:	Low- and intermediate-level waste
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
Modern2020:	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal
PARS:	Phenomenological Analysis of Repository Situations
QA:	Quality assurance
QC:	Quality control
RD&D:	Research, development and demonstration
RSC:	Rock Suitability Classification
RTD:	Resistance temperature detector
THMCR:	Thermal, hydraulic, mechanical, chemical and radiological
URL:	Underground research laboratory
URCF:	Underground rock characterisation facility
WMO:	Waste management organisation
WP:	Work package
ZFD:	Discrete fracture zone, part of the excavation damage zone (in French)

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 la Gestion des Dechets Radioactifs	Andra	France
Amberg Infraestructuras	Amberg	Spain
Arquimea	Arquimea	Spain
AREVA NC SA[1]	AREVA NC SA	France
CeskeVysoke Uceni Technicke v Praze	CTU	Czech Republic
DBE Technology GmbH	DBETEC	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	The 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

[1] In January 2018, Areva was renamed Orano.

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1 Introduction

1.1 Background

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project is a European Commission (EC) project funded by the Euratom research and training programme 2014-2018. The Project is running over the period June 2015 to May 2019, and a total of 29 waste management organisations (WMOs), 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 post-closure safety case and the wider scientific programme.
- 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 EBS Monitoring Plan in Finland, the Highly-active Industrial Pilot Experiment in France, the Long-term Rock Buffer Monitoring Experiment in France, and the Full-scale Emplacement Experiment in Switzerland. An assessment and synthesis of several 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, development and demonstration (RD&D) on monitoring for geological disposal.
- WP6: Communication and dissemination, to include an international conference, a monitoring school, and the Modern2020 Synthesis Report.

The Modern2020 Project focuses on monitoring of the underground repository system (including engineered barriers and near-field rock) during the operational phase[2] to support decision making and to build further confidence in the post-closure safety case (referred to as *repository monitoring* within the Project). This is where the greatest challenges lie in terms of strategy and technology, and where the greatest gains can be made through international collaboration. Challenges related to repository monitoring are associated with the slow rate at which the majority of relevant processes occur relative to the duration of the monitoring period, understanding the relevance of transient processes occurring on relatively short timescales to long-term performance, and the potential impacts of monitoring on passive safety.

Repository monitoring is undertaken in parallel with monitoring related to other objectives, including (MoDeRn, 2013):

- To support operational safety.

[2] According to the NEA (2012), the operational phase consists of three main stages: (i) the emplacement cell construction and waste emplacement stage; and (ii) the observation stage; (iii) closure of the facility.

- To support environmental protection.
- To support nuclear safeguards.
- To support repository programme governance and stakeholder engagement.

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 an integrated and coherent monitoring programme.

This report is Deliverable D2.2 of the Modern2020 Project and is one of three deliverables from WP2:

- Deliverable D2.1 (White *et al*., 2017) summarises the outcomes from Task 2.1, which addressed the link between repository monitoring programmes and the post-closure safety case, and developed a preliminary version of the Modern2020 Screening Methodology, a process for selecting parameters to include in a repository monitoring programme.
- Deliverable D2.2 (this report) describes the outcomes from Task 2.2, in which seven test cases were undertaken. These test cases focused on the identification of repository monitoring parameters in seven waste management programmes and were used to test the application of the Modern2020 Screening Methodology and inform the development of a revised version.
- Deliverable D2.3 (White *et al*., 2019) describes the outcomes of Task 2.3, which considered evaluation of monitoring results, development of response plans and decision-making processes.

1.2 Objectives of this Report

The objectives of this report are to:

- Demonstrate application of repository monitoring parameter screening methodologies in seven national programmes.
- Document the screening methodologies applied in each national programme and the outcome of their application.
- Reflect the impact of programme maturity on the ability to define an actual monitoring programme.
- Discuss the benefits of developing a monitoring programme at different stages of implementation.
- Provide guidance on what aspects of a monitoring programme could be developed at each stage of implementation (e.g. siting, construction, commissioning and different stages of operation).
- Present a revised version of the Modern2020 Screening Methodology, taking into account feedback from the test cases.

1.3 Scope and Approach

Task 2.2 considered seven post-closure safety cases, for repositories in France (Cigéo repository), Germany (ANSICHT safety case), the Netherlands (OPERA safety case), Switzerland (Opalinus Clay safety case), Finland (TURVA 2012 safety case), Sweden (SR-Site safety case) and the Czech Republic (Reference Project 2011), as outlined in Table 1.1.

For each post-closure safety case, a test case was undertaken to examine the development of monitoring programmes related to the safety case. At the start of the task, guiding instructions were developed to ensure that programme-specific work followed a common approach. The guiding instructions included a list of issues for each test case to address, split into the following categories: system description; parameters to monitor; added value with the engineered barrier system (EBS) monitoring; and monitoring results as support for decision making during the operational phase. The guiding instructions are reproduced in Appendix A. Test cases were instructed to focus on the issues in the "parameters to monitor" category, while system description and added value issues were intended to provide a supporting framework and could be described in less detail. It was recognised that decision making issues may be less developed, and test cases were asked to address them as far as possible in order to provide input to Task 2.3. The information on decision making provided in the test cases is analysed in White *et al*. (2019), and is not discussed in detail herein.

The approach used in each test case was specific to the programme stage, requirements and context of each national programme. It was recognised that development of a comprehensive screened list of monitoring parameters is a detailed and labour-intensive activity, particularly as it is necessary to understand and consider the expected evolution of candidate parameters in order to determine whether they can be effectively monitored. Therefore, in addition to progressing screening activities and identifying possible monitoring parameters, the focus of the work was on testing the methodologies that might be used in waste management programmes and understanding how these screening approaches work in practice.

Note that, with the exception of the ANSICHT test case, the results from the test cases relate to this exercise only, and do not represent fully underpinned decisions on parameters that would or would not be monitored in monitoring programmes implemented by WMOs in the future. The ANISICHT test case represents a preliminary iteration of the monitoring programme that could be implemented in a geological repository programme in Germany.

Table 1.1: Specification of participating test cases, comprising the responsible organisation and safety case considered.

WMO	Safety Case	Reference	Description
Andra	Cigéo	Andra (2016a; 2016b)	The safety assessment for Cigéo, the planned repository for high-level waste (HLW) and long-lived intermediate-level waste (ILW-LL) in the Callovo-Oxfordian Clay in France, based on the Safety Options Report 2016.
DBETEC	ANSICHT	Jobmann *et al.* (2017)	The new safety assessment concept developed for a repository sited in clay in Germany.
Nagra	Opalinus Clay	Nagra (2002a; 2002b)	Demonstration of disposal feasibility for spent fuel, high-level waste (HLW) and long-lived intermediate-level waste (ILW) in a clay host rock in Switzerland.
NRG	OPERA	Verhoef and Schröder (2011)	An evaluation of the technical feasibility and safety performance of a repository for low and intermediate-level waste (L/ILW) and HLW in the Boom Clay, in the Netherlands.
Posiva	TURVA 2012	Posiva (2012)	Posiva's 2012 safety case for disposal of spent fuel in crystalline rock in Olkiluoto, Finland.
SKB	SR-Site	SKB (2011)	Long-term safety for the final repository for spent nuclear fuel at Forsmark, Sweden.
SURAO	Reference Project 2011	Pospíšková *et al*. (2012)	Update of the reference project of a deep geological repository in granite at a hypothetical locality, Czech Republic.

The test cases were progressed by each WMO internally and were documented in standalone test case reports. These are reproduced as Appendices to this report[3]. In addition, integrated discussion of the test cases was undertaken at project workshops:

- A task kick-off meeting was held in Thalwil, Switzerland, in February 2016, to plan the work.
- Interim results of the test cases were presented and discussed at a workshop in Paris in March 2017.
- Final outcomes of the screening test cases were presented and discussed at a further workshop in Rome in June 2017.

This workshop included detailed feedback from the test cases on application of the Modern2020 Screening Methodology, which has been taken into account in development of a revised version of the Screening Methodology as presented in this report.

1.4 Report Structure

The remainder of this report is set out as follows:

- Section 2 presents a summary of the preliminary version of the Modern2020 Screening Methodology that was developed in Task 2.1 (White *et al*., 2017) (the full version is provided in Appendix B). This formed the basis for the screening carried out by the test cases.
- Section 3 summarises the seven test cases. Section 3.1 presents short summaries of each test case, focusing on what activities were carried out, the objectives of the respective monitoring programmes, the monitoring strategies envisaged and the processes and parameters identified through the work. Section 3.2 then presents a comparative table summarising relevant contextual information, aspects relating to the screening activities undertaken, and key outcomes of the test cases.
- Section 4 provides a discussion of the test case-specific information presented in Section 3, drawing together the main points of learning across all test cases. These fall into two main topics: the process followed by the test cases (Section 4.1), including discussions on when to develop a monitoring programme, and the results of the test cases (Section 4.2). The latter incorporates a parameter-wise compilation of the monitoring targets identified by the test cases, together with the justification and proposed monitoring strategy/ technology given in the test case.
- Section 5 presents the revised version of the Modern2020 Screening Methodology, which supersedes the preliminary version presented in Task 2.1 (White *et al*., 2017) and takes into account feedback from the test cases.
- Section 6 sets out the key conclusions that can be drawn from the Modern2020 Project regarding parameter identification and screening.
- A list of references is provided in Section 7.
- Appendix A provides the guiding instructions for the test cases.
- Appendix B provides the preliminary version of the Modern2020 Screening Methodology in full.
- Appendices C-I provide the test case reports:

[3] Note that there may be inconsistencies between the main part of this report and the test case reports included as appendices. This is due to the long timescale of Task 2.2 and the fact that updated information has been provided during the report review process that supersedes the information available when the test case reports were produced.

- Appendix C is the test case report for the Cigéo test case.
- Appendix D is the test case report for the ANSICHT test case.
- Appendix E is the test case report for the Opalinus Clay test case.
- Appendix F is the test case report for the OPERA test case.
- Appendix G is the test case report for the TURVA 2012 test case.
- Appendix H is the test case report for the SR-Site test case.
- Appendix I is the test case report for the Reference Project 2011 test case.

2 Modern2020 Screening Methodology

2.1 Introduction

In this section a summary of the Modern2020 Screening Methodology is presented. The Modern2020 Screening Methodology is a generic process for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. The preliminary version, as developed in Task 2.1 (White *et al*., 2017), was used as the basis for the screening in the test cases. It is summarised below (and reproduced fully in Appendix B) to provide the necessary background to the test case summaries and discussion of outcomes in Sections 3 and 4 respectively. The revised version of the Screening Methodology, which addresses feedback from the test cases, is presented in Section 5.

2.2 Summary of the Methodology

The Modern2020 Screening Methodology was developed to further elaborate the MoDeRn Monitoring Workflow, which was one of the outcomes from the MoDeRn Project (MoDeRn, 2013). The MoDeRn Monitoring Workflow envisaged development of a preliminary parameter list that would be screened for feasibility in order to identify the parameters to be included in the monitoring programme.

Monitoring of the repository during the operational phase has the potential to introduce safety hazards, could impact passive safety following closure, and poses logistical challenges. Therefore, it is important that the inclusion of each parameter in a monitoring programme is carefully considered and its need justified. This is consistent with both IAEA safety requirements (IAEA, 2011), which state that a repository should be passively safe and not rely on a post-closure monitoring programme to provide assurance of safety; and NEA guidance (NEA, 2014), which states that it is important to select a limited number of parameters through identification of those which would sufficiently demonstrate the attainment or approach to the passive safety status of the disposal system.

The Modern2020 Screening Methodology was developed as an extension to the MoDeRn Monitoring Workflow in support of the development of a traceable and justified list of monitoring parameters. However, the Screening Methodology assumed that the starting point for development of a list of parameters might be a list of possible processes rather than a list of parameters, and the MoDeRn Monitoring Workflow was modified accordingly (Figure 2.1).

The Modern2020 Screening Methodology (and the MoDeRn Monitoring Workflow within which the Screening Methodology sits) is envisaged as an iterative process that would be repeated multiple times during the operational phase of the repository. Interactions with the regulators and other stakeholders would occur during operation of the Methodology in a manner consistent with the regulatory process and with the WMO stakeholder engagement plan. The Screening Methodology might be re-run in parallel with a periodic update to the post-closure safety case or in response to unexpected results from the monitoring programme (responding to monitoring results is discussed further in White *et al*. (2019)).

One consequence of the Screening Methodology being iterative is that parameters are not screened out of the process at any stage. Instead, parameters are *parked*, so that they remain within the system and can be considered in the next iteration of the Methodology. Parking of parameters requires traceable screening decisions to be made, for example in evaluation tables or in databases. Templates for recording screening decisions were discussed with Task 2.1, but were not included in the guidance on the Modern2020 Screening Methodology presented in White *et al*. (2017). However, some templates have been developed as part of the test cases reported herein. Furthermore, parking of parameters is not considered to lead to a need for onerous re-evaluation of parameters at each iteration of the Screening Methodology; each WMO can choose not to re-evaluate the parked parameters if they so wish.

The philosophy that underpins the Modern2020 Screening Methodology is to consider each potential monitoring process in turn at three interlinked levels:

- Processes.
- Parameters.
- Technologies (feasibility).

First, the potential relevance of the process and value in monitoring it, with respect to the post-closure safety case, is evaluated. For processes considered to be both relevant and valuable, one or more parameters that could be used to monitor the process are identified. For each parameter, possible monitoring strategy and technology options are identified and the expected parameter evolution with respect to each option determined. The technical feasibility of each strategy and technology option is then judged against the expected parameter evolution for each option in turn. Once technical feasibility has been assessed, the outcome is reviewed to determine whether there are technically feasible options that allow the parameter to be taken forward. This evaluation allows consideration of whether there are sufficient parameters to monitor each process identified earlier. If there are insufficient parameters to monitor the process, the earlier steps in the Methodology would have to be revisited. Finally, the Methodology includes cross-comparison of monitoring parameters to check completeness and appropriate redundancy, and to ensure that an integrated monitoring programme is developed.

The Methodology is intended to be indicative and flexible rather than prescriptive, and can be regarded as a template that can be adapted by individual WMOs to suit particular needs. Flexibility includes, for example, the possibility to modify the starting points and approaches as appropriate for each waste management programme. Examples of how the Screening Methodology has been modified are provided in the test cases presented herein.

The preliminary version of the Modern2020 Screening Methodology developed in Task 2.1 and used as an input to the work reported herein (Task 2.2) is illustrated in Figure 2.2.

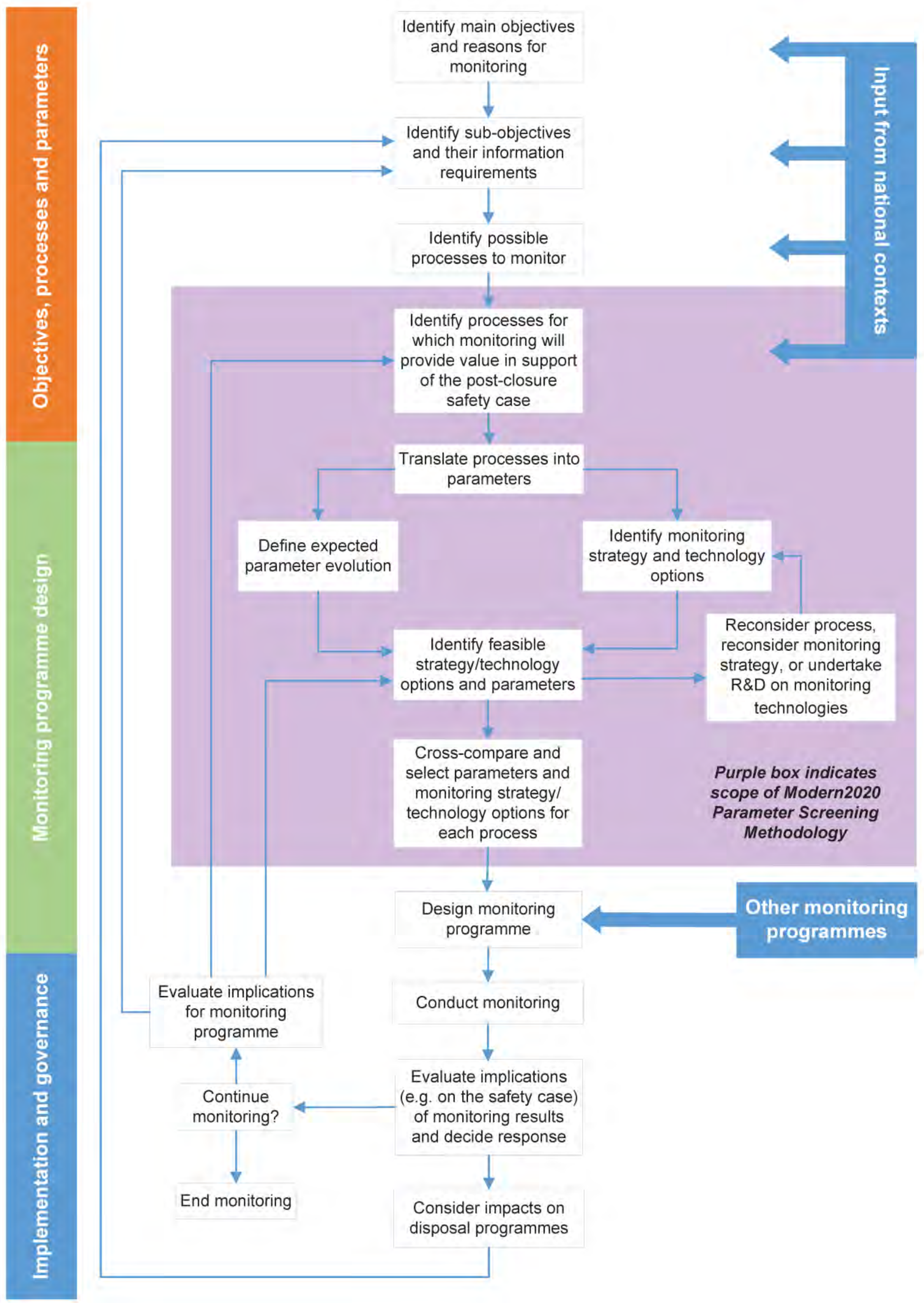

Figure 2.1: The MoDeRn Monitoring Workflow revised in Modern2020 Task 2.1 to account for the further consideration of methods for parameter screening undertaken in that task (White *et al*., 2017)). In addition to an elaboration of the middle part of the Workflow, changes from the version developed in the MoDeRn Project (MoDeRn, 2013) include 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..

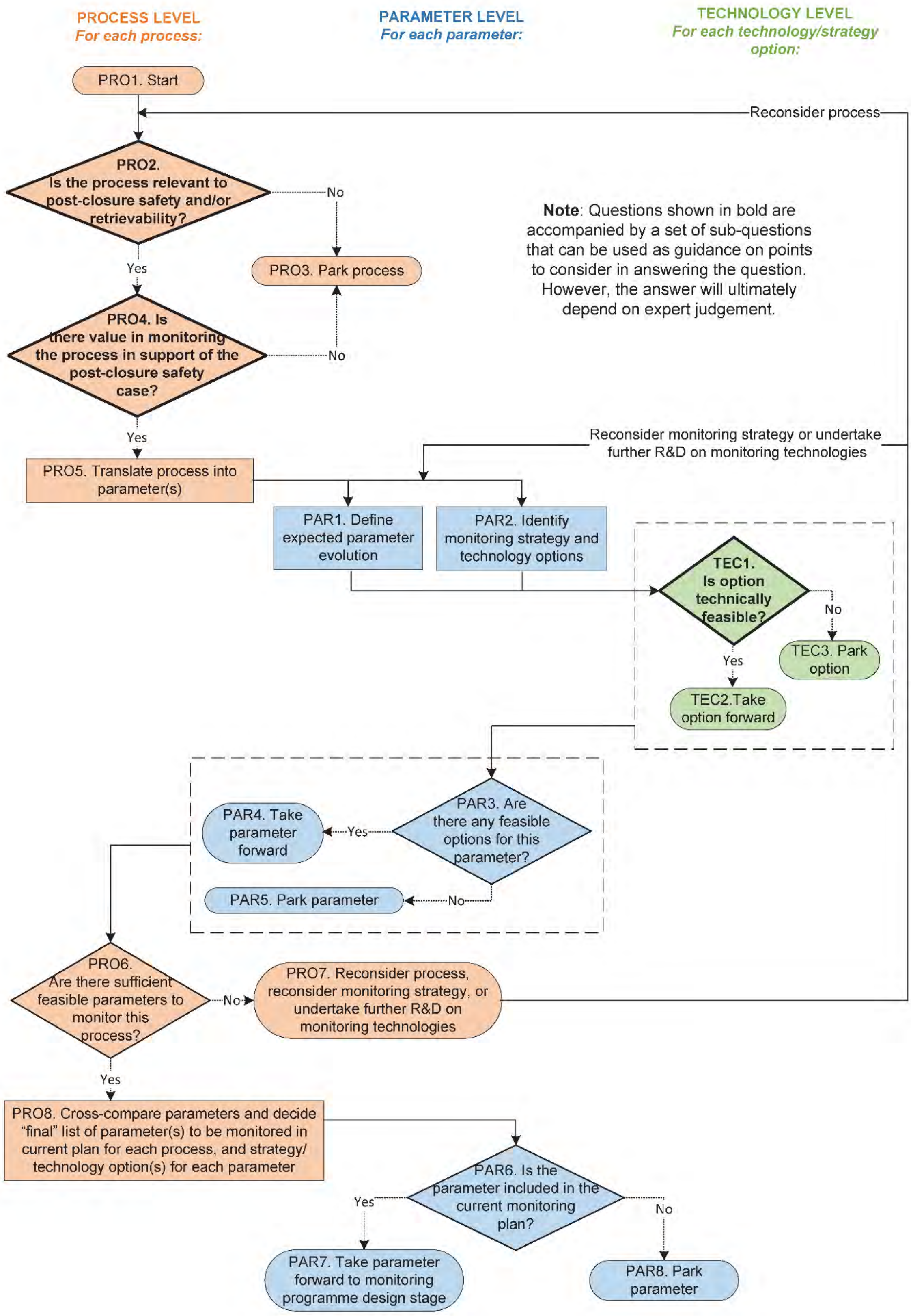

Figure 2.2: Illustration of the preliminary version of the Modern2020 Screening Methodology developed in Task 2.1 and used as an input to Task 2.2 (White *et al.*, 2017).

3 Summary of Test Cases

This section summarises the test cases undertaken in Task 2.2.

Section 3.1 presents summary descriptions of each test case, focusing on how identification and screening (where applicable) of monitoring parameters have been undertaken by each organisation, and the results of this process. The test cases also provided descriptions of the EBS/host rock system, monitoring objectives and monitoring strategy; sufficient information is included about these to provide the necessary background to the parameter identification/screening activities.

Most test cases also provided feedback on and/or suggested changes to the Modern2020 Screening Methodology, based on the experience of applying it in a specific context. These comments and how they have been addressed are not detailed in this report (as it focuses on outcomes rather than methodology) and hence are not included in the test case summaries. However, the test case reports are included in full as appendices to this report, providing the original feedback as well as further contextual information.

Section 3.2 presents a comparative overview table summarising key contextual information (relating to both disposal concept and repository monitoring drivers), aspects relating to the screening activities undertaken, and key outcomes (including, where appropriate, the parameters identified for monitoring).

Note that, with the exception of the ANSICHT test case, the results from the test cases relate to this exercise only, and do not represent fully underpinned decisions on parameters that would or would not be monitored in monitoring programmes implemented by WMOs in the future.

3.1 Test Case Summaries

This section provides the test case summaries, as follows:

- Section 3.1.1, the Cigéo test case, which is provided in full in Appendix C.
- Section 3.1.2, the ANSICHT test case, which is provided in full in Appendix D.
- Section 3.1.3, the Opalinus Clay test case, which is provided in full in Appendix E.
- Section 3.1.4, the OPERA test case, which is provided in full in Appendix F.
- Section 3.1.5, the TURVA 2012 test case, which is provided in full in Appendix G.
- Section 3.1.6, the SR-Site test case, which is provided in full in Appendix H.
- Section 3.1.7, the Reference Project 2011 test case, which is provided in full in Appendix I.

3.1.1 Cigéo Test Case

Andra plans to dispose of high-level waste (HLW) in the Cigéo geological disposal facility in the Callovo-Oxfordian Clay of the Paris Basin[4]. The design of the facility envisages that HLW will be emplaced in small-diameter tunnels referred to as disposal cells (Figure 3.1). The disposal cells will be lined with a low-carbon steel sleeve to facilitate the emplacement process and retrievability of the waste if so desired in the future (Andra, 2016a). This design formed the basis of the Cigéo test case (Appendix C).

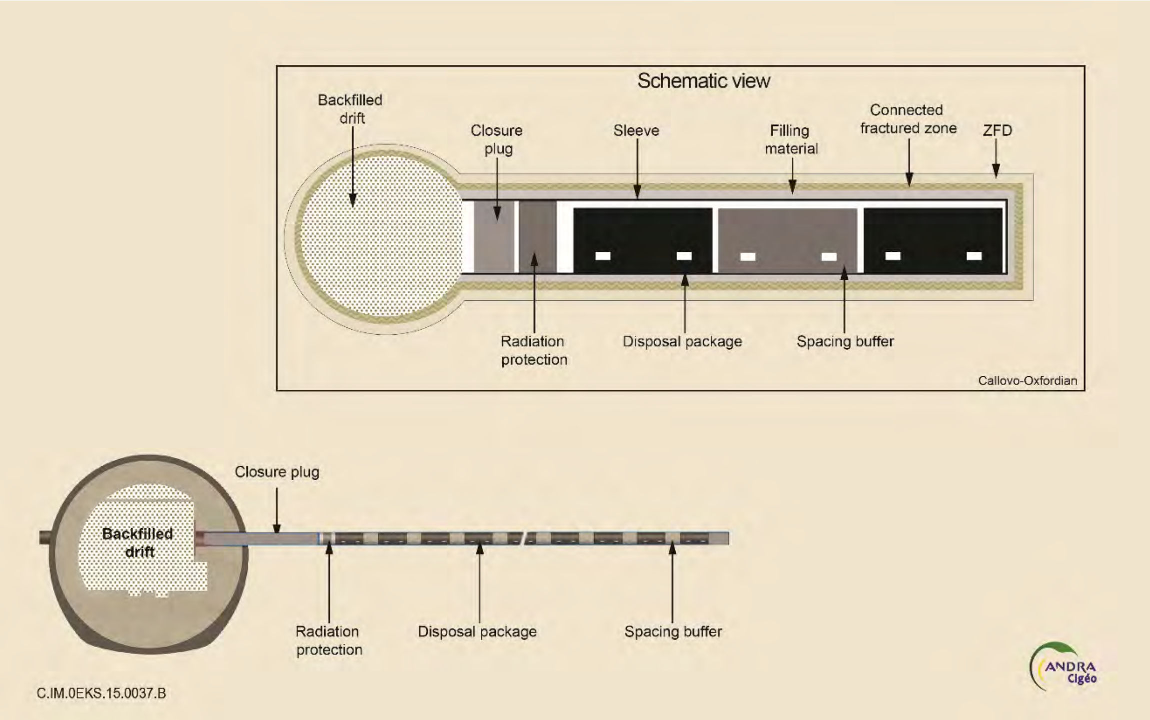

Figure 3.1: Illustration of the HLW disposal cell design. ZFD is the French acronym for the discrete fracture zone, part of the excavation damage zone.

Andra's monitoring programme for post-closure and retrievability has the following objectives:

- To check the ability to retrieve waste packages.
- To check that post-closure safety is ensured as expected, by:
  - Tracking the evolution of the repository system during the operational period to confirm it is evolving as expected.
  - Increasing confidence in the understanding of processes affecting long-term safety.

It is currently envisaged that the repository monitoring programme will be based on instrumentation of a limited number of disposal cells. Monitoring will commence during the first period of repository operation, known as the Industrial Pilot Phase, with some cells heavily instrumented, allowing monitoring of all selected parameters.

Andra has developed a structured process for identification of monitoring parameters, which starts with the identification of the post-closure safety functions and retrievability function of each component of the repository, followed by identification of phenomenological processes that may potentially affect these safety functions. Quantification of such phenomenological processes leads to the definition of selected indicators (parameters) that can be monitored.

For the purposes of the test case, Andra extended its parameter identification methodology by starting with a consideration of the main phenomenological processes that could occur in the

[4] It is planned that ILW-LL will also be disposed of in the Cigéo facility.

disposal cell and surrounding near-field rock. The combination of these processes corresponds to the expected evolution of the disposal cell and near field during the operational and post-closure phases. Five main processes were identified for the HLW cell (illustrated in Figure 3.2):

- Heat production by HLW glass.
- Time dependent deformation of the clay host-rock.
- Thermo-hydraulic-gas transient.
- Oxidation of the clay host-rock.
- Corrosion of metallic parts.

The five processes were screened using the Modern2020 Screening Methodology. First, the relevance to post-closure safety and/or retrievability was assessed by consideration of all of the supplementary guidance questions included in the Methodology (see Appendix A), with the answers feeding into an expert judgement assessment of the overall relevance. Three processes were parked at this stage: heat release from the HLW glass, resaturation of the near-field rock and bacterial activity.

Next, the value in monitoring the process was considered. Andra assessed the processes according to their value in relation to both long-term safety and retrievability. All processes other than the thermal-hydraulic-gas transient were judged to have value for one or the other of these purposes, and parameters were identified that would allow monitoring of this set of processes (Table 3.1).

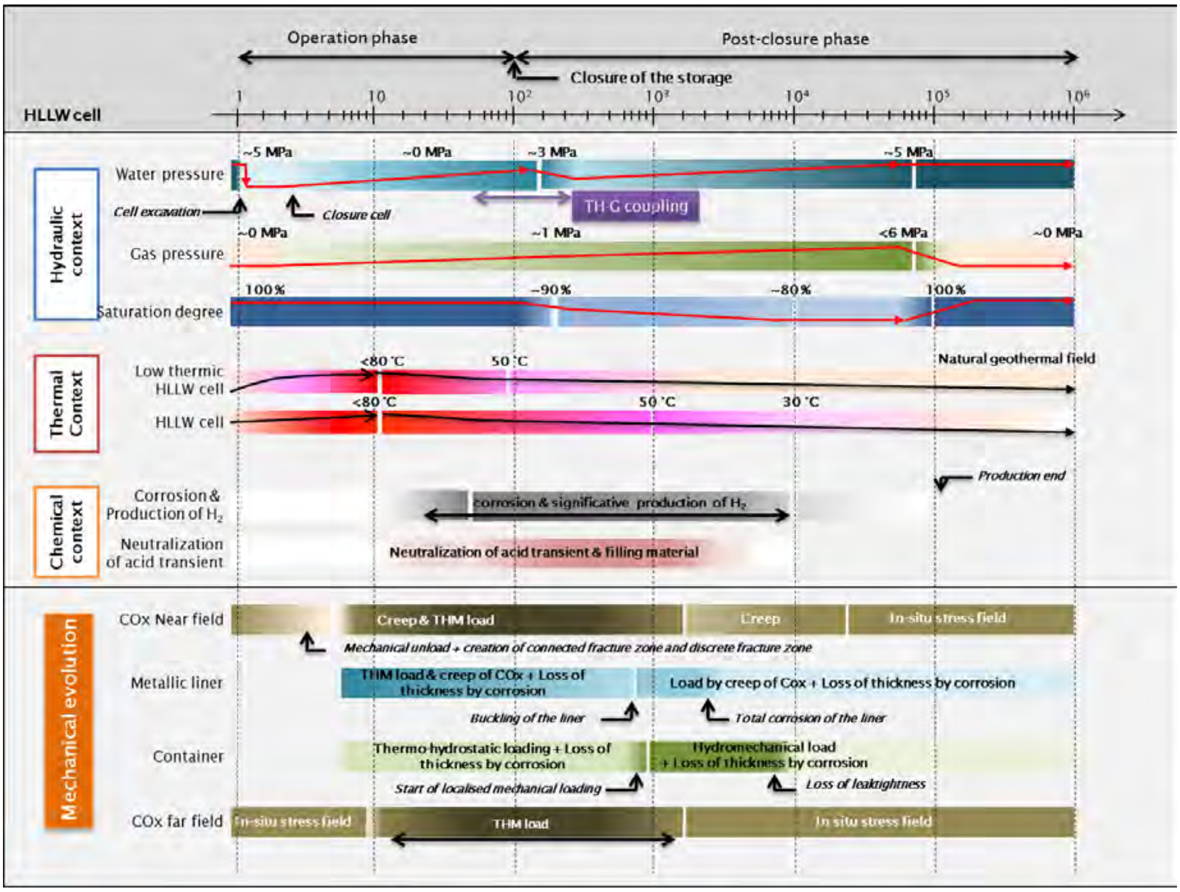

Figure 3.2: Illustration of the processes and their couplings influencing the evolution of the disposal cell and near field.

Table 3.1: Monitoring processes and parameters identified in the Cigéo test case.

Phenomenological process and relevant component	Selected parameter
Thermal evolution of the near field clay host rock	Temperature of the clay host rock
Thermal induced pressurisation of the clay host rock	Effective stress of the clay host rock
	Pressure in the clay host rock
Thermal evolution of the disposal cell	Temperature at the surface of overpack
Generation of H_2 in the disposal cell	None selected as yet
Metallic sleeve deformation	Sleeve displacement
	Thermo-mechanical load on overpack
Mechanical evolution of the clay host rock	Clay host rock creep
Corrosion of the overpack	Corrosion rate
Neutralization of the acid transient by the filling material	pH of the water in the disposal cell

The test case report argues that parameter evolution can be evaluated through consideration of the likely scale of changes rather than specific values. For example, for monitoring the deformation of the cell sleeve, Andra argues that precision on the order of millimetres to centimetres is required for this process. In Andra’s view, this is sufficient to move on to later steps of the Modern2020 Screening Methodology (i.e., modelling of the expected evolution in detail is not necessarily needed for the purpose of defining requirements on monitoring technologies, at least in early iterations of the Methodology).

For each parameter, feasible techniques for monitoring the parameter were identified by Andra. Hence, all of the parameters were determined to be feasible and could be included in a monitoring programme at this stage.

3.1.2 ANSICHT Test Case

The site selection process for a geological repository for spent fuel, HLW and L/ILW in Germany has recently restarted. This process includes consideration of clay and crystalline host rocks. The ANSICHT Project developed a safety assessment methodology for a repository in clay host rocks based on two sites, one in northern Germany and one in southern Germany (Jobmann *et al*., 2017). The repository concept for the northern Germany site, which considers a repository constructed within the Barremian-Hauterivian Clay, was considered for the ANSICHT test case (Appendix D). This concept envisages disposal of canisters containing spent fuel and HLW in vertical boreholes, as illustrated in Figure 3.3.

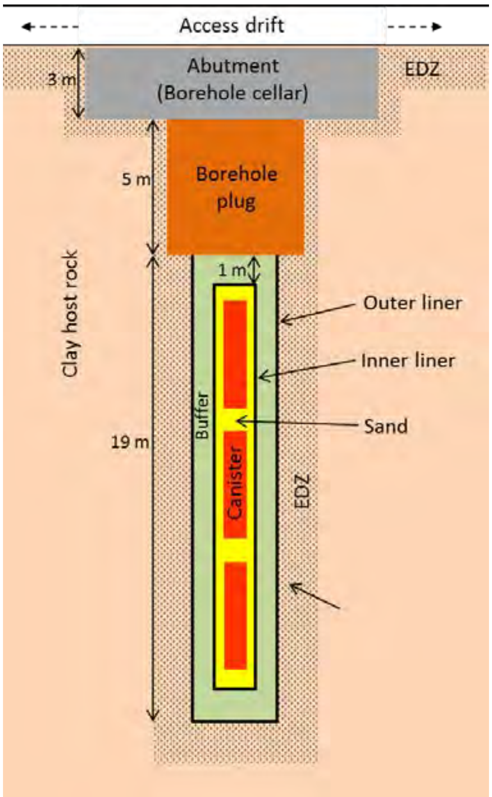

Figure 3.3: Illustration of the disposal concept for the northern Germany site considered in the ANSICHT test case. The borehole plug would be constructed from bentonite and the abutment would be constructed from cementitious materials.

In the ANSICHT test case, the aim of repository monitoring is to systematically monitor the properties of the geological sequence, the hydrogeological conditions, the waste and the impact of the repository on the environment. High-level goals to be achieved by a suitable monitoring concept were defined as:

- The monitoring concept has to be consistent with the current German regulatory framework.
- The concept shall be based on the MoDeRn Monitoring Workflow (MoDeRn, 2013).
- The concept shall allow, to the extent possible, verification that the identified performance targets or safety function indicators for the geotechnical barrier can be met.
- The concept shall allow, to the extent possible, verification that the integrity of the host rock or the containment providing rock zone is not endangered by repository implementation.

- The monitoring concept shall be developed as a *process concept* which explicitly includes learning effects during the whole operational phase. The process concept shall be structured by milestones.
- Monitoring results shall be included in decision sequences as basic information, especially for the successive implementation of new seals and the associated monitoring systems to be installed.
- The monitoring concept shall be designed so that it is possible to assess the possibilities and limits of post-closure monitoring during the operational phase whilst taking into account the emplacement concept or the sequence of emplacement.
- The monitoring concept shall be updated at least every 10 years in parallel with the required update of the safety case.

The monitoring strategy envisaged in the ANSICHT test case is monitoring of both waste and dummy canisters (heaters) within the repository emplacement area (Figure 3.4). The approach is to focus monitoring on specific emplacement fields, specific emplacement boreholes, and specific seals. In order to benefit from the experience gained in previous monitoring activities, monitoring will start with the first emplacement field in which waste will be emplaced (identified as 1 in Figure 3.4). Monitoring in a further five emplacement fields is envisaged in the test case in order to address potential spatial variability within the repository footprint (Figure 3.4).

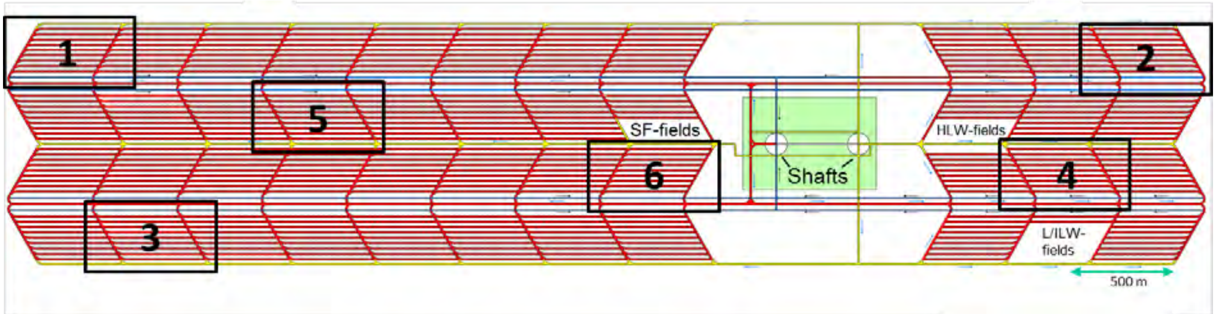

Figure 3.4: Potential arrangement of monitoring fields as envisaged in the ANSICHT test case. Monitoring fields are indicated by the black rectangles with the numbering indicating the order in which the monitoring fields will be implemented.

The ANSICHT test case focused on monitoring of the emplacement borehole seal, i.e. the borehole plug and the borehole abutment (Figure 3.3), and, in particular, monitoring related to the performance targets for the plug and abutment. These performance targets have been set such that, if they are met, the overall safety function of the borehole seal (to "minimise the advective flow into the borehole and out of it") will be achieved. The targets are based on a combination of modelling and experiments, and are subdivided into hydraulic and mechanical targets. They include targets set for permeability following saturation, swelling pressure, expansion of the bentonite element of the seal (listed as "*loosening-up of the bentonite element*"), and limits on tensile stresses acting on the bentonite (listed as "*bentonite shall be free of tensile stresses*").

Potential monitoring processes were identified through review of an existing catalogue of features, events and processes (FEPs) relevant to the Barremian-Hauterivian clay, and by selecting those processes that may influence the performance targets. Ten processes were identified as being potentially able to influence these performance targets (Table 3.2), and these formed the starting part for the screening process. For the ANSICHT test case, the approach that was adopted to screening was to use the supplementary questions included as part of the Modern2020 Screening Methodology. Each question was evaluated using expert judgement and processes included if one answer to the supplementary question was yes (i.e. if there was one specific reason to include the process in the monitoring programme).

Following consideration of the relevance of the process to post-closure safety and the potential value of monitoring the process, the list of processes was evaluated to identify parameters to monitor and the expected evolution of the parameter. Translation of processes into parameters was undertaken using expert judgement; seven monitoring parameters were identified through this activity. The expected evolution of each parameter was determined using numerical simulations.

For the test case, the strategy of monitoring boreholes was evaluated and a couple of technology options were identified for each parameter. The technical feasibility for monitoring of the strategy/technology combination was assessed using the supplementary questions included in the Modern2020 Screening Methodology. For this step, a single no answer to the supplementary questions would result in the strategy/technology combination being parked. However, no strategy/technology combination was parked as a result of this screening and all seven parameters were included in the final list of parameters.

Table 3.2: Processes and associated parameters identified in the ANSICHT test case for monitoring of the emplacement borehole seal.

Process	Parameter
Fluid inflow from the drift above through abutment and bentonite plug	Permeability
Mechanical load on the abutment from above (backfill mass, rock pressure at later times)	Vertical pressure
Convergence of the emplacement borehole (after emplacement)	Parked following process screening
Fluid pressure from below due to thermal expansion and gas generation	Pore pressure
Saturation evolution of the bentonite plug	Water saturation
Swelling pressure evolution of the bentonite plug	Swelling pressure
Chemical alteration of minerals (swelling pressure reduction)	Parked following process screening
(Heat flow) temperature evolution in bentonite plug	Temperature
Fluid flow through the bentonite plug out of the borehole	Permeability
Displacement of the abutment in direction to the drift above	Vertical displacement

3.1.3 Opalinus Clay Test Case

The Swiss disposal concept envisages that spent fuel and HLW disposal canisters would be emplaced horizontally in a centred position on bentonite block pedestals in small-diameter tunnels excavated in the Opalinus Clay of northern Switzerland as illustrated in Figure 3.5 (Nagra, 2016). The Opalinus Clay test case (Appendix E) was based on information from Nagra's Project Opalinus Clay (Nagra 2002a; 2002b; and 2002c), which presented a comprehensive description of the post-closure radiological safety assessment of a repository, and more recent work in support of the ongoing Swiss site selection process.

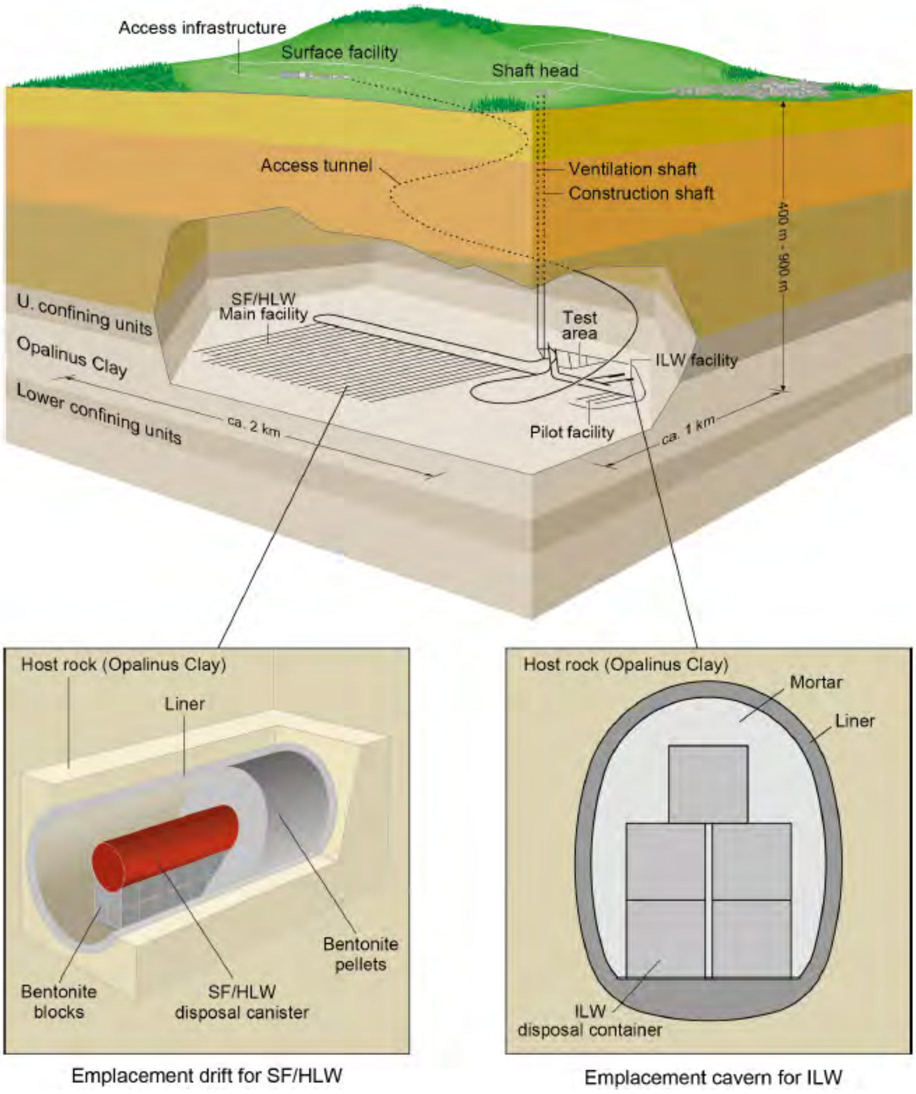

Figure 3.5: Possible layout for a deep geological repository for spent fuel, HLW and long-lived ILW in the Opalinus Clay, Switzerland (from Nagra, 2016).

Nagra's disposal strategy is based on the concept of monitored long-term geological disposal. This concept envisages an extended period of monitoring, during which radioactive waste can be retrieved without undue effort (KEG, 2003), and the emplacement of a representative fraction of the waste in a pilot facility that:

- Serves as a demonstration facility for emplacement technology.
- Provides information on the behaviour of the barrier system and to check predictive models.
- Allows early detection of any unexpected and undesirable system evolution.

- Provides input for decisions regarding the commencement of operations and eventually the closure of the entire facility.

In addition to monitoring of the pilot facility, the disposal rooms of the main facility and the access tunnels can be monitored. Furthermore, a test facility, or facility for underground geological investigations, will provide additional information in support of decision making, and some of this information can be classified as monitoring.

Nagra developed and applied its own iterative methodology for identifying and screening parameters, rather than trialling the Modern2020 Screening Methodology. However, the two approaches are based on many of the same ideas, and equivalent steps between them are identified throughout the test case report. Steps in the Nagra methodology not explicitly represented in the Modern2020 Screening Methodology are accounted for in the supplementary guidance questions. In addition, Nagra has developed a database tool to assist in the application of its own approach, which can be used (for example) to document relationships between phenomena, parameters and technologies, and to generate tables for use in reports and/or presentations.

Nagra's approach used a number of pre-existing concepts and tools in the Swiss programme, including:

- FEPs: an existing Opalinus Clay FEP list and database that includes 482 FEPs in 18 categories.
- Requirements: these include regulatory guiding principles and Nagra-developed provisional requirements on the disposal system and on the system elements.
- Assumptions made in the existing Reference Case model for safety assessment.
- Safety function indicators: Nagra-defined parameters that measure the consequences of potentially detrimental phenomena on post-closure safety functions, together with criteria that, if met, show that the safety functions are intact.

Step 1: Identification of potentially detrimental safety-relevant phenomena

Nagra initially considered phenomena rather than processes, so as to include discrete events that might be detected by monitoring as well as continuous processes. Starting from the FEP list, FEPs known with confidence to a) have zero or negligible chance of occurrence, b) have a minimal detrimental impact on the disposal system, or c) occur over too long a timescale to be detected by monitoring, were screened out. The remaining FEPs were combined and/or reformulated to reflect potentially detrimental phenomena.

These phenomena were then checked against all existing requirements and reference case model assumptions, and those having potential to compromise any requirement or assumption were deemed to be "potentially relevant".

Step 2: Parameters relevant to long-term safety

The next step was to identify potentially relevant parameters, not yet considering the feasibility or value of monitoring them. These were considered to be parameters that:

- Quantify, influence (in terms of timing, rate, spatial extent etc.) or indicate the occurrence of a potentially-relevant phenomenon.
- Define a requirement on the system or system components.
- Define reference safety assessment model assumptions.
- Are safety function indicators.
- Are required for the indirect evaluation of another candidate parameter that cannot be determined directly. These requirements were added later, at the feasibility stage assessment of the primary parameter).

Step 3: Candidate monitoring parameters

The next step was to screen the safety-relevant parameters to identify parameters that have the potential to evolve significantly during the monitoring period.

Step 4: Parameters amenable to monitoring in practice

This step determined whether the identified potentially relevant parameters can be measured or monitored in practice, and if so, where and at what stage of repository development. Strategic options include monitoring in an on-site test facility, another underground research laboratory (URL) or a surface laboratory; in the pilot facility (before or after backfilling), in the repository emplacement rooms (before backfilling) or access ways (before or after backfilling); and geosphere monitoring (from the surface or via boreholes). In general, monitoring in the pilot facility is preferred to monitoring in the repository.

Possible technologies available for monitoring each parameter were considered in terms of the need for maintenance and/or repeated calibration; means of data transmission (wired/wireless); and technology readiness level. Example evaluations of some technologies are presented in the test case, with parameter evolution considered implicitly. This step is a work in progress for Nagra, and the outcome of the test case is a partial listing of options judged to be potentially available for some parameters.

Step 5: Models and criteria (assessment of usefulness)

This is the final step in Nagra's screening approach. Relevant criteria (as used in framing requirements and/or reference model assumptions, as well as safety function indicator criteria) were assigned to each parameter. An assessment was then made of whether, on the basis of modelling, there is any uncertainty that the criterion will be satisfied within the monitoring timeframe. If there is such uncertainty, the parameter was deemed useful to monitor. If there is confidence that the criterion will be met over the monitoring timeframe but uncertainty thereafter, it may be useful to monitor the parameter to build confidence in model validity. If there is high confidence that the criterion will always be satisfied, the usefulness of monitoring is considered to be limited to increasing the confidence of other stakeholders in the validity of models.

At the end of these steps, Nagra identified two parameters that may be useful to monitor, as there is uncertainty about whether relevant criteria will be met that could be addressed through monitoring during the operational period:

- Temperature in the near-field host rock.
- Fluid (porewater) pressure in the near-field host rock.

3.1.4 OPERA Test Case

The management of radioactive waste in the Netherlands is based on a policy of long-term interim surface storage. To maintain preparedness for geological disposal, research is undertaken into geological disposal. This research includes the six-year OPERA research programme, which commenced in 2011 (Verhoef and Schröder, 2011) and ended in 2018. The OPERA programme included development of a safety case for geological disposal of spent fuel, HLW, ILW, LLW and depleted uranium. In this concept, disposal of spent fuel from research reactors and HLW is envisaged to take place in small-diameter tunnels, with the waste overpacked in concrete supercontainers (Figure 3.6).

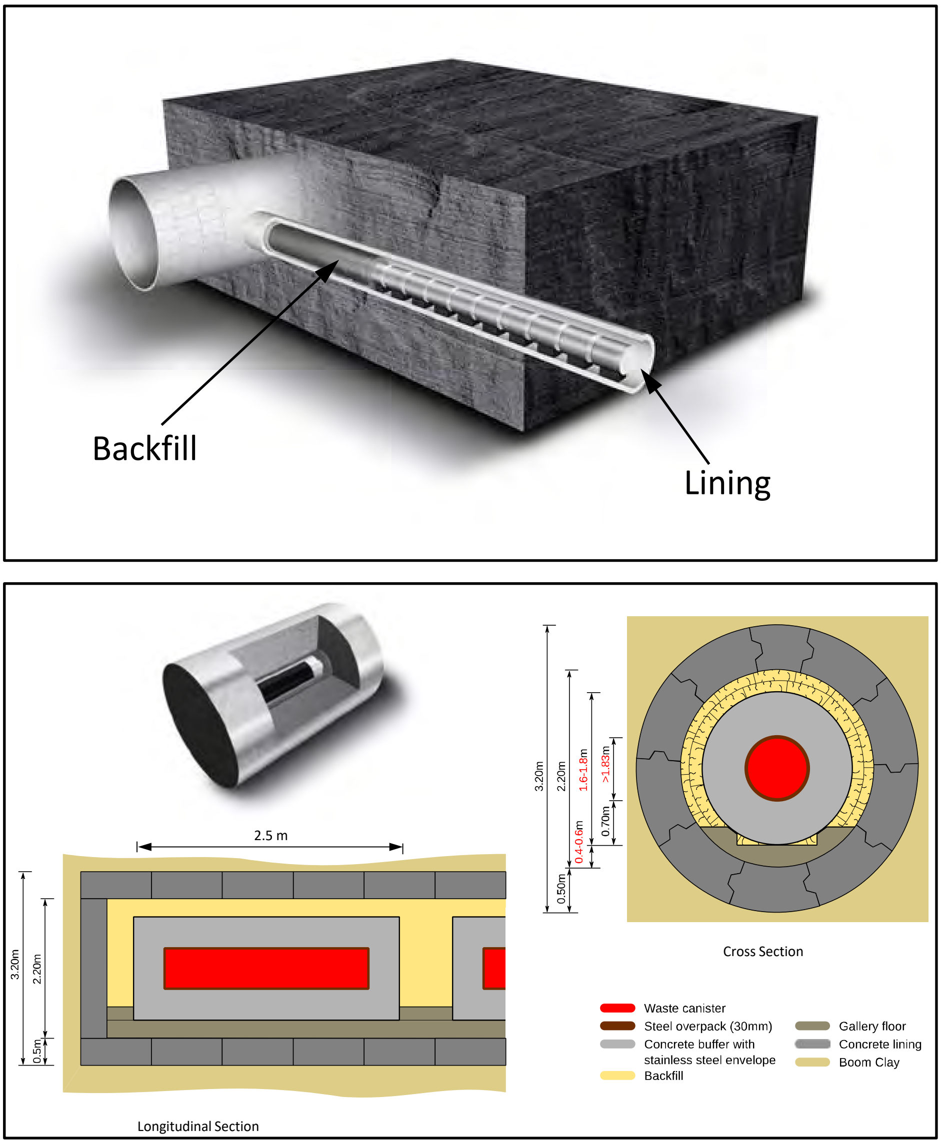

Figure 3.6: Illustration of the disposal concept considered in the OPERA safety case. Top figure shows the configuration of the disposal tunnels and bottom figure shows cross-sections and 3D image of the supercontainer.

The topic of repository monitoring is currently being addressed in the Netherlands in a generic fashion, and no guidance or specific requirements on the repository monitoring programme are available. Therefore, NRG had to elaborate more specific objectives for its test case, focusing on the initial identification of processes and parameters for all repository components, increasing understanding of the role of monitoring within the post-closure safety case in the Dutch programme, and the identification of uncertainties and knowledge gaps.

The test case (Appendix F) followed a two-stage approach, consisting of:

1. Stage 1: Derive preliminary parameter list.
2. Stage 2: Undertake a test screening of the preliminary parameter list.

Stage 1: Preliminary parameter list

The approach used to develop the preliminary parameter list was as follows:

- Identify and describe the safety functions of each repository component.
- Define relevant scenarios (including normal evolution and alternative evolution scenarios).
- For each scenario, link safety functions to FEPs based on the existing OPERA FEP database.
- Screen the resulting FEP list to identify a generic list of processes, together with affected safety functions and applicable scenarios, by removing irrelevant FEPs such as those relating to disposal in salt host rocks.
- Systematically describe processes and related parameters for each barrier.

The outcome was a list of candidate processes and parameters for each barrier in the disposal concept, which formed the basis for the screening undertaken in Stage 2.

Stage 2: Screening

For the sake of available resources, screening (using the Modern2020 Screening Methodology) was undertaken for processes relevant to the OPERA supercontainer only, as this concrete structure is the main engineered barrier of the OPERA disposal concept. Following the analysis in Stage 1, eleven processes provided the basis for the screening test (Table 3.3).

These processes were screened for relevance to safety. No processes were parked in this step, as all of the processes were derived from consideration of safety functions. Then these processes were screened for value; however, it was argued that, in the current state of the Dutch programme, there are no justifiable reasons for parking individual processes and so all processes were screened in (i.e. no processes were parked).

Association of processes with parameters was undertaken as part of Stage 1 of the OPERA test case. For evaluation of the technical feasibility of monitoring the identified parameters, a general summary of thermal, hydraulic, mechanical, chemical and radiological (THMCR) parameter evolution was prepared (Figure 3.7). By simple expert judgement, a more condensed list of "representative parameters" was then derived. Five parameters were judged, at this stage in the process, to be less relevant, more difficult to measure or not to result in measurable changes in parameter values over the monitoring period (Table 3.3). However, these parameters were not parked (screened out) by a systematic feasibility analysis, due to the current lack of sufficient information in the Dutch programme that would support such an analysis.

Defining and evaluating strategy/technology options is considered to be less urgent in the Dutch programme and was only undertaken at a high level. In NRG's opinion, not enough detail is available to quantitatively assess the technical feasibility of monitoring the identified parameters, but a first attempt was made as part of the test case, with the result that the monitoring of all parameters was considered to be generally feasible or to require more information for a judgement to be made. The OPERA test case also concluded that if options are not technically feasible now, there is sufficient time available in the Dutch programme to develop them to the required level.

Table 3.3: Processes and associated parameters identified for the supercontainer as candidate monitoring parameters in the OPERA test case.

Title	Process	Parameter
Carbon steel overpack		
SC-1 - Mechanical disturbance	Mechanical disturbance of carbon steel overpack as a result of corrosion (stress corrosion cracking, cold cracking, welding)	Pressure Displacement
SC-2 - Steel corrosion	Steel corrosion following water ingress, resaturation	Redox potential H_2 presence
Concrete buffer		
SC-3 - Thermal evolution	Thermal evolution	Not taken forward (process parked) following considerations of parameter evolution or relevance
SC-4 - Water ingress	Water ingress – resaturation, flooding	Not taken forward (process parked) following considerations of parameter evolution or relevance
SC-5 - Geochemical evolution	Geochemical evolution due to porewater/concrete interaction	pH Redox potential Porewater chemistry
SC-6 - Mechanical load (external forces)	Mechanical load evolution due to external forces	Pressure Displacement
SC-7 - Mechanical load (thermal processes)	Mechanical load evolution due thermal processes (expansion)	Not taken forward (process parked) following considerations of parameter evolution or relevance
SC-8 - Corrosion induced cracking	Corrosion induced cracking of concrete buffer	Not taken forward (process parked) following considerations of parameter evolution or relevance
Steel envelope		
SC-9 - Steel corrosion	Steel corrosion due to interaction with Boom Clay porewater	Redox potential H_2 presence
SC-10 - Mechanical load	Mechanical load evolution as a result of external forces	Pressure Displacement
Supercontainer		
SC-11 - Release of radiation	Potential radiation exposure	Not taken forward (process parked) following considerations of parameter evolution or relevance

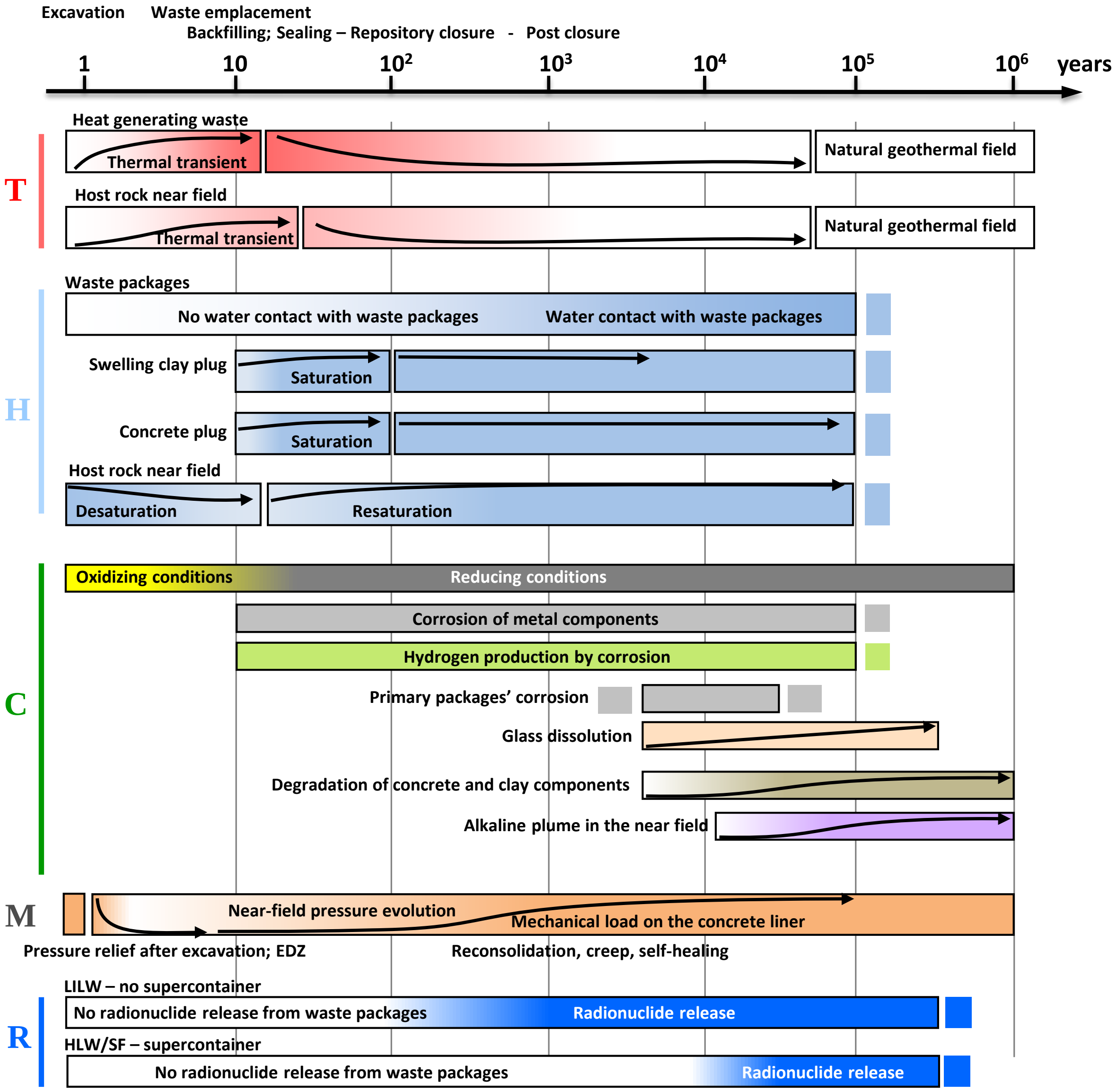

Figure 3.7: General overview of parameter evolution used for screening in the OPERA test case.

3.1.5 TURVA 2012 Test Case

Posiva's safety concept for the geological disposal of spent nuclear fuel is based on the KBS-3V design and the characteristics of the Olkiluoto site in which the repository is under construction. In the KBS-3V design (Figure 3.8), the spent nuclear fuel assemblies will be placed into copper canisters with cast iron load-bearing inserts, and the canisters will be emplaced vertically in individual deposition holes bored in the floor of deposition tunnels excavated in crystalline host rock. The canisters will be surrounded by a swelling bentonite clay buffer material that will separate them from the bedrock.

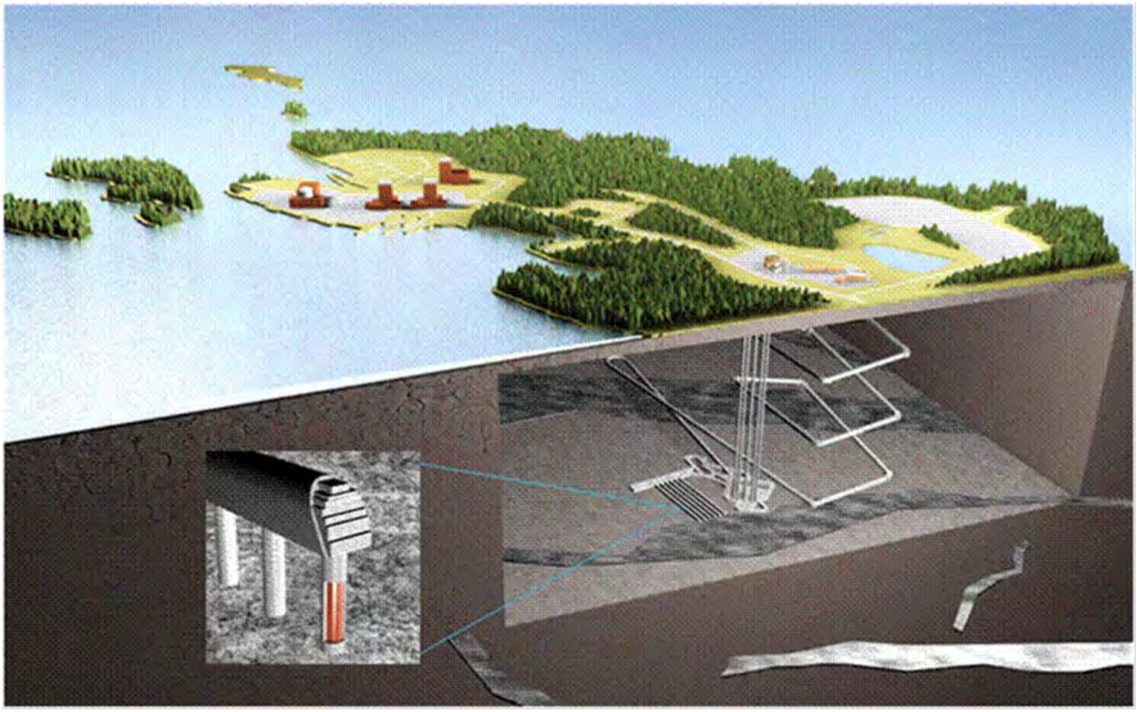

Figure 3.8: Illustration of the Olkiluoto repository considered in the TURVA 2012 test case.

Posiva has an existing monitoring programme, consisting of five sub-programmes:

- Hydrogeochemistry.
- Rock mechanics.
- Surface environment.
- Hydrology and hydrogeology.
- EBS monitoring.

The EBS monitoring sub-programme has not yet been substantially developed. In Posiva's safety case strategy, it is anticipated that most knowledge about the repository system and its evolution will be obtained through a combination of laboratory and *in situ* tests. Quality control and quality assurance procedures will be used to check that the as built state of the repository is consistent with assumptions made in the post-closure safety case. A limited role is foreseen for direct monitoring of EBS components, which can only occur while each component is accessible (i.e., before the next barrier is emplaced). For some EBS monitoring, it is possible that monitoring could be done indirectly via monitoring of host rock properties that influence the performance of the EBS (see below for examples). In addition, Posiva has an extensive programme of site characterisation and research activities, including its Rock Suitability Classification (RSC) (McEwen *et al*., 2012) process for assessing the suitability of each deposition hole location before waste is emplaced into it.

Posiva established a working group to perform screening using the Modern2020 Screening Methodology, and developed a proforma template for recording the results (Appendix G). Posiva's safety case for the spent fuel repository at Olkiluoto is currently being updated, so most information and references supporting the test case are from the earlier TURVA 2012. However, updated requirements, where available, have been used as input.

The starting point for the screening was the performance targets set for each component of the EBS within Posiva's requirements management system. These performance targets have been defined such that, if they are met, the safety functions will be fulfilled.

For each performance target, the relevant EBS component was identified, together with one or more relevant process(es). An assessment was then made of whether there is relevance and value for post-closure safety. One or more parameter(s) that could be used to monitor each process were identified, and a high-level, qualitative expected evolution defined for the process/parameter(s) in question. A short description of how monitoring could be done was then developed (if several options exist, all were described), and technical feasibility assessed for each option (recorded as "yes" or "no" with associated discussion). An overall assessment of whether the parameter should be monitored was then determined, together with identification of key uncertainties and how they can be resolved, and discussion of how the monitoring results could be used to elucidate EBS behaviour.

Results are presented in the test case report (Appendix G) in three tables relating to different EBS components:

- Canister, for which six performance targets were considered.
- Buffer, for which eight performance targets were considered.
- Backfill, including the deposition tunnel plug, for which five performance targets were considered.

Once each performance target was screened, the resulting processes and parameters were compiled in a table listing the processes of relevance to the performance targets, associated parameters of interest and, for each parameter the result of the screening (Table 3.4):

- The parameter is parked.
- The parameter will be investigated through quality assurance (QA)/quality control (QC), full-scale test/demonstrator, or *in situ* single component tests.
- The parameter will be monitored during the operational phase.

In the test case, for the canister, buffer and backfill, all parameters will be investigated through QA/QC, full-scale demonstrators and *in situ* tests (i.e. no direct operational monitoring). Groundwater flow and chemistry (parameters indirectly related to the canister, buffer and backfill) will be monitored throughout construction and operations. Additionally, seismicity and temperature in tunnels (parameters indirectly related to the canister and buffer), will be monitored throughout construction and operations.

In situ tests will be used to gather knowledge regarding canister geometry (at installation and dismantling), and will also be used for both the buffer and backfill, to gather knowledge on mineralogy, chemistry, geometry, dry and bulk density, water content (all at installation and dismantling), and swelling pressure (via sensors). In addition, pore structure at installation and dismantling will be monitored in relation to the buffer only, and relative humidity (via sensors) and piping and erosion (via visual observation at dismantling) will be monitored in relation to the backfill only.

Table 3.4: Processes and associated parameters identified in the TURVA 2012 test case. Parameters in parentheses would be monitored indirectly with respect to the full-scale or *in situ* test (e.g. in surrounding groundwater).

Process	Parameter	Component	Result of Screening: How Addressed				
			Parked	**QA/QC**	**Full-Scale Test**	**Single Component *In Situ* Test**	**Operational Monitoring**
Seismic events, Reactivation/ displacement	Seismicity monitoring	Canister					X
	Rock displacement	Canister		X			X
	Rock displacement velocity*	Canister	X				
Metal corrosion	Groundwater chemistry (sulphides, oxygen, etc.)	Canister			(X)	(X)	X
	Corrosion potential	Canister	X				
	Composition	(Canister) buffer and backfill		X	X	X	
Glaciation	Maximum long-term pressure load, design issue	Canister		X			
Stress redistribution	Canister geometry changes	Canister			X	X	
Heat transfer	Temperature**	Canister		X	X	X	X
Mineral alteration	Buffer composition	(Canister)/ Buffer		X	X	X	
Water uptake and swelling (density homogenisation)	Geometry	Buffer		X	X	X	
		Backfill			X	X	
	Density (dry and bulk)	Buffer		X	X	X	
		Backfill		X	X	X	
	Water content, degree of saturation	Buffer		X	X	X	
	Swelling pressure	Buffer			X	X	
		Backfill			X	X	
	Mineralogy	Buffer		X			
		Backfill		X			
	Piping and erosion	Backfill			X	X	
	Pore structure	Buffer		X	(X)	(X)	
Water uptake and swelling (saturation)	Water content and distribution	Backfill			X	X	

Process	Parameter	Component	Result of Screening: How Addressed				
			Parked	QA/QC	Full-Scale Test	Single Component *In Situ* Test	Operational Monitoring
	Relative humidity	Backfill			X	X	
	Pressure (in different parts of backfill)	Backfill			X	X	
	Mineralogy	Backfill		X			
	Dry density	Backfill		X			
	Water content	Backfill		X			
	Relative humidity	Backfill			X	X	
Water uptake and swelling (swelling pressure development)	Pressure (Swelling pressure)	Backfill			X	X	
	Pressure (plug lead through)	Backfill	X				
Erosion	Density (at start and in dismantling)	Buffer			X	X	
		Backfill			X	X	
	Leakage water quantity and composition (through/past plug)	Backfill					X
	Groundwater composition	Backfill			(X)	(X)	X
	Swelling clay content	Backfill		X			
	Geometry	Backfill		X			
Leaching	Mineralogy	Buffer		X	X	X	
	Chemistry	Buffer/ ground-water		X	X	X	X
Groundwater recharge and water exchange (dilution)	Groundwater chemistry	Buffer			(X)	(X)	X
Deformation	Density	Buffer		X			
	Mineralogy	Buffer		X	X	X	
Aqueous solubility and speciation	Groundwater chemistry	Backfill			(X)	(X)	X
	Chemistry	Backfill		X			
	Mineralogy	Backfill		X			

*Rock displacement velocity is parked with respect to monitoring to build further confidence in the post-closure safety case, but will be monitored to meet other objectives, for example for safeguards reasons.

**Temperature would be measured using non-intrusive methods from access tunnels.

3.1.6 SR-Site Test Case

SKB has submitted a licence application for a spent fuel repository in Forsmark, Sweden, based on the SR-Site safety assessment (SKB, 2011). The repository would be based on the KBS-3V concept, in which copper canisters with a load-bearing cast iron insert containing spent fuel are surrounded by bentonite clay, deposited at approximately 500 m depth in groundwater saturated, granitic rock (Figure 3.9). The planned repository layout is illustrated in Figure 3.10.

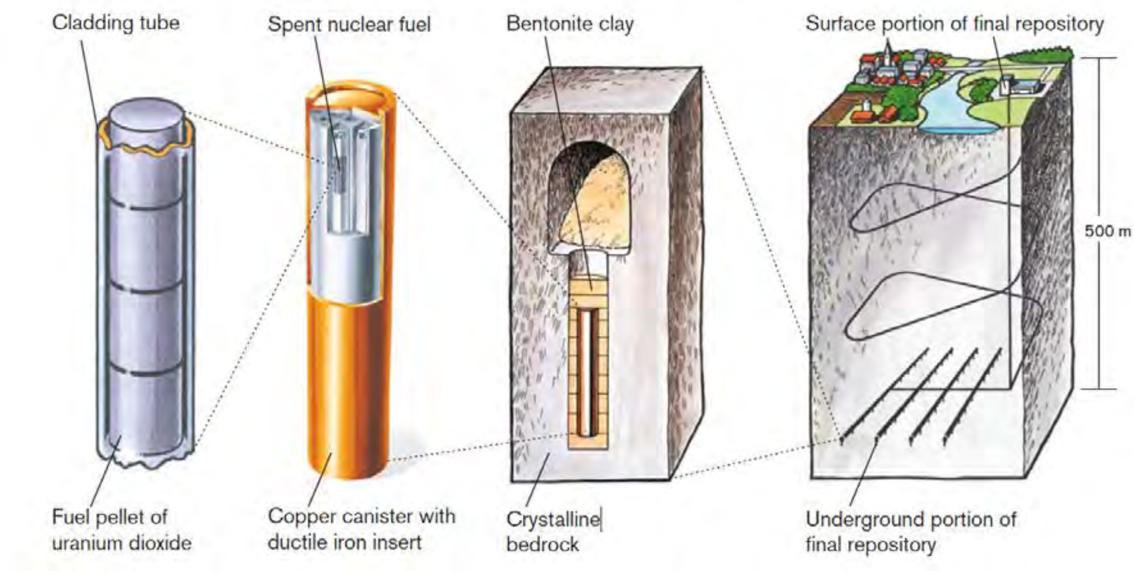

Figure 3.9: Illustration of the KBS-3V concept for disposal of spent fuel.

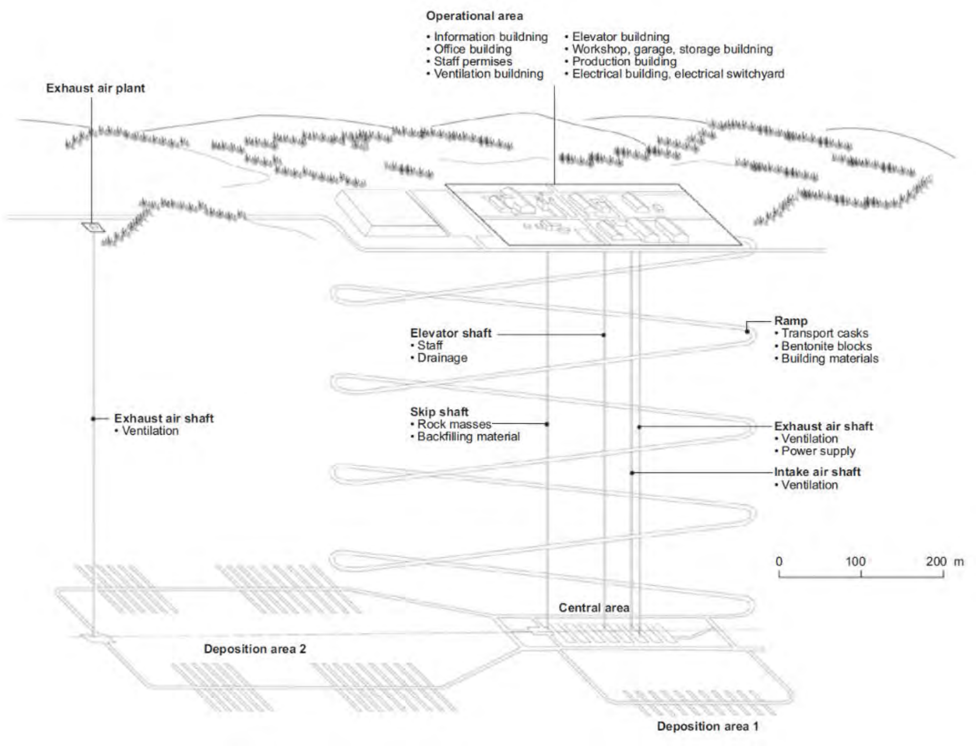

Figure 3.10: Illustration of the planned layout of SKB's repository showing the location of the underground functional areas (Access, Central and Deposition areas) and the surface facilities.

SKB has performed many experiments concerning the function of barriers at the Äspö Hard Rock Laboratory in south-eastern Sweden. These experiments have included extensive monitoring of system performance and provide knowledge of how the KBS-3V system will perform over long periods (e.g. the Prototype Repository experiment, for which operation commenced in 2001 (Svemar *et al*., 2016) and will be continued at least until 2020 (SKB, 2017)). Based on knowledge gained from such activities, SKB has concluded that direct measurements from gauges installed in the buffer and canister may be difficult to interpret and may jeopardise the function of the barrier. Observations that support such a conclusion include:

- In the Prototype Repository experiment, a rise in the measurements recorded in the majority of the pore water pressure sensors was observed immediately after drainage of the experiment was shut off (Goudarzi and Johannesson, 2005). This was interpreted to be the result of water flowing along the pressure sensor cables, even though installation of the sensors had included an attempt to mitigate such flow.
- Also in the Prototype Repository experiment, total pressure cells located close to each other gave significantly different total pressure measurements (Goudarzi and Johannesson, 2005). Other total pressure sensors have provided measurements inconsistent with relative humidity sensors located in the same volume SKB has concluded that deciding which of these sensors provide values that most closely resemble the actual values is challenging, and requires extensive intervention and calibration activities, which is not possible before dismantling.
- After dismantling of the Temperature Buffer Test (Åkesson, 2012) some of the sensors were re-calibrated and were shown to have drifted about 5-10% during the five-year test. In SKB's view, it is a significant challenge to predict the drift of monitoring sensors over extended monitoring periods (i.e. decade-long monitoring periods).

On the other hand, important information on the development of the barriers may be obtained by measuring the composition of the groundwater surrounding the repository in conjunction with specific long-term field experiments that are excavated and evaluated after a certain period.

Additionally, there are other types of monitoring that SKB is undertaking, including environmental monitoring for environmental impact assessment (EIA) purposes, and monitoring of the geosphere for characterisation purposes. In practice, all of this monitoring contributes to one monitoring system (Figure 3.11) (SKB, 2007).

Nonetheless, the function of the repository shall be monitored, even after emplacement of the spent fuel, but the primary purpose of any EBS monitoring undertaken by SKB will not be to identify faults, mistakes or deviations in the manufacturing and installation procedure/process. These tasks are handled through the quality control programme.

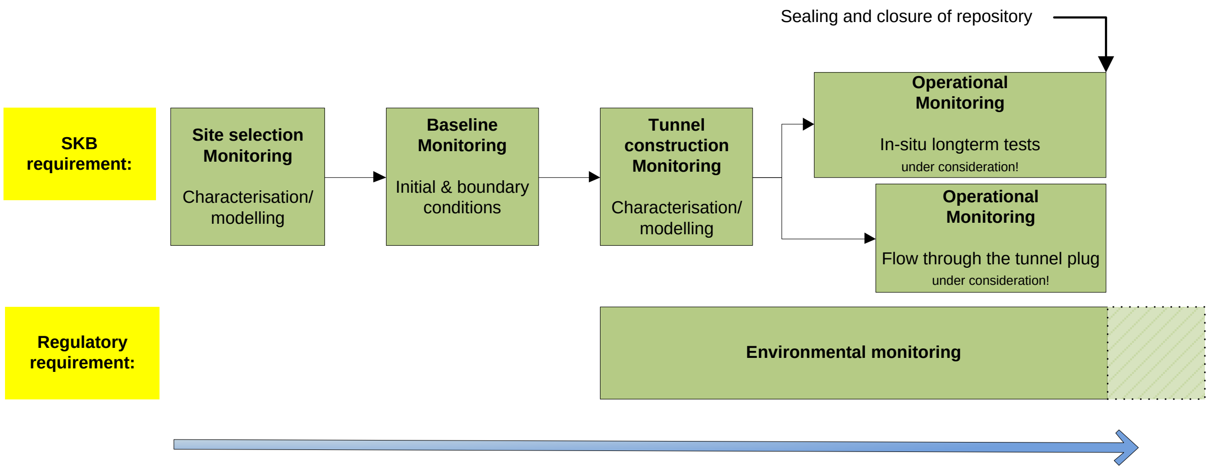

Figure 3.11: Schematic sequencing of different type of monitoring and their objectives in SKB's programme.

In SKB's test case (Appendix H), the starting point for identifying parameters was safety functions (rather than processes), for which relevance to safety has already been established, and for which relations/interdependencies of processes have already been considered within the SR-Site performance assessment (SKB, 2011). This was considered by SKB to be more workable because processes are often coupled, so it is difficult to assess their relevance to post-closure safety if considered in isolation.

In order to quantitatively evaluate safety, safety functions are related to measurable or calculable quantities, often in the form of barrier conditions. These are referred to as safety function indicators. Furthermore, in order to determine whether a safety function is maintained or not, quantitative criteria against which the safety function indicators can be evaluated over the period covered by the safety assessment are established. These are referred to as safety function indicator criteria.

Screening was undertaken for three safety function indicators, relating to different barrier components: hydraulic conductivity / swelling pressure (backfill), charge concentrations of cations (buffer) and copper thickness (canister). These indicators were chosen to illustrate different monitoring strategy elements. For each process (safety function indicator), the Modern2020 Screening Methodology was followed and the outcomes of each step tabulated (Table 3.5).

Table 3.5: Monitoring parameters, parameter options and plans identified in the SR-Site test case.

Monitoring Parameter	Parameter Option and Monitoring Plan
Loss of buffer mass due to piping and erosion affecting hydraulic conductivity and swelling pressure	In the calculations of buffer erosion in the post closure safety assessment for different inflow conditions to the deposition tunnel and deposition holes a limited flow past the plug was assumed. For some cases a tight plug reduces the buffer erosion in certain deposition holes. Hence a tight plug increases the robustness of the repository. The flow past the plug can however not be directly coupled to the safety functions of the buffer or backfill. *Impact on passive safety*: As there are no installations in the buffer/backfill there cannot be any impact of the monitoring system on the monitoring.
Electrical conductivity of water around the backfill and buffer for chemical erosion process	Monitoring of groundwater chemistry through sampling at repository level is already performed. This is done in the framework of the host-rock monitoring programme. *Impact on passive safety*: This strategy entails no monitoring of the active repository and does not risk to jeopardise it.
Copper thickness of the canister	*In situ* batch-experiments with copper coupons as proxy for canister for weight-loss analysis, retrieved after different periods. There is no monitoring plan but is considered in the planning. *Impact on passive safety*: This strategy entails no monitoring of the active repository and does not risk to jeopardise it.

3.1.7 Reference Project 2011 Test Case

The Czech programme is at an early stage of implementation, currently focusing on siting. Limited previous work has been undertaken on developing a repository monitoring programme, and consequently the Reference Project 2011 test case (Appendix I) focused on the identification of possible monitoring parameters rather than screening to decide which should be monitored.

The main components in the Czech concept are the canister, buffer, backfill, openings (host rock affected by excavation work), and other components (including plugs, grouting and construction materials) (Pospíšková *et al.*, 2012). These components can fulfil their safety functions only under certain host rock environment conditions, which SURAO split into external and internal factors. A total of 13 safety functions have been identified across all components, and are listed in the test case report. Expected behaviour of the EBS is formulated in terms of high-level statements of expectation of the identified safety functions being fulfilled for each component.

In the Reference Project 2011 test case (Appendix I), possible parameters to monitor were identified through i) analysis of safety functions and performance/safety assessment assumptions (i.e., parameters needed to verify the assumptions), and ii) discussions with Czech researchers, particularly those who have been involved in relevant URL RD&D activities (including testing the monitoring of specific parameters).

Technical feasibility was not explicitly assessed as part of the test case, although consideration of potential methods for monitoring parameters has started. It is expected that potential monitoring technologies will be tested in URLs in future experiments, and then technologies selected for use in the repository based on such tests.

SURAO believes that the Modern2020 Screening Methodology is a useful tool for realising all aspects of monitoring programme development, but has not applied it yet because the Czech programme is not yet sufficiently mature.

3.2 Overview of Scope, Context and Outcomes of Test Cases

Table 3.6 presents a comparative overview table summarising key contextual information (relating to both disposal concept and EBS monitoring drivers), aspects relating to the screening activities undertaken, and key outcomes (including, where appropriate, the parameters identified for monitoring).

Table 3.6: Comparative overview of the seven test cases, including key contextual information (relating to both disposal concept and repository monitoring drivers), aspects relating to the screening activities undertaken, and key outcomes (including parameters identified for monitoring). Note that, in general, this information applies only to the test cases and should not be taken as indicative of how monitoring may be implemented in the future.

	Cigéo	**ANSICHT**	**Opalinus Clay**	**OPERA**	**TURVA 2012**	**SR-Site**	**Reference Project 2011**
Test case context – disposal concept							
Waste	HLW (Cigéo is also for long-lived ILW, but only elements relevant to HLW are considered in test case)	HLW, spent fuel	Spent fuel, HLW, ILW	Spent fuel from research reactors, HLW, ILW, LLW and (for identifying processes); only HLW for screening	Spent fuel	Spent fuel	Spent fuel, HLW, long-lived ILW (separate repository at same site)
Host rock	Clay (Callovo-Oxfordian Clay)	Clay (Barremian-Hauterivian Clay)	Clay (Opalinus Clay)	Clay (Boom Clay)	Crystalline (mainly migmatised gneisses of the Fennoscandian Shield)	Crystalline (mainly granitoids of the Fennoscandian Shield)	Crystalline (no specific formation)
EBS concept	HLW disposal packages emplaced in small-diameter horizontal cells lined with a low-carbon steel sleeve. Crushed clay host rock or bentonite-based backfills and seals (with concrete elements for support) emplaced at closure.	SF/HLW canisters emplaced in vertical boreholes (3 in each) within inner liner (void space filled with sand), compacted clay buffer and outer liner. Boreholes sealed with a bentonite plug and concrete abutment. Tunnels backfilled and sealed.	SF/HLW emplaced horizontally in drifts on bentonite blocks surrounded by bentonite pellets and liner. ILW containers emplaced in caverns surrounded by mortar and liner. Tunnels backfilled and sealed.	SF/HLW packaged in supercontainers (waste canister, steel overpack and concrete buffer as one entity); ILW/LLW in concrete/steel containers. Containers emplaced horizontally end to end in disposal drifts. Drifts backfilled with grout and sealed.	KBS-3V: Copper canisters with a load-bearing cast iron insert containing SF are surrounded by bentonite clay in individual vertical deposition holes bored in the floor of deposition tunnels. Tunnels backfilled and sealed.	KBS-3V: Copper canisters with a load-bearing cast iron insert containing SF are surrounded by bentonite clay in individual vertical deposition holes bored in the floor of deposition tunnels. Tunnels backfilled and sealed.	Steel-based canisters emplaced in vertical or horizontal boreholes, surrounded by bentonite. All void spaces backfilled and sealed.

	Cigéo	ANSICHT	Opalinus Clay	OPERA	TURVA 2012	SR-Site	Reference Project 2011
Test case context – repository monitoring							
Repository monitoring objectives	• Check that installations run as expected and defined in the operational safety analysis. • Check the ability to retrieve waste packages • Check that post-closure safety is ensured as expected (track the initial evolution of the repository system). • Increase confidence in knowledge for longer-term safety assessment. • Confirm prior expectations and enhance knowledge of relevant processes.	• Verify whether identified performance targets for geotechnical barriers can be met. • Verify whether the integrity of the host rock is intact. • Allow improvement/ optimisation of the geotechnical repository components and/or the monitoring system. • Provide basic information to decision sequences (e.g. successive implementation of new seals). • Provide redundancy to QA.	• Provide information on EBS behaviour. • Check predictive models. • Early detection of any unexpected/ undesirable system evolution. • Provide input to decisions on start of operations and final closure of entire facility.	Not listed systematically, but the detection of anomalies from the expected evolution is stated to be "one of the objectives of monitoring".	• Verify that the EBS is functioning as planned. • Support understanding of expected behaviour by reassuring safety, or by implying a need to enlarge the modelling parameter field. • Feed into regular safety case updates.	• Build further confidence in the understanding demonstrated in the safety case. • Identify "unknown unknowns".	• Justify assumptions made in performance and safety assessments. • Validate safety assessment results. • Verify compliance with safety functions. • Feed into periodic safety case updates. • Adapt/ optimise construction technologies, repository layout or EBS properties.

	Cigéo	ANSICHT	Opalinus Clay	OPERA	TURVA 2012	SR-Site	Reference Project 2011
Repository monitoring programme emphasis	Behaviour of the disposal cells, EBS and near field	Evolution of important repository components	Phenomena that could potentially damage the host rock	No specific emphasis identified	Performance of the EBS	Performance of the EBS	No specific emphasis identified
High-level repository monitoring strategy	Industrial pilot phase for HLW undertaken prior to routine operations, with monitoring of heavily instrumented cells located within the main repository footprint.	Representative components of the repository selected for monitoring (monitoring fields, boreholes and seals). Dummy boreholes and/or sacrificial borehole(s) may be used. "Process concept" structured by milestones and explicitly incorporating learning. Monitoring of early filled and sealed fields allows "post-emplacement" monitoring.	EBS monitoring focused on pilot facility, plus possible monitoring of disposal rooms and access tunnels in main repository while accessible.	No formal requirements or plans yet. Preference for *in situ* monitoring, with other options (pilot facility, URL demonstrators etc.) also considered.	Indirect monitoring preferred. Theoretically a possibility of direct monitoring of EBS components at installation, but only until another component is emplaced on top of it. *In situ* tests also possible.	No monitoring sensors to be emplaced in barriers. Some direct monitoring possible, e.g., flow through tunnel plugs. Long-term experiments/batch tests (e.g. copper corrosion coupons) *in situ* or in pilot facility.	No formal requirements or plans yet. Direct monitoring preferred where possible.
Assumed repository monitoring timeframe	~100 years	100-150 years	Not explicitly mentioned; "as long as deemed necessary"	100 years	100 years (operational period). No intention to monitor after closure	60-100 years (operational period). No intention to monitor after closure	Not yet specified (operational period ~100 years)

	Cigéo	ANSICHT	Opalinus Clay	OPERA	TURVA 2012	SR-Site	Reference Project 2011
Retrievability/ reversibility requirements	Ability to reverse the disposal process/ retrieve waste packages during the operation period (~100 years) is a legal requirement.	Retrievability has to be ensured during the operational period and for a period of 500 years after repository closure.	Easy retrieval not a requirement, but must show that retrieval would at least be feasible.	Requirement for retrievability "in the long term", after the closure of the repository.	Requirement for retrievability.	No requirements.	Not stated.
Test case process							
Approach to and scope of test case	Has developed own approach to parameter screening, but in the test case followed the Modern2020 Screening Methodology as closely as possible. Only HLW cell considered.	Restricted to North Germany model. Used Modern2020 Screening Methodology. Parameters identified for vertical emplacement borehole seal (including concrete abutment).	Developed and used own approach to parameter screening. This methodology is similar to and compatible with the Modern2020 Screening Methodology. Examples presented at each step.	Focused on identifying preliminary list of processes (affecting all repository components, including EBS and host rock). Processes for one barrier (OPERA supercontainer) taken through the Modern2020 Screening Methodology.	Used Modern2020 Screening Methodology to screen parameters relating to EBS components in deposition holes/tunnels.	Modern2020 Screening Methodology used to evaluate example parameters: hydraulic conductivity / swelling pressure (backfill), charge concentrations of cations (buffer) and copper thickness (canister).	Focused on identifying possible processes and parameters to monitor (relevant to all EBS components) - no screening carried out and Modern2020 Screening Methodology not used.
Starting point for parameter identification in test case	Set of phenomenological processes (from Phenomenological Analysis of Repository Situations (PARS)).	Site-specific FEP catalogue.	Potentially relevant phenomena identified from Opalinus Clay FEP list.	OPERA FEP database (for identifying preliminary list of processes).	Already-defined performance targets.	Already defined safety functions, safety function indicators, and safety function indicator criteria.	Safety functions.

	Cigéo	**ANSICHT**	**Opalinus Clay**	**OPERA**	**TURVA 2012**	**SR-Site**	**Reference Project 2011**
Definition of expected behaviour of the system during the monitoring period, and use in screening	High level qualitative descriptions and quantitative simulations of expected thermal, hydraulic, mechanical and chemical processes. Not used explicitly in evaluating feasibility of monitoring parameters.	Detailed modelling described for relevant parameters relating to a single vertical emplacement borehole seal, including pressure build-up and water saturation (with and without gas production and heat generation). Used to feed into evaluation of technologies and selection of sensors.	High level description of repository-level evolution, plus modelling of three example candidate parameters (temperature of emplacement rooms, fluid pressure in host rock, fluid pressure at bentonite/rock interface). Used to assess usefulness of monitoring these parameters.	Qualitative discussion and illustration of key THMCR processes during repository evolution. Methodology set out for using these in evaluation of technologies, but only undertaken at a high level.	High-level qualitative description of repository-level expectations. Not used explicitly in evaluating feasibility of monitoring parameters.	Example given for piping/erosion in the buffer, backfill and deposition tunnel plug. Not used explicitly in evaluating feasibility of monitoring parameters.	High-level statements of expected EBS performance in terms of meeting safety functions.
Test case outcomes							
Parameters identified for monitoring following screening (see Table 4.1 for details)	• Cell temperature • Near-field temperature gradient • Rock porewater pressure and pH • Rock permeability • Total pressure on cell sleeve • Cell sleeve diameter and strain • Cell atmosphere (H_2, O_2 concentration, relative humidity) • Thickness and corrosion rate of cell sleeve and overpack	*In bentonite plug and concrete abutment:* • Temperature • Porewater pressure • Flow velocity (permeability) • Swelling pressure *In bentonite plug only:* • Water saturation *In abutment only:* • Vertical pressure • Vertical displacement	*"Partial list":* • Temperature of near-field host rock • Porewater pressure in the near-field host rock • Gas pressure at the bentonite host-rock interface	*For carbon steel overpack, concrete buffer and steel envelope:* • Pressure • Displacement • Redox potential *For overpack and envelope only:* • H_2 presence *For buffer only:* • Porewater pH • Porewater chemistry	*In tunnels:* • Groundwater flow and chemistry • Seismicity and rock displacement • Temperature *During* in situ *tests:* • *Canister*: geometry • *Buffer and backfill*: mineralogy, chemistry, geometry, dry and bulk density, water content, swelling pressure • *Buffer*: pore structure • *Backfill*: relative humidity, piping and erosion	*Of the example parameters screened:* • Flow through deposition tunnel plug • Copper corrosion (batch experiments) [Groundwater chemistry at repository level is already in host rock monitoring programme.]	None (no screening carried out). List of potential monitoring parameters (prior to screening) provided.

	Cigéo	**ANSICHT**	**Opalinus Clay**	**OPERA**	**TURVA 2012**	**SR-Site**	**Reference Project 2011**
Monitoring system description and implementation	Location (type of cell) and technology (sensor type) identified for each parameter, plus guiding principles for the selection and use of technologies.	Described in detail for emplacement borehole seal and concrete abutment, including requirements on sensors, general principles for use of sensors, location and number of sensors.	Not yet developed as it is too early in the programme.	Not yet developed as it is too early in the programme.	Description of different strategies to be employed (QA/QC, full-scale demonstrators, *in situ* tests) and identification of which are suitable for each parameter.	High-level description stating that, beyond monitoring of flow through deposition tunnel plugs and copper corrosion via batch tests, no EBS monitoring is planned.	High-level description in relation to URL monitoring, with statement that URL results will be used to determine implementation in repository.
Role of monitoring in decision making (this topic is addressed in Task 2.3, and is not discussed in depth in this report)	Not considered in test case.	Monitoring data will be evaluated at key milestones/ decision points, feeding directly into programme-level decisions such as moving between operational phases. These decisions occur in a defined sequence and involve defined groups of different stakeholders.	Monitoring data will input to decisions on the start of operations and final closure of entire facility, and could potentially input to decisions on moving between different operational phases. A draft generic response plan for non-conforming monitoring results has been produced.	Not considered in test case.	Monitoring data will be compared to “action limits” (not yet set for EBS monitoring parameters), which will trigger further evaluation and a decision on how to respond. Decisions will be taken according to internal guidance and responsibilities defined in company management systems. Interpreted data are published periodically; annual reports are also publicly available.	Monitoring results would ideally be used for checking against expected behaviour, but resaturation processes are so slow that obtaining usable results might be difficult. Any unexpected results would need to be assessed to explain the discrepancy.	Monitoring results will be used by regulators in making licencing/ closure decisions. Early discussion of monitoring programme can help build confidence with public stakeholders.

4 Discussion of Test Cases

This section provides a topic-wise discussion of the test cases. Section 4.1 compares and contrasts the processes used in the test cases. Section 4.2 provides a discussion of the objectives, strategies and parameters adopted in the test cases.

4.1 Process Followed by the Test Cases

The majority of test cases used the Modern2020 Screening Methodology as the basis for identifying parameters to be monitored. However, most test cases adapted the Methodology in some way to suit their own context, demonstrating the flexibility and wide applicability of the Methodology.

Starting points

The starting point for the test cases varied from one test case to another, with the Cigéo, ANSICHT, OPERA and Opalinus Clay test cases choosing to identify processes from a FEP list[5], while the TURVA 2012, SR-Site and Reference Project 2011 test cases preferred an approach based on safety functions and/or requirements. For Posiva and SKB, this reflects the fact that safety-relevant processes have already been considered in the definition of safety function-related requirements, and the explicit focus in the test case on safety functions. The fact that, despite these different starting points, all test cases succeeded in following the Methodology, demonstrates its flexibility.

Consideration of wider safety case activities

Monitoring should be considered as part of the wider safety case (White *et al*., 2017). A sufficient understanding of processes, and mitigation of uncertainties, must be achieved through the safety case, as passive safety cannot rely on monitoring. As discussed in White *et al.* (2017), monitoring provides an opportunity to build further confidence in the safety case. Activities that develop a sufficient understanding of processes in the safety case include RD&D (including fundamental scientific understanding, laboratory experiments, materials testing, procedure development, full-scale *in situ* experiments, modelling and application of the results from natural analogues) and quantitative safety assessment. Arguments developed through these means are supported through the application of quality control during emplacement to demonstrate that the as-built repository is consistent with the assumptions in the safety case.

Step PRO4 of the Modern2020 Screening Methodology asks whether monitoring a particular process would provide additional information over and above such activities. However, most of the test cases did not explicitly discuss other arguments presented in the safety case (based on *a priori* understanding) as an input to a decision of whether or not to monitor a particular process. As a result, very few processes were parked on the justification that monitoring them was considered to have no value; instead, parameters were parked because they were expected to evolve very slowly, with no quantifiable changes expected over the monitoring period. The TURVA 2012 test case was an exception to this general observation, in that some processes were stated to be verifiable through QA/QC and would therefore not be monitored. The SKB programme follows a similar approach.

The test cases were preliminary investigations into the process of identifying parameters that could be included in repository monitoring programmes. Therefore, WMOs could develop their programme-specific methodologies further by increased integration of repository monitoring programmes within the safety case and consider a range of approaches for building further confidence in process understanding alongside the parameter Screening Methodology.

[5] However, Andra's own process for identifying parameters to monitor starts from safety functions.

Test case scope

The test cases focused on different aspects of screening, including:

- Focusing on the initial steps of screening (determining the value in monitoring specific processes) and/or the steps preceding it (defining safety functions and developing FEP lists). The OPERA and Reference Project 2011 test cases are examples.
- Focusing on specific repository component(s). For example, the ANSICHT test case focused on monitoring of the borehole seals.
- Focusing on selected examples to allow a test of the process for identifying repository monitoring parameters. The Opalinus Clay and SR-Site test cases followed this approach.

This reflects two observations:

- Identifying and screening parameters to monitor, and documenting the justified results, are time-consuming and resource-intensive tasks. In particular, determining the expected evolution of parameters may require modelling and/or experiments for which results were not readily available in the appropriate form. The Cigéo test case illustrated one approach to addressing the difficulty in determining an expected evolution, i.e. considering the scale of deformation of the sleeve, rather than making explicit quantitative predictions.
- For less mature programmes, where such work has not yet been carried out and implementation of geological disposal is many years in the future, some WMOs feel that it is too early to implement the later steps in the Screening Methodology. However, for these less mature programmes developing the test cases is useful in demonstrating the feasibility of repository monitoring to play a valuable role in building further confidence in the post-closure safety case during the operational period.

Evaluation of technologies

Owing to the preliminary nature of the test cases, consideration of the technology to be used to monitor each parameter was not a particular focus.

For mature programmes that have undertaken many URL experiments, including full-scale mock-ups (e.g. Svemar *et al*., 2016) there is a good understanding of the available technologies and their application. For less mature programmes, there is a long period before operations start and selecting technologies at this stage may be considered premature.

Nonetheless, the test cases have highlighted some of the considerations that will need to be taken into account when selecting technologies. In particular, each technology will have to be tested for its impact on the post-closure safety case. This could include identification of the processes that could occur in response to the presence of the technology and assessment of the impact that these processes may have on the safety functions of the multi-barrier system. For some test cases, such assessment is made unnecessary by adopting a strategy of not including monitoring sensors in specific barriers.

Consideration of technologies also requires an evaluation of the operational hazards of installing the technologies, the impacts on logistics (i.e. emplacement schedule) and cost. However, these issues were not explicitly addressed in the test cases. Within the Modern2020 Project these issues were broached in Work Package 3 (which involved research into various repository monitoring technologies and included consideration of qualification (IRSN *et al*., 2019)) and Work Package 4 (in which *in-situ* demonstrations of repository monitoring strategy and technology were implemented).

Justifying and recording screening decisions

Screening decisions were justified in some test cases through explicit use of the supplementary guidance questions provided within the Modern2020 Screening Methodology. This included the Cigéo and ANSICHT test cases, where each supplementary question was answered in turn and criteria established to justify the screening decision (e.g. if all supplementary questions are answered yes, the process/parameter is screened in rather than being parked). For these test cases, the screening decisions were recorded using matrices that listed the answer to each supplementary question for each process/parameter.

Other test cases used an expert judgement decision, informed by the supplementary questions, but without an explicit answer being provided against each question. This included the TURVA 2012 test case in which a proforma was prepared to record the screening decisions for each performance target considered in the test case. Whichever approach is taken, it is possible (and necessary) to ensure traceability by recording a written justification.

The test cases highlighted several important considerations for recording of screening decisions. These include:

- Maintaining a link between the screening decisions and monitoring objectives, for example, in the Cigéo test case, Andra distinguished monitoring parameters selected for building further confidence in the post-closure safety case and those selected for checking the ability to retrieve waste packages, and maintained this distinction throughout the screening process.
- Maintaining a link between monitoring parameters and the component of the EBS or near field in which the parameter will be monitored. It is also important to distinguish if a parameter is being monitored in one component (e.g. the geosphere) in order to provide an indication of the behaviour of a different component (e.g. the buffer).

Future development of the justification and recording of screening decisions will need to provide more detail on the justification for screening decisions. In the several test cases, yes/no answers were provided to justify screening decisions. As the Modern2020 Screening Methodology is an iterative process expected to operate throughout the operational period of the repository, sufficient information needs to be provided for the decisions to be understood by persons not involved in the original screening.

Impact of programme maturity on ability to develop a monitoring programme

The test cases have demonstrated that decisions on parameter screening are more readily undertaken by programmes with detailed safety case approaches and detailed modelling of repository performance. Extensive RD&D provides a good platform for developing safety case arguments and providing the underpinning data and models to support these arguments. For such programmes, decisions on the additional value that can be gained through monitoring during the operational period might be more readily made.

More mature programmes, with concept-and/or site-specific designs and safety cases at an advanced stage of development, are able to model expected parameter evolutions with a greater level of confidence. This means that technology/strategy options for monitoring can be realistically evaluated and selected, and detailed monitoring plan design work (including type, number and precise locations of sensors) can proceed. In contrast, programmes that do not have this level of underpinning and/or do not envisage starting monitoring for a considerable time (by which time technologies may have substantially changed), are able to make only limited progress in terms of the selection and emplacement of sensors.

In addition, more mature programmes may have undertaken more extensive consultation with stakeholders, including regulators and citizen stakeholders; if this is the case, they may, as a result, have a more developed understanding of stakeholder expectations regarding monitoring. Where such dialogue is advanced, it may be possible for the expectations of the stakeholders to be taken into account in developing the monitoring programme.

Benefits of developing (aspects of) a monitoring programme at different stages of implementation

However, this is not to say that less mature programmes should not begin planning for repository monitoring at an early stage. The advantages of integrating repository monitoring into early planning (before any decision has been made regarding a specific site or design) include:

- Allowing sufficient time for technology development. If a need is identified to monitor a parameter for which no feasible options currently exist, then it may be possible to undertake significant technology development before the monitoring system needs to be deployed.
- Ensuring that design decisions do not foreclose monitoring options that may be deemed necessary. While there is still flexibility in repository design, it can be developed iteratively alongside a monitoring plan, rather than monitoring programmes facing restrictions imposed by a design that is already set.
- Helping to build stakeholder confidence that repository performance will be checked during the operational period.
- Early thinking about monitoring may allow some information/confidence requirements initially identified as monitoring objectives to be addressed through long-term experiments instead of or in addition to monitoring.

Repository monitoring has different uses at different stages in the implementation of geological disposal (e.g. siting, construction, commissioning, operation). Thinking about monitoring early ensures that relevant aspects of the monitoring programme can be developed and implemented at the appropriate times, and that these are as useful as possible with respect to monitoring in later stages.

For example, it may be important to establish monitoring of key near-field parameters well before operations begin, to provide a baseline against which to compare operational monitoring data. Similarly, monitoring during commissioning and/or during the early stages of operation may lead to enhanced understanding of processes and performance of specific aspects of the underground repository system that can be incorporated into procedural or design improvements in latter operations. Finally, monitoring of sealed deposition holes, tunnels or parts of the repository, while operations continue elsewhere and access ways are still open, may provide an opportunity to evaluate the logistics and usefulness of monitoring after the closure of the repository.

4.2 Results of the Test Cases

General progress on internal thinking on repository monitoring

For all participating organisations, undertaking the test case has moved forward internal thinking on monitoring and the development of parameter lists. The test cases provide a good ground for overall reflection and discussion on monitoring objectives, motivations and strategy, which can sharpen arguments and/or provide input for rethinking these aspects.

All test cases have made progress in systematically developing parameter lists according to the MoDeRn Monitoring Workflow and consistent with the Modern2020 Screening Methodology, even though most WMOs treated the task as an isolated exercise rather than as an integrated part of their programme (DBETEC being the exception).

Repository monitoring objectives

A variety of different objectives for monitoring were identified and recorded in the test cases. These primarily fall into two categories:

- To provide an indication of EBS and near-field rock behaviour and/or repository performance. This can then be checked against expectations and allow identification of any anomalous behaviour. Although not expected, anomalous behaviour might be the result of processes that have not previously been recognised (so called *unknown unknowns*). Repository monitoring can be used to update knowledge and models, and potentially lead to optimisation of repository or monitoring programme design.

- To build further confidence (for example, confidence in the WMO and/or its safety case) by demonstrating knowledge of processes or the ability to model processes, and to understand the THMCR evolution of the near field. Ultimately, repository monitoring may feed into a continued demonstration that the repository is safe by providing additional data to substantiate THMCR models and/or by demonstrating that a WMOs modelling approach is valid.

Additional objectives specific to individual test cases were also identified, for example to check the capability to retrieve waste packages (Cigéo test case) and to provide redundancy to QA procedures (ANSICHT test case).

The different objectives identified by the test cases have a direct influence on both the value judgements made when deciding if a process should be monitored, and on more detailed aspects of the screening such as identifying strategy/technology options and evaluating whether their impacts are acceptable.

Some monitoring programmes may include a specific objective to identify unknown unknowns. This is likely to be challenging, since by definition the processes and parameters in question cannot be characterised in advance. Such parameters could include those that are influenced by many coupled processes, and it is likely that their identification would be addressed during a holistic review of all selected parameters prior to monitoring programme design. However, this issue was only addressed in one test case (SR-Site test case).

High-level strategies

High-level monitoring strategies (such as whether the barriers around emplaced waste can be monitored *in situ*, or should be monitored through another approach such as a pilot facility or batch tests) have also had a direct influence on how the Modern2020 Screening Methodology has been applied in the test cases. Most WMOs already had well-developed ideas about high-level monitoring strategies (or general strategic principles) prior to undertaking their test cases, and these are discussed in detail in White *et al*. (2017).

Monitoring strategies can incorporate a wide range of approaches. The TURVA 2012 test case describes an intention to use *in situ* tests, which would later be dismantled, to investigate the change in key properties of some repository components (such as geometry of the canister and density, water content and extent of piping/erosion in the buffer and backfill) over time. Such tests are not classed by Posiva as monitoring, whereas similar batch tests used by SKB (for example, to track copper corrosion) are considered in the SR-Site test case to be part of the monitoring programme. Furthermore, there is also overlap between monitoring and related activities, such as site characterisation (including application of site characterisation criteria such as Posiva's RSC) and QA/QC.

Identification of parameters to be monitored

With the exception of the Reference Project 2011 test case of SURAO, all test cases identified several parameters that, following screening, could be included in a programme-specific repository monitoring programme. As previously noted, none of these are comprehensive lists of all parameters owing to the scope defined for the test cases, but they all represent progress towards this goal. The results of the test cases are also only trial developments of parameter lists and do not represent monitoring parameters that WMOs intend to monitor without further consideration.

Table 4.1 compiles the monitoring parameters identified by the test cases, together with the reason the parameter was selected and the strategy/technology option that could be used. This provides a comprehensive overview, for different national contexts, of some parameters that might be considered for monitoring, and why and how the parameters might be monitored.

Comparing the parameters identified by the different test cases, there is minimal overlap and there is no common parameter for all test cases. In addition, the locations and reasoning for monitoring the same parameter vary significantly between test cases. This leads to a clear conclusion that there is no "standard" list of parameters that should be monitored in every monitoring programme; each national context has its own drivers, constraints and objectives, which exert a strong influence on choices of monitoring parameters, and need to be carefully considered when developing the monitoring programme. Therefore, Table 4.1 should NOT be taken as a suggested list of monitoring parameters to be applied more widely.

Role of monitoring in decision making

The role of monitoring in decision making was considered at a high level by most of the test cases. Three main contributions were identified across the test cases:

- Providing input to key programme-level decision points, such as the start of operations, final closure of the facility, and moving between different operational phases.
- Identifying the need for and feeding into decisions taken in response to unexpected results (for example, comparing monitoring results to predefined limits, where exceedance would trigger further investigation and a decision on how to respond). Note, however, that a decision would not be taken solely on the basis of monitoring data.
- Providing information to external stakeholders (including regulatory, government and public stakeholders) to help build confidence and enable them to be involved in key decisions, where such involvement is identified as part of a WMO's wider interactions.

Decision making is discussed further in the Task 2.3 report (White *et al*., 2019).

Table 4.1: Summary of parameters identified for monitoring by the test cases, together with the reasons for monitoring and the strategy/technology option selected for monitoring, as given in individual test case reports. Note that, in general, this information applies only to the test cases and should not be taken as indicative of how monitoring may be implemented in the future. Rows in purple indicate clay host rock concepts; rows in green indicate crystalline host rock concepts.

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
Temperature	Disposal cell and surrounding near-field rock	Cigéo	Highly relevant to post-closure safety and retrievability (in that it provides information about possible rock deformation). Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored directly in some disposal cells using Pt probe and/or optical fibre sensors.
	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT	Provides information about heat flow and temperature evolution in the seal, which is relevant to the performance target that the bentonite element shall be free from tensile stresses. Monitoring could provide confidence that the repository is behaving as expected.	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using resistance temperature detector (RTD) or fibre optic-based systems.
	Near-field host rock	Opalinus Clay	A criterion has been set for host rock temperature that it should remain below the maximum palaeotemperature experienced by the host rock (if met, thermally-induced mineralogical changes can be excluded). Based on modelling, there is some uncertainty as to the extent to which the criterion will be satisfied within the monitoring timeframe, so it is deemed useful to monitor.	Monitored in pilot facility (before and after sealing) using wired fibre-optic distributed temperature sensors and/or wired or wireless thermocouples.
	Canister, but measured in tunnels	TURVA 2012	Related to the performance target that the canister should not impair the safety functions of other barriers, hence relevant to post-closure safety, although primarily verified through design, dimensioning and QC (limited value in monitoring).	Monitored indirectly from tunnels (not directly related to a specific requirement on the canister).
Porewater pressure	Near-field rock	Cigéo	With temperature, provides information about interstitial overpressure in the near-field host rock, which is relevant to post-closure safety. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored directly in some disposal cells using vibrating wire or optical fibre piezometers.

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT	Provides information about fluid pressure from below (due to thermal expansion and gas generation), which is relevant to the overall safety function of the seal and to the related performance target that the bentonite element shall be free of tensile stresses. Monitoring could reduce uncertainty and/or increase knowledge beyond that gained from the wider RD&D programme and/or provide confidence that the repository is behaving as expected and/or support repository design improvements and/or feed into periodic safety case updates.	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using vibrating wire and/or fibre optic sensors.
	Near-field host rock	Opalinus Clay	A criterion has been set for host rock porewater pressure that it should remain below lithostatic pressure at repository depth (if met, the possibility that preferential release pathways will be generated by hydraulic fracturing can be excluded). Based on modelling, there is reasonable confidence that this criterion will be met within the monitoring timeframe but less confidence thereafter; therefore, monitoring may be useful to check the ability of the models to accurately predict later evolution.	Monitored in on-site underground rock characterisation facility (URCF).
Fluid (gas) pressure	At the bentonite/host rock interface	Opalinus Clay	Gas pressure should remain below 80% of lithostatic pressure. This criterion is met if pathway dilation can be excluded and the analysis of the system can be simplified. Based on modelling, there is uncertainty as to whether this criterion would be met at least after the monitoring timeframe and possibly within it as well (depending on whether conservative gas generation rates are used), so it is deemed to be useful to monitor.	Monitored in on-site test facility (URCF), pilot facility (before and after sealing) and potentially in emplacement rooms, using distributed fibre optics and/or pressure sensors.
Permeability/ groundwater flow velocity	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT	Provides information about fluid flow through the deposition hole seal, both into and out of the borehole. These are processes that are directly relevant to the overall safety function of the seal and to the related performance targets on permeability and swelling pressure of the bentonite element, and have an impact on modelled system performance. Monitoring could reduce uncertainty and/or increase knowledge beyond that gained from the wider RD&D programme and/or can provide confidence that the repository is behaving as expected and/or support design improvements and/or feed into periodic safety case updates.	Monitored by an indirect method using pressure sensors at different monitoring levels in dummy boreholes as well as in monitoring boreholes.
	Tunnels and host rock around repository	TURVA 2012	Indirectly related to canister, buffer and backfill as these elements are designed to perform within specific boundary conditions. If these conditions are maintained in the geosphere then there is confidence that the canister, buffer and backfill will perform as designed, so they are considered useful to monitor. May include "light" monitoring of flow through deposition tunnel plugs.	Monitored directly from tunnels (away from deposition holes). Deposition tunnel plugs monitored visually while accessible.

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
	Deposition tunnel plug	SR-Site	Provides information about piping/erosion in the buffer, since flow through the plug is related to flow through unsaturated deposition holes and could therefore indicate piping. This process is directly related to the safety function for the buffer to limit advective mass transfer. There is value in monitoring during the early development of the repository.	Monitored directly during operations until tunnels backfilled, using a weir.
Confining pressure	Total pressure on cell sleeve	Cigéo	Provides information about the mechanical load acting on the cell sleeve, which is relevant to demonstrating retrievability of the disposal package. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored directly in some disposal cells, using optical fibre sensors.
	Vertical pressure on deposition hole seal (concrete abutment)	ANSICHT	Provides information about the mechanical load on the abutment from above (including backfill mass and, later, rock pressure), which is relevant to the performance target on the expansion of the bentonite element (increase in plug length). Monitoring could support design improvements.	Monitored directly in monitoring deposition boreholes at a number of “monitoring levels”, e.g. using vibrating wire and/or fibre optic sensors.
	Supercontainer – carbon steel overpack	OPERA	Provides information about mechanical disturbance to the overpack due to corrosion, cold cracking or welding, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Supercontainer – concrete buffer	OPERA	Provides information about mechanical load (from external forces) on the buffer, which is indirectly relevant to the supercontainer safety function of preventing contaminant release and in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Supercontainer – steel envelope	OPERA	Provides information about mechanical load (from external forces) on the envelope, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
Swelling pressure	Deposition hole seal (bentonite plug and concrete abutment)	ANSICHT	Provides information about the swelling pressure evolution of the bentonite plug, which is relevant to the performance target on the swelling pressure of the bentonite element, and has an impact on modelled system performance. Monitoring could reduce uncertainty beyond the knowledge that gained from the wider RD&D programme and/or provide confidence that the repository is behaving as expected and/or support repository design improvements.	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using vibrating wire and/or fibre optic sensors.
	Buffer	TURVA 2012	Directly relevant to several buffer performance targets, e.g. isostatic load from the buffer swelling pressure should be <10 MPa in the lower part of the buffer; swelling pressure should be less than the yield strength of copper canister and Olkiluoto host rock.	Monitored in full-scale and/or *in situ* test, using sensors.
	Backfill	TURVA 2012	Directly relevant to several backfill performance targets, e.g. swelling pressure at all points in the deposition tunnel >0.1 MPa in fully saturated state; backfill shall contribute to the mechanical stability of the deposition tunnels.	Monitored in full-scale and/or *in situ* test, using sensors.
Diameter	Cell sleeve	Cigéo	Provides information about the deformation of the sleeve, which is relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored directly in some cells using optical fibre sensors. Evolution of the sleeve will also be measured directly by 3D scanning.
Strain	Cell sleeve	Cigéo	Provides information about the deformation of the sleeve, which is relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored directly in some cells, using optical fibre sensors.
Geometry	Canister	TURVA 2012	Directly relevant to several canister performance targets: canister must remain intact, copper shell must remain >0mm, should withstand asymmetric buffer swelling pressure loads of 3-10 MPa, which are relevant to overall safety function of preventing radionuclide release.	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
	Buffer	TURVA 2012	Provides information about buffer water uptake, related to performance targets that buffer displacement should be limited, diffusion should be the dominant transport mechanism, and limits on isostatic load from buffer swelling. The process takes a long time, however, *in situ* tests could provide performance model validation.	Monitored in full-scale and/or *in situ* test (at installation and dismantling).

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
	Backfill	TURVA 2012	Provides information about backfill water uptake, related to performance targets on backfill hydraulic conductivity, swelling pressure, limited deformation and requirement to contribute to mechanical stability of tunnels. The process takes a long time, however, *in situ* tests could provide performance model validation.	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
Displacement	Deposition hole seal (vertical displacement of concrete abutment)	ANSICHT	Provides information about the displacement of the concrete abutment in the direction of the drift above, which is relevant to the performance target on the expansion of the bentonite element (increase in plug length). Monitoring could reduce uncertainty beyond the knowledge gained from the wider RD&D programme and/or provide confidence that the repository is behaving as expected and/or support repository design improvements.	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using specific displacement sensors.
	Supercontainer – carbon steel overpack	OPERA	Provides information about mechanical disturbance to the overpack due to corrosion, cold cracking or welding, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Supercontainer – concrete buffer	OPERA	Provides information about mechanical load (from external forces) on the buffer, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Supercontainer – steel envelope	OPERA	Provides information about mechanical load (from external forces) on the envelope, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Tunnels and host rock around the repository	TURVA 2012	Seismicity, including potential rock displacements, are indirectly related to the canister, buffer and backfill (e.g. related to performance targets for canister to remain intact and for copper shell to remain >0mm thick), with an emphasis on suitable deposition hole locations. If such locations are seismically suitable then there is confidence that the barrier elements will perform as designed.	Indirect, regional monitoring. Also addressed through the RSC methodology.

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
Hydrogen concentration	Cell atmosphere	Cigéo	Relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored directly in some cells using LiDAR and/or thermal gas conductivity and/or gas density and viscosity measurements.
	Supercontainer – carbon steel overpack	OPERA	Provides information about steel corrosion of the overpack following water ingress, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could provide confidence that the system has been implemented as designed.	Not defined.
	Supercontainer – steel envelope	OPERA	Provides information about steel corrosion of the envelope due to interaction with Boom Clay porewater, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could provide confidence that the system has been implemented as designed.	Not defined.
Oxygen concentration	Cell atmosphere	Cigéo	Relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored in some cells using sensors based on luminescence.
Relative humidity	Cell atmosphere	Cigéo	Provides information about the explosivity of the cell atmosphere, which is relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored in some disposal cells using capacitive sensors (based on an electrical capacitor).
	Backfill	TURVA 2012	Provides information about water uptake and swelling, which are relevant to several backfill performance targets.	Monitored in full-scale and/or *in situ* test (using sensors).
Water content/ saturation	Deposition hole seal (bentonite plug)	ANSICHT	Provides information about the saturation evolution of the bentonite plug, which is relevant to the overall safety function of the seal and to the related performance targets on permeability and swelling pressure of the bentonite element, and has an impact on modelled system performance. Monitoring could reduce uncertainty beyond the knowledge gained from the wider RD&D programme and/or provide confidence that the repository is behaving as expected and/or support repository design improvements.	Monitored directly in monitoring deposition boreholes at a number of "monitoring levels", e.g. using azimuthal deep resistivity (ADR) or ThetaProbes.
	Buffer	TURVA 2012	Related to characteristics and processes affecting performance of buffer, e.g. water uptake and swelling.	Monitored in full-scale and/or *in situ* test (at installation and dismantling).

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
	Backfill	TURVA 2012	Related to characteristics and processes affecting performance of backfill, e.g. water uptake and swelling.	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
Porewater pH	Near-field rock	Cigéo	Provides information about the neutralisation of the filling material, which is relevant to post-closure safety. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Not defined.
	Supercontainer – concrete buffer	OPERA	Provides information about geochemical evolution due to porewater/concrete interaction, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
Porewater / groundwater chemistry	Supercontainer – concrete buffer	OPERA	Provides information about geochemical evolution due to porewater/concrete interaction, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Host rock around repository	TURVA 2012	Indirectly related to canister, buffer and backfill as these elements are designed to perform within specific boundary conditions. If these conditions are maintained then there is confidence that they will perform as designed, so they are considered useful to monitor.	Monitored directly from tunnels (away from deposition holes).
		SR-Site	Relevant to safety functions for backfill and buffer to retain sufficient mass over their lifecycle. To do this, they must be stable in contact with groundwater with a certain total charge equivalent of cations. Therefore, the relevant parameter is the electrical conductivity of the host rock groundwater. There is limited value in monitoring in order to build further confidence in the post-closure safety case as the relevant process is very slow; however, groundwater chemistry is already monitored through sampling at repository level as part of the host rock monitoring programme.	Monitored via borehole sampling.
Redox potential	Supercontainer – carbon steel overpack	OPERA	Provides information about steel corrosion of the overpack following water ingress, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could provide confidence that the system has been implemented as designed.	Not defined.

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
	Supercontainer – concrete buffer	OPERA	Provides information about geochemical evolution due to porewater/concrete interaction, which is directly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could reduce uncertainty beyond knowledge derived from the wider RD&D programme.	Not defined.
	Supercontainer – steel envelope	OPERA	Provides information about steel corrosion of the envelope due to interaction with Boom Clay porewater, which is indirectly relevant to the supercontainer safety function of preventing contaminant release in the abandonment of facility and poor sealing alternative evolution scenarios. Monitoring could provide confidence that the system has been implemented as designed.	Not defined.
Thickness	Cell sleeve	Cigéo	Relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored in some cells using corrosion coupons.
	Overpack	Cigéo	Relevant to post-closure safety. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored in some cells using corrosion coupons.
Corrosion rate	Cell sleeve	Cigéo	Relevant to demonstrating retrievability of the disposal packages. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored indirectly in some cells using electrical resistance probes and mass loss of coupons.
	Overpack	Cigéo	Relevant to post-closure safety. Monitoring could provide confidence that the repository is behaving as expected and/or feed into repository design improvements and/or feed into periodic safety case updates.	Monitored in some cells using electrical resistance probes and mass loss of coupons.
	Canister	SR-Site	Directly related to safety function for canister to withstand corrosion (indicator criteria: copper thickness must remain >0mm). There is value in monitoring as understanding the early stages of corrosion may provide additional detailed and/or site-specific understanding not gained through previous RD&D.	Monitored indirectly using corrosion coupons (*in situ* batch tests).
Mineralogy and chemistry	Buffer	TURVA 2012	Related to performance of buffer as expressed in several performance targets (e.g. maintain favourable chemical conditions, should deform sufficiently to maintain canister integrity).	Monitored in full-scale and/or *in situ* test (at installation and dismantling).

Parameter	Element(s) parameter relates to	Test case that selected parameter	Reasoning for monitoring parameter, as given in test case	Strategy/technology selected for monitoring the parameter in test case
	Backfill	TURVA 2012	Related to performance of backfill (e.g. performance target that backfill should have limited potential to be a source of sulphide).	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
Density (dry and bulk)	Buffer	TURVA 2012	Related to various characteristics and processes affecting performance of buffer (e.g. water uptake) as expressed in performance targets (e.g. buffer displacement should be limited, diffusion should be the dominant transport mechanism, limits on isostatic load from buffer swelling, should deform sufficiently to maintain canister integrity).	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
	Backfill	TURVA 2012	Related to various characteristics and processes affecting performance of buffer (e.g. water uptake) as expressed in performance targets (e.g. backfill hydraulic conductivity, swelling pressure, limited deformation and requirement to contribute to mechanical stability of tunnels).	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
Pore structure	Buffer	TURVA 2012	Directly related to the performance target that the buffer should have sufficiently fine pore structure to filter radiocolloids, which is directly relevant to post-closure safety.	Monitored in full-scale and/or *in situ* test (at installation and dismantling).
Piping and erosion	Backfill	TURVA 2012	Directly relevant to hydraulic conductivity of the backfill, which is the subject of a performance target, as well as to homogenisation of density.	Monitored visually in full-scale and/or *in situ* test (at installation and dismantling).

5 Revised Modern2020 Screening Methodology

As described above, the preliminary version of the Modern2020 Screening Methodology (summarised in Section 2 and provided in full in Appendix B) was trialled by the seven test cases in Task 2.2. Feedback from the test cases has been taken into account in producing a revised version, which is presented in this section.

The Methodology is presented in two parts:

- Section 5.1 provides an introduction to the Methodology.
- Section 5.2 presents the Methodology, describes each step in it, and provides supplementary guidance on specific steps.

5.1 Introduction to the Modern2020 Screening Methodology

The development of the Modern2020 Screening Methodology is motivated by a desire to develop a justified and needs-driven monitoring programme. As noted in NEA (2014), 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 (Section 5.2) provides guidance on the steps that a WMO may take in identifying and managing a list of repository monitoring parameters, linked to processes, and repository monitoring strategies and technologies. The list of parameters is intended to form the basis for repository monitoring system design at each stage of an iterative repository monitoring programme that evolves through the implementation of geological disposal.

The context for the Screening Methodology is provided by the MoDeRn Monitoring Workflow (Figure 5.1), which describes the steps prior to screening (specification of monitoring objectives and identification of a preliminary list of monitoring processes) and those that come after parameter screening (design, operation and responding to monitoring results).

The Modern2020 Screening Methodology is illustrated in Figure 5.2 (revised following the test cases from the preliminary version illustrated in Figure 2.2 based on discussions between Modern2020 Project partners at Project workshops), in which the Methodology is organised into three columns that take into account the interplay between processes, parameters, and technologies (monitoring strategies are considered in parallel with technologies). These elements are fundamentally linked and are considered together for the purposes of screening. The Methodology itself 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 strategy/technology option 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 after an initial application of the Methodology by a WMO so that there is a starting point to focus the dialogue.

The Screening Methodology is intended to be iterated multiple times (Figure 5.3); the parameter list after one iteration is not fixed 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 specific monitoring results or a periodic update to the post-closure safety case.

In each iteration, answers to the questions will be a judgement made on the basis of available information at the time, and will likely be given with some degree of uncertainty. They may change in the future if there is new information.

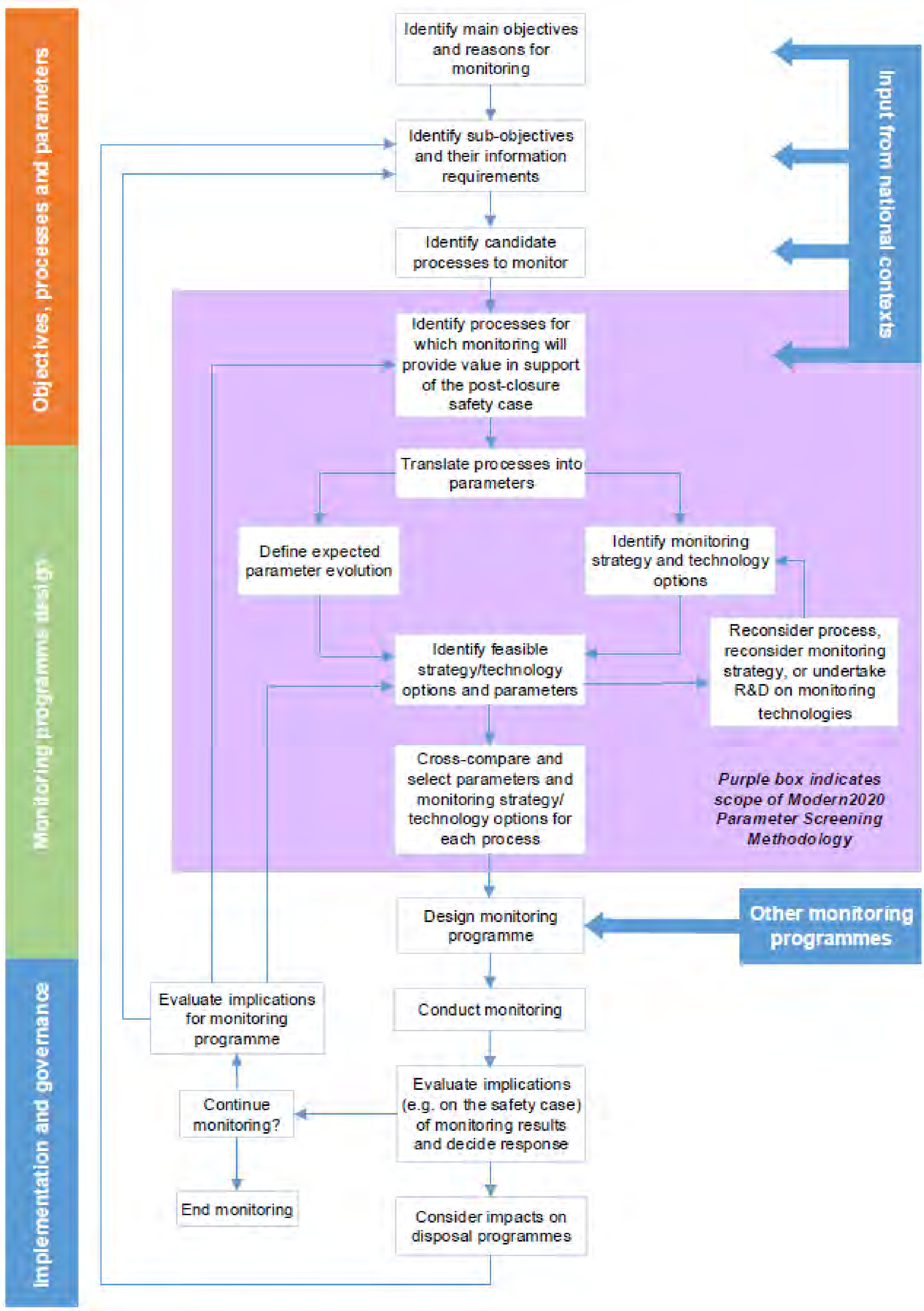

Figure 5.1: The MoDeRn Monitoring Workflow, with minor change made in response to the test cases undertaken in Task 2.2. The box that originally read "Identify processes to monitor" has been changed to read "Identify candidate processes to monitor".

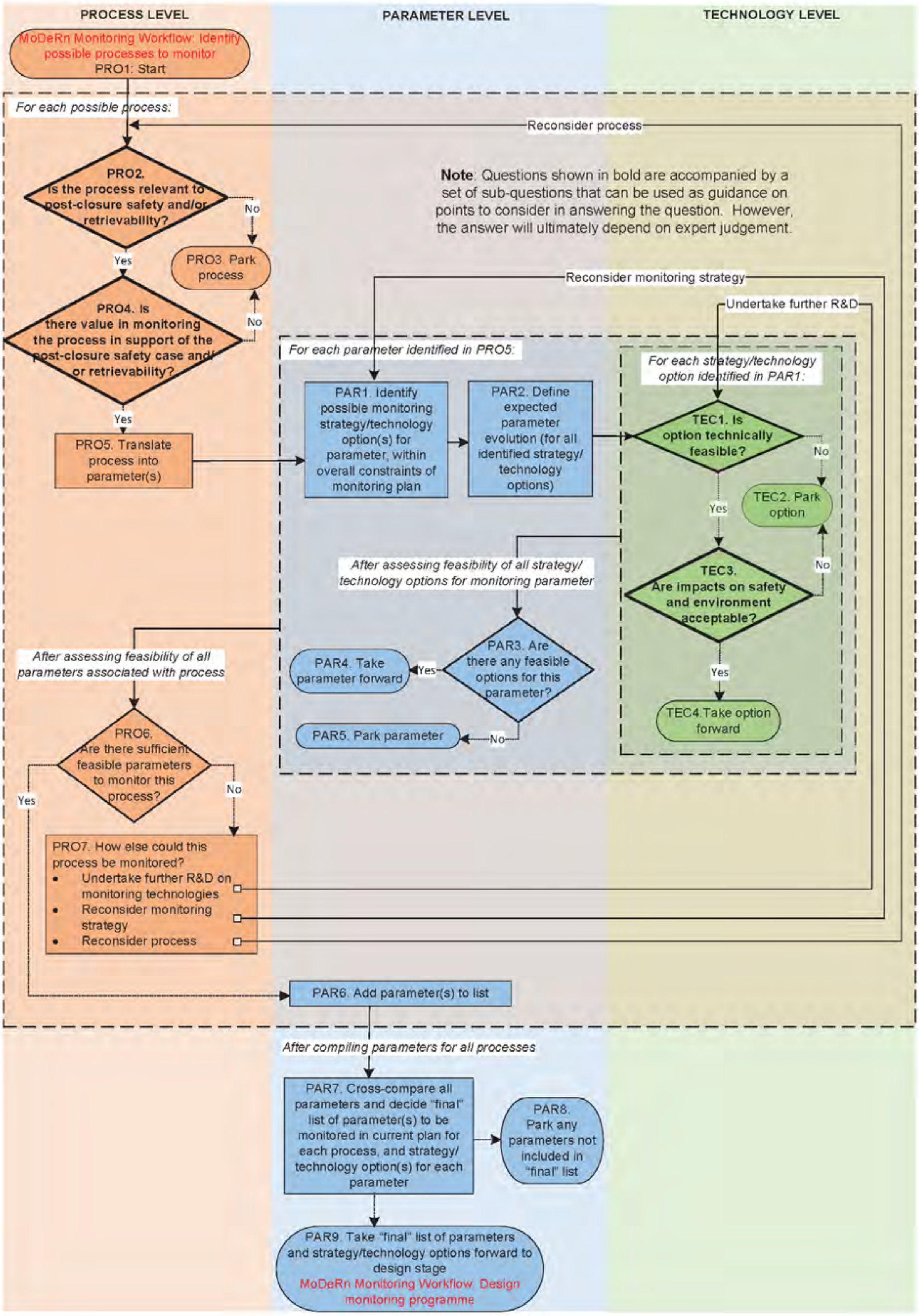

Figure 5.2: Revised version of the Modern2020 Screening Methodology.

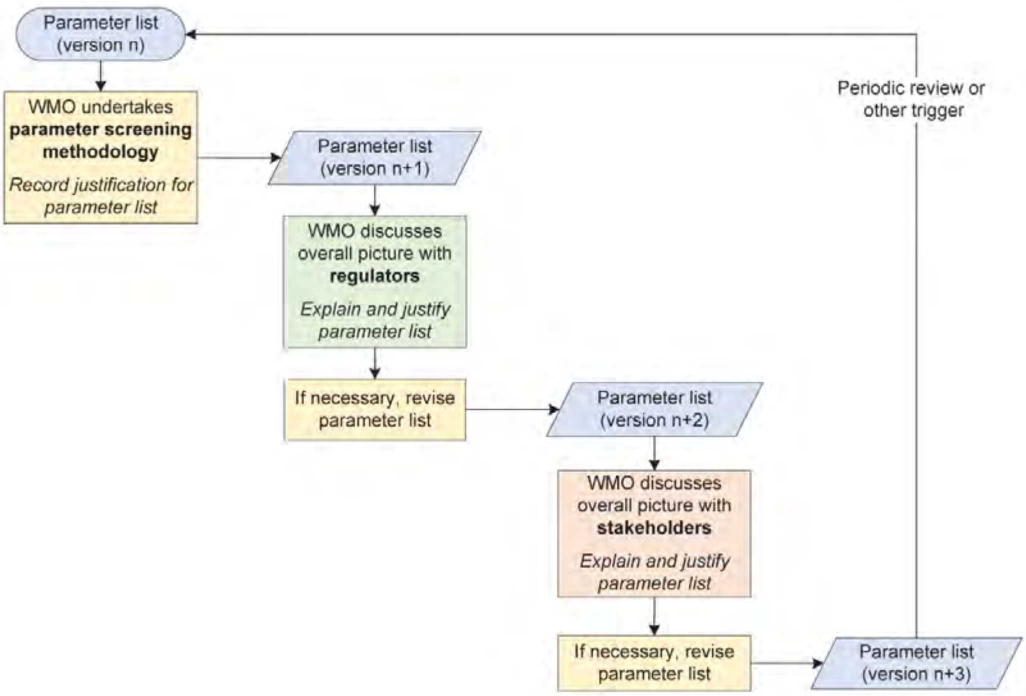

Figure 5.3: Illustration of a possible iterative implementation of the Modern2020 Screening Methodology, showing the situation in which a WMO engages with regulators following the first iteration and public stakeholders following the second iteration. There are multiple ways in which such iteration and 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.

The 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 5.2. Sets of guidance questions have been developed for four of the steps in the Screening Methodology (PRO2, PRO4, TEC1 and TEC4) and are included in the description of steps in Section 5.2. 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 in the context of a specific programme; therefore, there is no prescriptive metric for relating sub-question answers to an overall answer.

It is envisaged that WMOs will record detailed responses to these sub-questions and/or others that they consider to be relevant (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 (for example, to compare two alternative options or to rank processes in order of importance to monitor).

The Methodology provides a basic framework for recording the results of the screening. No prescriptive guidance on recording results has been provided, because multiple approaches are possible and WMOs may have their own systems (e.g. document templates or databases) that they wish to use. However, it is important to record decisions, and to provide clear justifications for them, at each step, in order to provide transparency and allow for future review. A well-designed system for recording screening results will also ensure that links between processes and the parameter(s) needed to monitor them (and strategy/technology options to do this) are maintained.

The Methodology is also suitable for use as a basis for developing other types of monitoring programme as well as those focused on repository monitoring of the EBS and near field (for example, environmental monitoring programmes). If used in this way, aspects of the Methodology relating to post-closure safety would need to be modified to reflect other objectives, but the same principles would apply.

5.2 The Modern2020 Screening Methodology

Each step in the Modern2020 Screening Methodology is explained below in the order that it would be reached working through a single iteration of the flowchart. The titles of the steps are colour-coded (as per Figure 5.2) 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, for example based on an analysis of the post-closure safety case, a (generic or site-specific) FEP list or a consideration of safety functions. A process may also come into consideration by other means, for example through discussion with regulators or public stakeholders. Note that many of these processes will relate to a specific repository component. Where a process affects multiple repository components, it may be appropriate to treat them as separate processes for the purposes of screening (this decision will be made by individual WMOs).

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.

Several different approaches to using the Methodology are possible. For example, a single process can be taken all the way through the Screening Methodology (up to step PAR6) before moving onto the next process. Alternatively, each step in the Screening Methodology can be applied to a set of processes (perhaps relating to a specific repository component) before moving onto the next step.

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

The 2014 NEA guidance (NEA, 2014) 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.

Depending on how the starting list of processes has been identified, this step may have already been addressed. For example, if processes have been identified through a consideration of safety functions, then their relevance to post-closure safety has already been established. However, this step still provides a useful check, as well as a framework for recording a justification, before moving onto the next step.

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 (and/or others identified by individual

WMOs) can also form (part of) the justification for monitoring a parameter to provide information on a process and the parameter(s) that represent it:

- Is the process related to one or more safety functions of any element of the repository system in any considered scenario?
- Is the process related to any safety function indicator or performance target?
- 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 support a decision to retrieve waste or otherwise reverse the disposal process?

WMOs for whom retrievability is an important consideration may wish to keep track of which processes are relevant to post-closure safety and which are relevant to retrievability (there may be some overlap). This can be done in the recording of the results; for example, as an attribute in a database.

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 and/or retrievability?

This question addresses the extent of the value to be gained by monitoring a safety/retrievability-relevant process. It is needed because there may be processes that are relevant to safety or retrievability 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 or redundancy.

A further consideration in determining the value of monitoring is whether changes will be quantifiable over the monitoring period. Some WMOs may argue that there is no value in monitoring processes where no quantifiable changes are expected, while others may consider that in some cases null results can be useful.

Deciding if there is value in monitoring a relevant 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:

- Could monitoring the process reduce uncertainty in repository performance over-and-above knowledge derived from RD&D? (Examples of RD&D include materials science, procedure development, full-scale experiments, natural analogues and fundamental scientific understanding.)

- Could monitoring provide value through validation of predictive models and/or helping to improve system models?
- 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 monitoring provide confidence that waste is retrievable, additional to that gained in other ways (for example, through long-term experiments)?
- Could monitoring the process address uncertainties more effectively than changes to the repository design (for example, increasing canister spacing if there is any concern about heat production)?
- Could monitoring the process support general repository or specific EBS 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?
- Could the changes to the repository system resulting from the process be quantifiable during the monitoring period?

If there is not considered to be value in monitoring the process, it should be parked (PRO3).

PRO5. Translate process into parameter(s)

Each process will have one or more associated parameters that may be monitored to provide information about it. For some processes, a single parameter may be identified, while others could be tracked using any one of several parameters (in which case it may be desirable to evaluate all possible options, particularly if there is a requirement for redundancy). Some processes may need more than one parameter to be monitored to enable the process to be fully characterised. If a process is translated into more than one parameter, the PAR1-PAR5 loop should be undertaken for all of them.

Parameters relating to a given process can be identified through expert knowledge (e.g. from an understanding of the operation of the process within a repository setting) and/or previous experience (e.g. from research into the process within the repository RD&D programme).

PAR1. Identify monitoring strategy and technology options

This step should be undertaken for each parameter identified in PRO5 for a given process.

Once parameter(s) associated with the process under consideration have been identified, the next step is to identify possible options for monitoring the parameter in question, taking each in turn. Each option will consist of a monitoring strategy (i.e. the high-level approach adopted in a monitoring programme) and a technology.

The choice of monitoring strategy will reflect the safety strategy under which the monitoring programme is being developed, and any high-level constraints or principles imposed by the wider context (expected to be defined outside of this Screening Methodology). Monitoring strategy may or may not vary between parameters, and one or more strategies may be considered for each parameter, depending on the programme. The choice of technology and its location will depend on the repository component being monitored as well as on the choice of strategy, and one or more options may be identified.

It is expected that, at this stage, a set of preferred strategy and technology combinations would be identified and evaluated, rather than all possible options. However, if both direct and indirect options are permitted under the wider safety strategy, both should be identified for evaluation at this stage[6].

PAR2. Define expected parameter evolution

As for PAR1, this step and should be undertaken for each parameter identified in PRO5 for a given process.

After identifying options for monitoring, it is necessary 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 at this stage in the Methodology 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.

If two strategy/technology options identified for the same parameter are expected to show different evolutions (for example, a direct *in situ* method that would measure values of the parameter of interest, versus an indirect or proxy method that would measure values of a different parameter reflecting a response to changes in the parameter of interest), expected evolution should be defined for both options.

The level of detail of the expected evolution should be consistent with how the options will be evaluated, and will depend on the programme implementation stage and how much information is available. It could range from an order-of-magnitude estimate at key time points (based on expert judgement) to a full evolution model based on experiments and numerical modelling. Note that, even at a late stage of implementation, it may not be feasible to develop a full evolution model for every parameter (for example, if significant variation is expected for every monitoring location). In this case, the expected evolution described in this step could bound the variability within the system, and the requirements on monitoring options derived from this evolution would ensure that proposed technologies were suitable in all situations.

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. Again, such uncertainty can be quantified at different levels of detail.

TEC1. Is option technically feasible?

This step is undertaken for each combined strategy/technology option identified in PAR1 for a given parameter.

This step evaluates whether the strategy/technology option in question is technically feasible (i.e., is it possible to implement, not yet considering any impacts of doing so), against the expected parameter evolution defined in PAR2. It is envisaged that technical feasibility will be evaluated based on both the current state-of-the-art technology and reasonable expectations for future development – i.e., whether an option is technically feasible now or will be at the time it is needed. This takes into account RD&D that is already underway and means that promising options are not parked simply because they are still under development, unless there is not enough time for sufficient development before a decision needs to be taken. As programmes move closer to implementation, they may require that options to be taken forward must already be technically feasible. It is important that any assumptions made about future developments are documented in the screening results, to assist in future review.

Guidance questions that can be used to support screening at this step are:

- Can the proposed technology meet sensitivity, accuracy and frequency requirements for monitoring the parameter over the monitoring period?

[6] A direct option is an *in situ* method that measures the actual values of the parameter of interest. An indirect option could be a proxy method that measures values of a different parameter that reflects a response to the parameter of interest, or an option for monitoring the parameter of interest not *in situ* (for example in a dummy package or batch test, or in an on-site rock characterisation facility).

- 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?

TEC2. 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 taken forward 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 new RD&D on technology development if necessary – see PRO7).

WMOs may wish to select a preferred option for monitoring a particular parameter, rather than taking forward several possible options. In this case, the TEC1 and TEC3 supplementary questions could be developed into a scored value framework, and the highest scoring option taken forward while the remaining options are parked.

TEC3. Are impacts on safety and environment acceptable?

As for TEC1, this step should be undertaken for each strategy/technology option identified in PAR1 for a given parameter.

This step evaluates whether a technically feasible option is acceptable in terms of its impacts. This includes the impact on the passive safety of the repository (for some WMOs, it is a legal requirement that any monitoring equipment shall not have a detrimental impact on the safety of the repository; for others there may be a trade-off between a small impact and the benefits of monitoring). Other impacts, for example on risks to workers and on the environment, can also be considered here. If impacts for an option are deemed not to be acceptable, the option should be parked (TEC2).

Guidance questions that can be used to support screening at this step are:

- 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?

TEC4. Take option forward

If option is considered to be technically feasible (based on the answers to the sub-questions in TEC1 or otherwise) and its impacts on safety and environment are considered to be acceptable (based on the answers to the sub-questions in TEC3 or otherwise), the option should be carried forward to the next stage in the Modern2020 Screening Methodology.

PAR3. Are there any feasible options for this parameter?

Once all strategy and technology options identified in PAR2 have been evaluated for technical feasibility and acceptability of impacts, the workflow moves back to the parameter level. If any one of the technology/strategy options identified for monitoring the parameter are feasible, then the answer to this question will be "yes". If there are no technically feasible options, the answer is "no" for this particular parameter and it should be parked.

However, there may be other parameters that were identified in step PRO5 that could provide information about the process under consideration, so this question needs to be asked (following technical evaluation of all options identified) for each of these parameters before moving on.

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?

Once all parameters identified in PRO5 have been through the PAR1-PAR5 loop to determine whether they are feasible to monitor, this question reviews whether the process under consideration can be feasibly monitored. In many cases a single parameter will be sufficient to provide the desired level of information about a process, in which case this step is redundant and will have the same answer as PAR3. However, in other cases it is possible that multiple parameters may be needed and the feasibility of the full set of required parameters will need to be reviewed in answering this question. In either case, the question should be straightforward to answer by considering which parameters have been parked and taken forward from the previous step.

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

If there are insufficient feasible parameters to monitor the process in question, it is necessary to reconsider:

- Whether further RD&D on monitoring technologies should be undertaken to develop promising options for monitoring the desired parameter(s) to a technically feasible level. This would involve returning to step TEC1.
- Whether a different high-level monitoring strategy could enable the desired parameter(s) to be monitored. This would involve returning to step PAR1.
- 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 value judgement that concluded that it should be monitored. This could include re-evaluation of how the process is treated within the post-closure safety case; for example, it may be possible to gain sufficient information about the process through other means (such as long-term experiments) that were not originally considered. 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. Following this path would involve returning to step PRO2.

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.

PAR6. Add parameter(s) to list

If there are sufficient feasible parameters to monitor the process under consideration, these should be added to the list of parameters to be monitored in the current monitoring plan (i.e. the one resulting from this iteration of the screening methodology). The additions for a given process may consist of only one parameter (if a single parameter was identified as being representative of the process and was found to be technically feasible) or several (if more than one independent parameter was identified as being representative of the process and a level of redundancy is required, or if several parameters are needed to give full information about the process).

PAR7. Cross-compare parameters and decide "final" list

The final steps in the Methodology occur after all processes (for a specific repository component or otherwise) have been considered, and technically feasible parameters (together with strategy/ technology options) for all of them have been compiled.

This step considers the resulting collection of parameters, and associated strategy/technology options, in a holistic manner. Its purpose is to ensure that the proposed parameter(s) and strategy/technology options 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", i.e., using the same parameter to monitor several processes, and/or using the same strategy and/or technology to measure several parameters (within redundancy requirements), can also be identified as part of this step. If identifying "unknown unknowns" (processes or effects that have not been recognised or identified as being significant in the safety case) is an objective of monitoring, this step may consider whether the collection of parameters and strategy/technology options resulting from screening is likely to address this objective, and if not, whether it can be modified to do so.

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 all processes under consideration, together with optimised strategy/technology combinations by which these parameters will be monitored.

Note that although this list is "final" in terms of the present iteration of the Screening Methodology, it is expected that there will be several such iterations before a repository monitoring programme is implemented (Figure 5.3) and potentially during operations. Therefore, the list may change in future.

PAR8. Park any parameters not included in "final" list

Any parameters not included in the "final" list as a result of the review undertaken in step PAR7 should be parked. This means that they should not be included in the current monitoring plan, but remain within the system, with a record of the justification for their status to provide transparency and allow future review.

PAR9. Take "final" list of parameters forward to design stage

Parameters to be included in the current plan following step PAR7 can be carried forward to the design stage when appropriate. This step links back to the MoDeRn Monitoring Workflow.

6 Overall Conclusions on Identifying and Screening Parameters

6.1 Conclusions from the Test Cases

Based on the discussion in Section 4 (in addition to the experiences and results of the individual test cases), the following conclusions regarding identifying and screening repository monitoring parameters can be drawn:

- Determining parameters to be monitored in an implementable and logical repository monitoring programme for the EBS and near field is challenging but achievable. Finding a balance (appropriate to the national context and drivers) between monitoring everything possible and monitoring only what is valuable (when compared to the resources required to collect the data and the potential safety implications) is a key challenge. Consistent with IAEA and NEA guidance, a repository should be passively safe without relying on monitoring, and so it is important that all monitoring activities are carefully considered and their need justified.
- Two principal justifications are possible: firstly, that parameters are relevant to post-closure safety and/or retrievability, for example through being directly linked to safety functions. However, monitoring during the operational phase to build further confidence in the safety case may include demonstrating general THMCR understanding as well as validating performance (for some WMOs), so a direct link to safety is not necessarily required for there to be value in monitoring a parameter.
- Further work on developing implementable monitoring programmes is ongoing for all WMOs. Activities undertaken in the test cases need to be extended to all relevant components of the underground repository system. There is also a need, in most programmes, to focus on more detailed aspects of monitoring programme design, such as selection of sensor type, number and locations. Detailed assessments of the impact of the monitoring system on the post-closure safety case (such as including sensors in models) will also need to be carried out, especially in cases where sensors are installed inside EBS components.
- There is no common set of parameters that should be monitored in every repository monitoring programme. Instead, the parameters to be monitored in each programme will depend strongly on the specific drivers, constraints and objectives identified in the national and repository-specific context.
- To be useful and traceable in the future, the screening process and its results must be transparent and understandable to future generations and external stakeholders. Therefore, WMOs must give thought to both the format and the level of detail of how results and their underpinning justification will be presented.
- Decisions on parameter screening are more readily undertaken by programmes with detailed safety case approaches and repository performance models, and a more developed understanding of stakeholder expectations regarding monitoring. However, there are advantages to planning repository monitoring at an early stage, such as allowing sufficient time for technology development, ensuring design takes account of monitoring needs, building stakeholder confidence, and enabling some information/confidence requirements to be addressed through long-term experiments instead of or in addition to monitoring. Early thinking about monitoring also ensures that aspects of monitoring relevant to different stages (e.g. siting, construction, commissioning and operation) can be developed and implemented at the appropriate time.

6.2 Conclusions on the Modern2020 Screening Methodology

Based on workshop discussions and the test case reports, the following high-level conclusions regarding the Modern2020 Screening Methodology can be drawn, which have been taken into account in developing the revised version (Section 5):

- The Screening Methodology is useful across the range of programmes involved in the task, is flexible and can be adapted to the needs of individual programmes. Its relative simplicity (although underpinned by detailed explanations) is appreciated, and, although the primary audience is technical monitoring specialists, may be helpful for engaging with external stakeholders on the topic of what can/should be monitored.
- The application of the Methodology guides users to provide justified reasons for monitoring a process, to clearly consider the possibilities and limitations of potential monitoring technology options, and to evaluate the impact of monitoring on safety in a transparent and traceable way.
- Many starting points are possible, including those where there has been no prior consideration of relevance to safety and those where relevance to safety is a key part of initial identification of processes. It should be noted that, in the latter case, there is a risk that non-safety-related monitoring, e.g. monitoring to demonstrate understanding of the system, might be missed.
- It should be noted that the Methodology is the explanation of steps, not the workflow itself (which is an illustration of the Methodology). However, it is likely that the best understanding of the Methodology will always result from face-to-face explanation.
- The Modern2020 Screening Methodology is part of the MoDeRn Monitoring Workflow, not a standalone activity, and therefore should be used in the context of the reasons for monitoring and safety case analysis undertaken in the wider consideration of monitoring.
- Processes need to be linked to a specific repository component or location in order to be meaningfully evaluated. This was widely recognised by the test cases.
- In some cases, for example if monitoring sensors are to be emplaced in critical barriers and/or left *in situ* after closure, there will be a need to assess the impact of monitoring sensors on post-closure performance. In the Screening Methodology, this is explicitly addressed in step TEC3, at the top level of the Methodology.
- The Screening Methodology could be used as a basis for developing other types of monitoring programme as well as one focused on the underground repository system (e.g. an environmental monitoring programme).

The Modern2020 Screening Methodology could benefit from feedback from WMOs undertaking further screening iterations as their programmes progress, and from other users, beyond the end of the Modern2020 Project. Thus, it is envisaged that testing, learning and improvement similar to that described in this report will continue in the future.

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Appendix A: Test Case Guiding Instructions

Each test case was asked to compile its complete work and findings in a test case report with a common outline as follows (with the issues listed in the Table A.1 to be addressed in the framework of these main headings):

1. Introduction
2. Monitoring objectives
3. EBS/Host-rock system
4. Monitoring parameter identification
5. Expected behavior of EBS
6. Monitoring system description and implementation
7. Monitoring in the confidence building and decision-making process

Table A.1: Issues to be addressed by each test case, as set out in the Task 2.2 Guiding Instructions.

Issues	Comments
1. System description	
a) What is the adopted approach for the system description: safety case, safety functions, features, events and processes (FEPs), proxies?	
b) Describe the EBS and host-rock processes	The purpose is to give an overview and a context, for deep details it is better to provide a reference.
c) Explain the set of parameters that are involved in the EBS/host-rock processes	This should cover a complete set which corresponds to what could be measured (=preliminary parameter list), being the population from which a sample of relevant parameters is drawn which shall be monitored.
2. Parameters	
a) Explain the implementation of the methodology/workflow for the parameter screening process, i.e. how to arrive at the parameters to actually monitor.	This is an adaptation to nation- and site specific of the generic Screening Methodology developed in Task 2.1.
b) Explain what parameters are actually going to be monitored (i.e. screened parameter list) and why.	The chosen parameters should be relevant and measurable and their monitoring not impact detrimentally on the safety of the system.
c) Describe the expected system behaviour/evolution of processes and measured EBS monitoring parameters (holistic).	System behaviour means the spatial-temporal development of an aggregate of monitored parameters of the coupled rock-EBS system.
d) What are the performance measures for the expected behaviour?	A performance measure is a qualitative method or quantitative measure or a combination of both to compare monitoring results with an *a priori* modelled behaviour. E.g., temperature evolution - comparison/correlation between the temperature time series for given points in space and or snapshots of many points in space at different time.

e) Explain the methodology of going from measured parameters to actual behaviour to comparison with expected system behaviour.	The intention is to have a transparent description of the stepwise process and underlying consideration/ motivations of going from single measured parameters to interpreted system behaviour based on an aggregate of monitored parameters and to compare this with expectations based on the *a priori* modelled results.
f) Describe a range of possible actions in response to measured "deviations"	Here it is necessary to explain the "baseline" i.e. expected behaviour and relate monitored parameters to it, then a discussion of feasible/possible bounds which are deemed "acceptable". Outside of these bounds are what may be envisaged as "deviations" which could be addressed by certain actions as a direct response.
g) Explain the methodology and application of quality control (QC) and quality assurance (QA) procedures for the implementation and operation of the EBS monitoring	If QC measures are relevant for the implementation of the EBS monitoring system then these should be described and explained
h) What are the uncertainties in the implementation and operation of the EBS monitoring and how are they handled: parameters, redundancy, system behaviour, (decision making)?	These relate e.g. to reliability of monitored data over long periods of time, what are they and how are they mitigated? Is parameter redundancy one way? Other uncertainties are interaction of regulators and citizen stakeholder with monitoring results – what is their interpretation and desire for action - how is this addressed?
i) Suggestions for improvement/revisions to the parameter screening process and the Screening template in Appendix B.	The trial of the Screening Methodology provides valuable experience which shall be utilised for improvement.
j) Explain how you assess whether the monitoring system might impact on the long-term safety of the EBS. What are your considerations and deliberations?	This issue is implicit through the Screening Methodology but shall be explicitly addressed.
3. Added value	
a) What are the motivations for undertaking EBS monitoring?	
b) Explain how EBS monitoring may support confidence building and decision-making process.	
c) Explain how EBS monitoring may contribute towards the interaction with citizen stakeholders in support of confidence building.	
4. Decision support	
a) Explain which decisions may be supported by monitoring results, if any.	
b) Explain how monitoring data may support the understanding of the expected behaviour with respect to repository operations and long-term safety (post closure).	
c) Describe the management functions (generic) required for the decisions making process and the involved deciders.	

Appendix B: Modern2020 Screening Methodology

B.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. 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. 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, 2013). 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 here 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 NEA (2014a), 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. At a high level, the identification of parameters to monitor could be visualised as three steps (Figure B.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.

B.2 The Modern2020 Screening Methodology

B.2.1 Methodology Summary and Supporting Diagrams

The Modern2020 Screening Methodology (Figure B.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 B.3) and a revised version of the MoDeRn Monitoring Workflow (Figure B.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 (Section B.2.3).

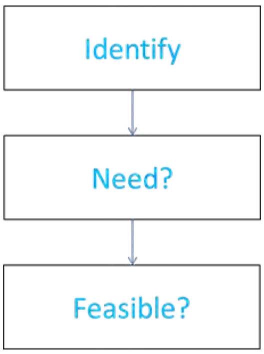


Figure B.1: The three basic steps in developing a parameter list.

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 B.3. Figure B.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 B.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.

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 B.2.2.

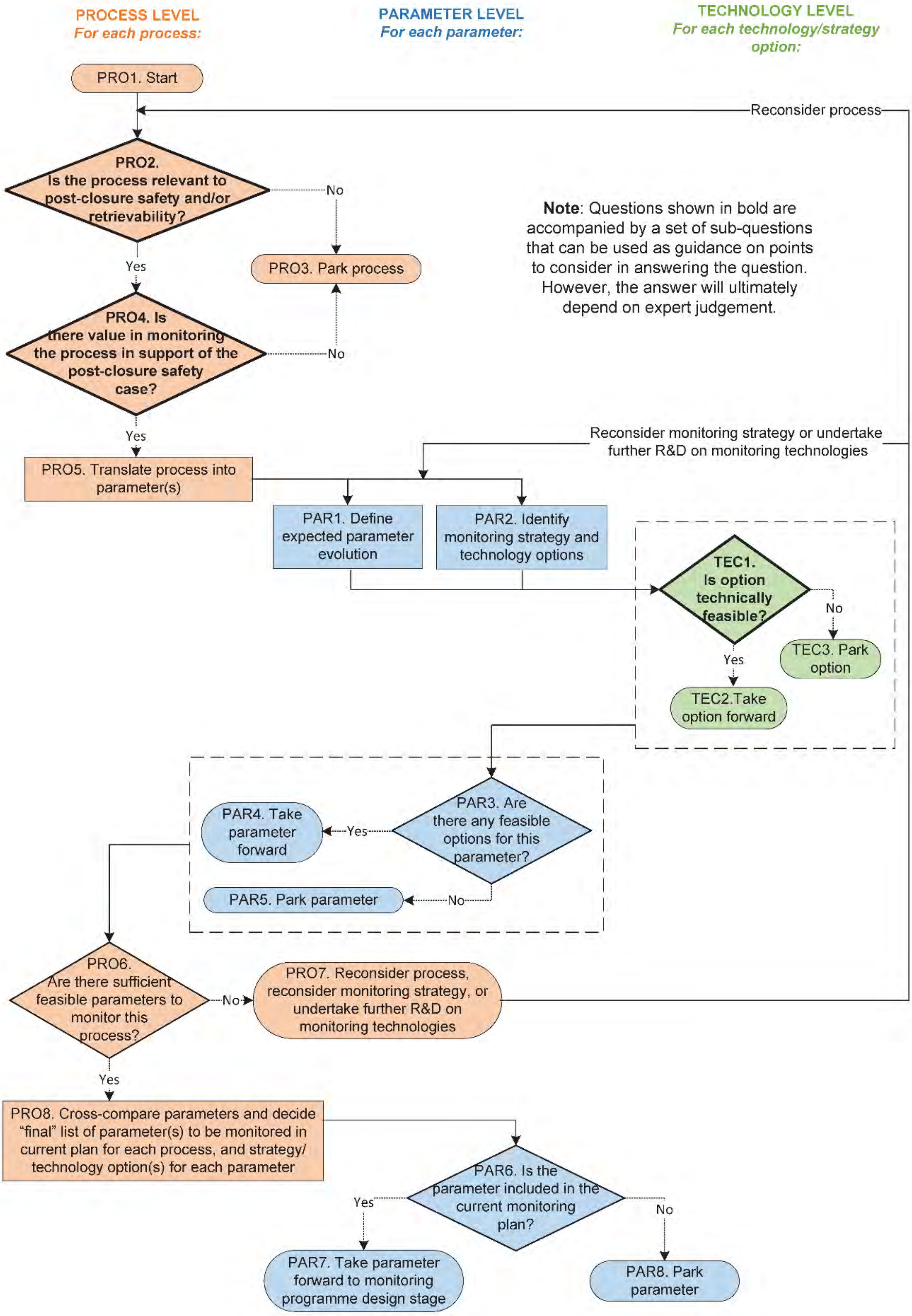


Figure B.2: The Modern2020 Screening Methodology.

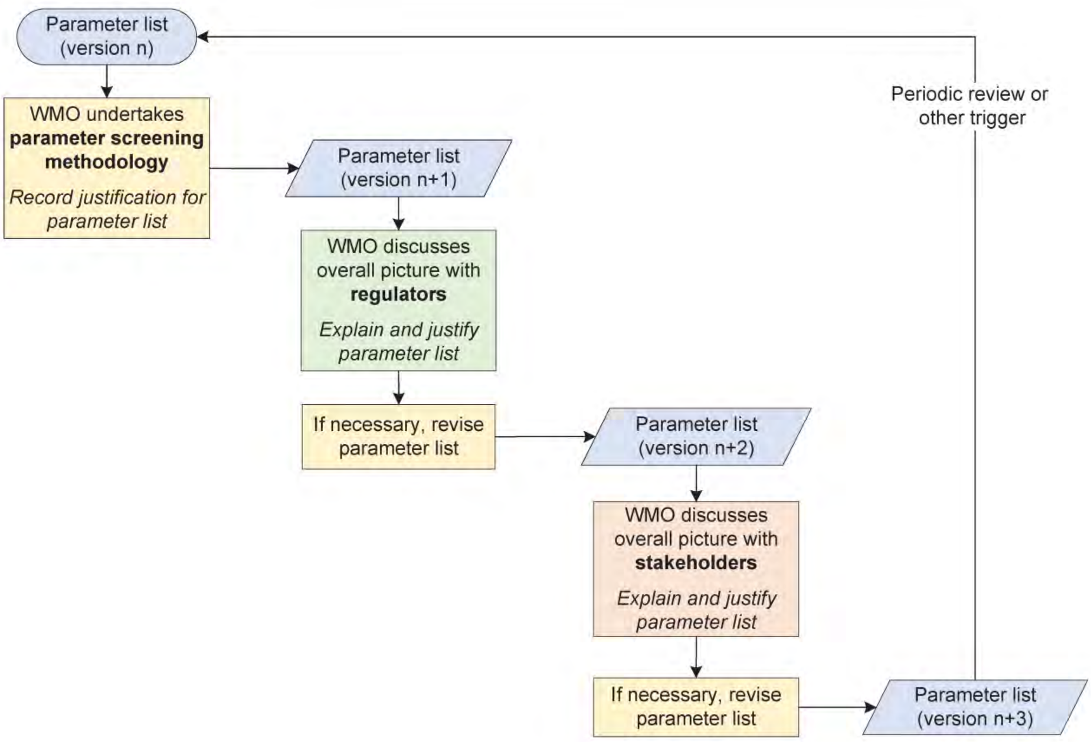


Figure B.3: Illustration of a possible iterative implementation of the Modern2020 Screening Methodology, showing the situation in which a WMO engages with regulators following the first iteration and public stakeholders following the second iteration. There are multiple ways in which such iteration and 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.

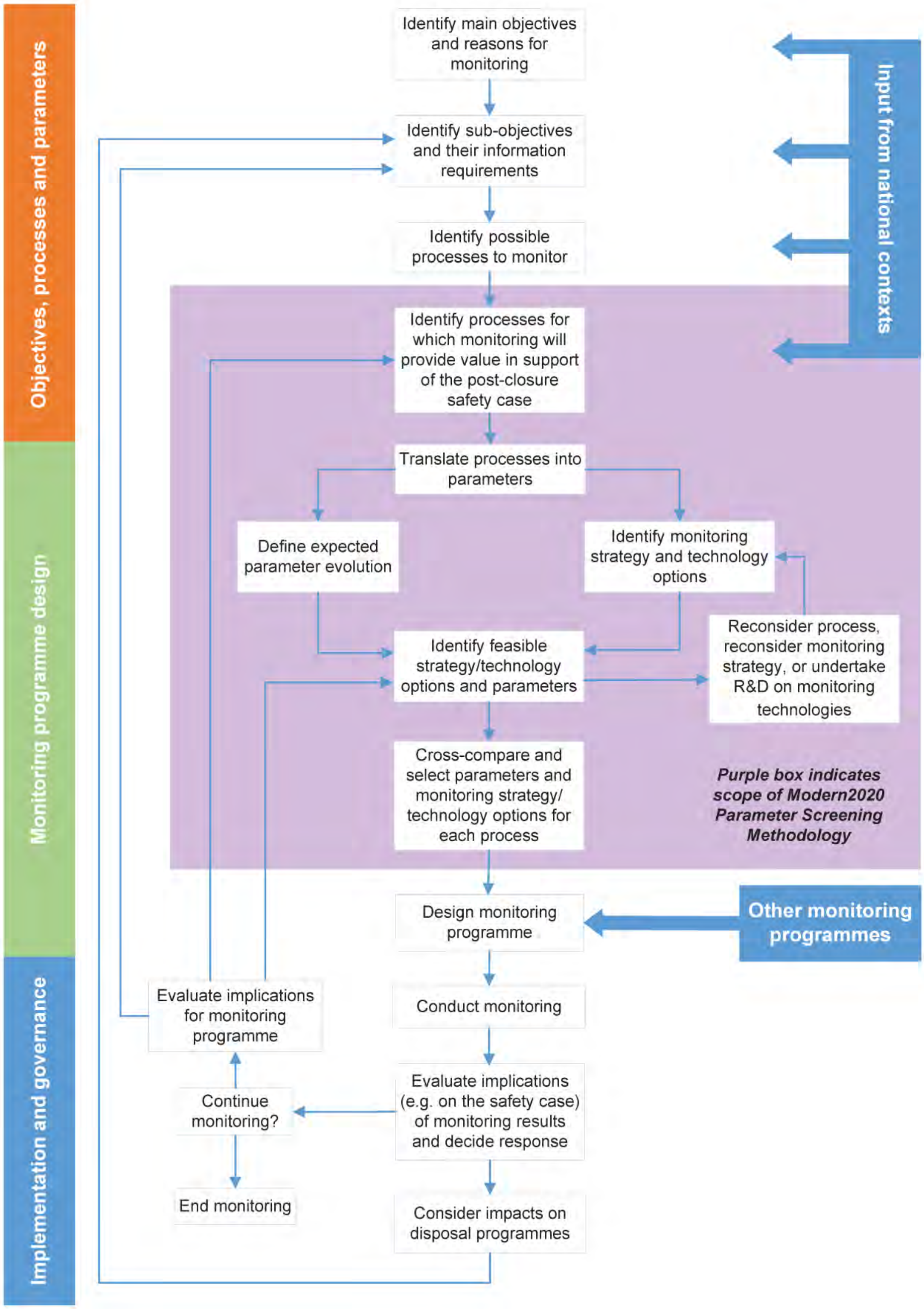


Figure B.4: Revised MoDeRn Monitoring Workflow, illustrating the relationship of the Workflow to the Modern2020 Screening Methodology. In addition to an elaboration of the middle part of the Workflow, changes from the published version include an amendment of the box originally reading “Identify processes 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.

B.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 B.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 B.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 B.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 B.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.

B.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 D2.1 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?

Appendix C: Cigéo Test Case (Andra)

Contents

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.

1.2 Objectives of this Report

The objective of Task 2.2 is to test the methodology identified in Task 2.1 to identify EBS and host-rock monitoring parameters for the national programmes considered in WP2. This report contributes to the deliverable D2.2**: Monitoring Parameter Screening: Test Cases** and addresses.

Each participant was asked to provide information on their storage project, illustrate the test of the methodology and suggest possible modifications, based on the following text organisation:

- What is the adopted approach
- EBS description
- Explain the set of parameters
- Descript the test of the methodology for the selection of the monitoring parameters
- Explain the stepwise process applied to our own disposal project
- Describe the technologies used.

The information presented in the following sections is issued from the Safety Options Report (2015) and do not incorporate the evolution of the thinkings and studies since that milestone.

2 System description

2.1 Cigéo

High-level waste (HLW) and intermediate-level long-lived waste (IL-LLW) cannot be disposed of in surface or near-surface facilities due to their high and/or long radioactivity that it remains hazardous for tens or hundreds of thousands of years. The 2006 Planning Act charged Andra with the task of designing and building a reversible disposal facility for this final waste. This facility is known, as Cigéo, industrial geological disposal project. The protection of human health and the environment is the fundamental objective of Cigéo.

The depth, design and construction of Cigéo in very low permeable argillaceous rock and in a stable geological site will make it possible to protect radioactive waste from human activities and natural surface phenomena (such as erosion) and confine these substances over very long periods of time.

Cigéo will no longer require human intervention after it is closed up. This means that the waste are protected and the burden of their management is not placed on future generations.

In accordance with the safety guide for the final disposal of radioactive waste in a deep geological formation published by ASN in 2008, the repository system in post-closure consists of three main components:

- The Callovo-Oxfordian, the host formation in which the Cigéo underground facility is situated;
- the waste disposal packages;
- the closed waste disposal facility with the seals.

The underground facility is designed in separate disposal areas for high-level waste (HLW) and intermediate-level long-lived waste (IL-LLW) in order to limit/avoid phenomenological interactions between these different waste categories.

The HLW consists of fission products and minor actinides separated from the uranium and plutonium during the reprocessing of spent fuel, calcined and incorporated into a glass matrix, which is poured into a stainless steel canister.

The IL-LLW consists mainly of the structural elements of spent fuel and waste associated with the operation, maintenance and dismantling of nuclear facilities. The overpacks used by the waste producers for conditioning the IL-LLW are of different types, shapes and sizes. They can be made from non-alloy steel, stainless steel, standard reinforced or fibre-reinforced concrete.

The primary waste containers are disposed of in "disposal packages"[7], which are placed in "disposal cells" in the underground facility. The disposal cells are tunnels (IL-LLW) or micro-tunnels (HLW) on a horizontal axis or slight slope dug out of the Callovo-Oxfordian formation:

- HLW micro-tunnel cells containing only one disposal package per cell section; each micro-tunnel has a metallic "sleeve" designed to provide mechanical support to the cell at least during its operation (left in place on post-closure);
- IL-LLW tunnel cells containing several disposal packages per cell section. The mechanical stability of these during operation is guaranteed by a concrete liner (left in place on post-closure).

Each disposal cell is served by one or more access drifts for its construction, the loading of the waste packages and management until closure. The liner of the access drifts ensures their mechanical stability during the operating phase.

The disposal cells are arranged in each of the zones mentioned above into one or more separate sections. One section is a dead-end grouping of disposal cells and drifts.

The sections are linked to the connecting structures between the surface and the underground facility by "connecting drifts". The connecting structures between the surface and the underground facility, known as "surface-to-bottom connections" consist of two ramps and vertical shafts in groups and a number of sections defined by their functions during operation. For the total closure of Cigéo, all the drifts in the underground facility are backfilled and sealed in places. The ramps and shafts will be backfilled and sealed.

2.2 The general safety approach

In 1991, the Act on the management of high-level and long-lived radioactive waste gave Andra - the French National Radioactive Waste Management Agency - the task of assessing the feasibility of a waste repository in a deep geological formation, particularly through the construction of underground laboratories (the second line in the Act). The ASN issued a basic safety rule in 1991 that set out the long-term safety expectations for the repository, the design principles, the criteria used to select suitable geological media and the terms of studies, and defined the fundamental objectives that must guide research on disposal. In 2008, ASN updated the objectives by publishing the safety guide for the disposal of radioactive waste in deep geological formations.

Safety iterations were implemented (Figure 21), based on the acquisition of phenomenological knowledge, the development of architecture and design, the development of safety methods appropriate to deep geological disposal and research and development on technological solutions.

This iterative approach is thus based on the close link between design, acquired knowledge and safety assessments, as illustrated in the figure below.

[7] *These packages contribute to the safety of the waste disposal facility while it is in operation, and as necessary also to its post-closure safety.* (2008 safety guide for the final disposal of radioactive waste in a deep geological formation)

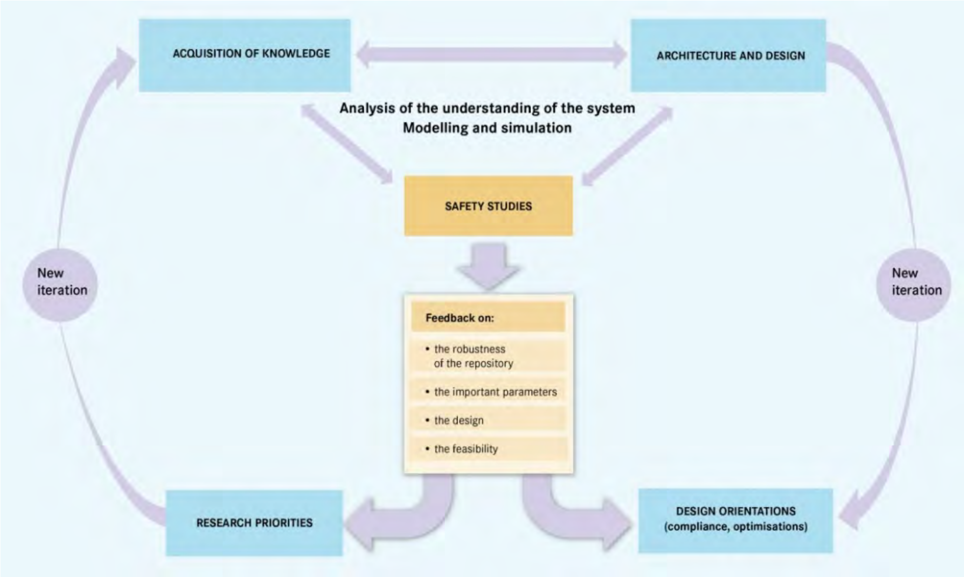


Figure 5: ILLUSTRATION OF THE ITERATIVE PROCESS

The assessment procedure used by Andra includes the following core components:

- a functional analysis (functions, components and associated performance) establishing a strong link with the design;
- a phenomenological analysis of the repository situations with time (operation and post-closure to 1 My) (current knowledge taking account of the chosen design options);
- a qualitative analysis of the uncertainties (based on the first two analyses);
- a development of scenarios;
- a quantitative evaluation of radiological impacts;
- an analysis of the results and new knowledge acquisition or new studies of design if necessary.

Each iteration involves knowledge acquisition and a study of the architectural designs consistent with this knowledge. With this available knowledge, models, experiments and demonstrators can be used to understand the behaviour of the concepts studied.

Thanks to this approach, much has been learned through successive iterations, gradually helping to guide the choice toward solutions which demonstrate the greatest robustness in view of uncertainties in our knowledge and introduce prevention and protection measures to guard against the risks and uncertainties identified.

Each intermediate safety iteration associated with the various milestones in the development of the Cigéo project was examined by the ASN and peer-reviewed. This contributed to the process of gradually identifying the safety issues, and led to the proposal of the safety options to which this document relates, in preparation for the construction licence application for Cigéo. These safety options therefore incorporate all experience feedback.

2.3 The post-closure safety functions

In order to meet the fundamental objective of protecting humans and the environment against the risks associated with dissemination of the radioactive substances and toxic elements in the waste, Andra has identified and organised post-closure safety functions of the Cigéo disposal system as follows:

The first safety function consists of isolating the waste from surface phenomena and human actions. The site of the repository and the depth at which it is located protect it from surface phenomena, erosion and everyday human activities, which should only affect the ground down to a depth of less than 200 m on a scale of hundreds of thousands of years. In accordance with the safety guide for the geological repository, the protection of humans must be guaranteed "without depending on institutional control, which cannot be relied on with any certainty for more than a limited period of time (...) (500 years)". The memory of the repository will be maintained for as long as possible. The technical solution chosen will provide a reasonable level of confidence over a very long period of time, such that the possibility of inadvertent human intrusion does not have to be considered until after 500 years, in accordance with the safety guide.

The second safety function consists of limiting the transfer to the biosphere of the radionuclides and toxic elements in the waste. This means controlling the physicochemical degradation of the waste, the packages and the engineered components, keeping the radionuclides and toxic elements as close as possible to their sources, and controlling the transfer pathways that could, in the long term, lead these elements into the biosphere. They are:

- aqueous pathways, as the radionuclides are liable to dissolve in water and migrate to the surface;
- gaseous pathways, as certain radionuclides can migrate in this form.

Water is the main factor for alteration of waste packages and the main transfer way for radionuclides and toxic elements. Controlling the aqueous ways is therefore a key objective of post-closure safety.

Limiting the transfer of radionuclides and toxic elements by water is the purpose of the following three safety sub-functions:

1. preventing/limiting the circulation of water;
2. restricting the release of radionuclides and toxic elements and immobilising them in the repository;
3. delaying and reducing the migration of radionuclides and toxic elements released into the clay host rock.

These three safety sub-functions rely primarily on the favourable characteristics of the Callovo-Oxfordian formation. The design of Cigéo (architecture, engineered components) and its operation aim to preserve these favourable characteristics.

While the Callovo-Oxfordian formation plays a central role in long-term safety, the packages and the repository's engineered components, specifically the underground facility's architecture on completion and closure structures, also contribute to containment of the waste and to maintaining the conditions for flows of water through the facility to be very slow.

One particular objective is to control the criticality risk associated with the presence of fissile isotopes in the waste. Andra checks that this risk is controlled as part of the safety assessment, on the basis of the mass of fissile material per package, the distribution of the waste packages in the disposal cells and the limited potential for the fissile isotopes to move or form concentrations, taking account of the evolution of the materials and of the void spaces in the disposal cells

2.4 A coordinated approach between safety during operational period and post-closure safety

The Andra approach is enabling design evolutions to be integrated throughout the development of Cigéo that will last about 150 years while ensuring post-closure safety.

As part of an iterative process, all changes in technical solutions affecting the closure structures and all changes to the architecture on completion will be examined using the most relevant indicators to check that performance and safety are guaranteed.

This approach links safety both in operation and post-closure. It provides a means of managing the improvements and technical evolutions foreseen for Cigéo throughout its operational period and the operating experience feedback, as well as incorporating any changes to regulations or practices nationally or internationally, while still guaranteeing the principle of defence in depth.

The feasibility of using new technologies in the disposal system design will therefore be confirmed by analysing their compatibility with safe operation of the facility and their compliance with the post-closure safety requirements.

Although the final closure of Cigéo will come about a century after the start of its operation, Andra has established a process for incorporating the post-closure safety requirements from the design stage and for checking that these requirements are met using an iterative process as part of the gradual development of the waste disposal facility (see Figure 4.4-1.

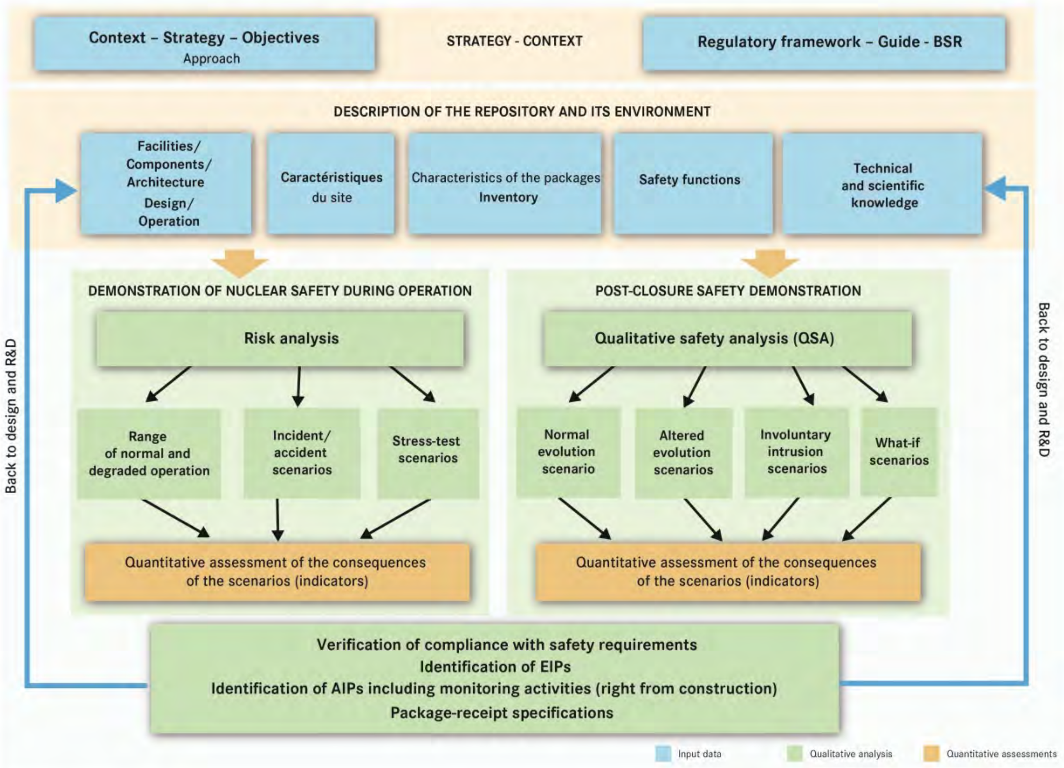


Figure 6: **DIAGRAM ILLUSTRATING THE COORDINATED APPROACH BETWEEN SAFETY IN OPERATION AND POST-CLOSURE SAFETY**

The coordinated approach consists of:

- identifying standards, regulations and the positions of assessors, and the national and international practices that guide choices and design principles and are used as the framework for the safety analysis;
- identifying the post-closure safety functions;
- establishing current knowledge of:
  - ✓ the waste packages (inventory and characteristics), and the geological medium of the site;
  - ✓ the facility at completion and its location in the Callovo-Oxfordian;
  - ✓ the technical solutions, particularly by using demonstrators;
  - ✓ the EBS and scientific understanding of the long-term evolution of the disposal system (engineered components and host formation) and its environment (surrounding formations, biosphere) taking into account Thermal, Hydraulic-Gas, Mechanical, Chemical and Radiological processes in time and space, and the pairing of these

different phenomena, particularly on the basis of multiple experiments conducted in laboratories and in situ at the Meuse/Haute-Marne Centre;

- the assessment stage, which must demonstrate that the design options fulfill the safety functions by means of:
  - ✓ analysis of the safety in operation of the disposal facility, in particular by analysing the risks and where necessary introducing preventive and protective measures to reduce these risks;
  - ✓ analysis of the post-closure safety of the facility, in particular by analysing the post-closure uncertainties through a qualitative safety analysis that identifies and evaluates, component by component, the uncertainties concerning the way that the behaviour of the disposal facility will evolve, identified in the phenomenological analysis of repository situations (PARS), to ensure that they are covered by design choices or in scenarios.

The safety functions described below are applicable to Cigéo throughout the operating phase and must be maintained in all incident or accident situations of internal or external origin or, at least, restored within time limits consistent with the objectives of protecting people and the environment defined for the Cigéo project.

- contain radioactive substances to protect against the risk of their dispersion;
- protect people from exposure to ionising radiation;
- manage safety with regard to the criticality risk;
- dissipate the heat produced by some waste;
- remove gases.

3 Description of the Cigéo EBS and clay host rock THMC processes

Clay host rock and engineered barrier system (EBS) are combined to provide post-closure safety associated to previously described safety functions of the disposal. The favourable properties of the clay host rock are the basis of the safety. The design of the EBS contributes to the disposal performances and has to preserve the favourable rock properties.

Note: Only elements dedicates to HLW are considered in this document.

3.1 The geological medium and the clay host rock

Geologically, the Meuse / Haute-Marne site (French host rock) corresponds to a part of the eastern region of the Paris Basin. In this region, the Paris Basin is composed of alternating sedimentary predominantly argillaceous and limestone layers, deposited in a stable marine environment during the Jurassic (165 – 135 Ma). These layers have a simple and regular geometric structure, and slope slightly toward the northwest (1 degree) in accordance with the general structure of the Paris Basin (bowl-shaped structure centered in the Paris area). Within the sedimentary sequence, the Callovo-Oxfordian layer has been selected for hosting a deep geologic repository.

The structural framework is stable, with natural mechanical stresses oriented in the same direction for the past 20 million years. From a seismotectonic perspective, the Paris Basin is a stable zone with very low seismicity, remote from active zones such as the “Fossé Rhénan” toward the east, the Alps (southeast), the Massif Central (south) and the Massif Armoricain (west). There is no detectable neo-tectonic activity or significant local seismic activity in the Meuse / Haute-Marne region, as indicated by the national seismic monitoring network and the local monitoring network implemented by Andra.

The Callovo-Oxfordian formation is a sedimentary clay-rich formation. It mainly consists of clay minerals (e.g., mainly illite and illite/smectite interlayered phases), representing up to 60% of the total rock mass, silts (fine quartz) and carbonates.

A large zone of study for the characterization of the geological medium was defined in 2005 by Andra, within which the Callovo-Oxfordian layer has physical and chemical properties similar to those observed at the URL. This zone is called the Transposition Zone (ZT). Based on the complementary studies developed on the transposition zone and in the URL, Andra proposed in 2009 a zone (~30 km²) of interest (ZIRA) for the implementation of future underground repository facilities. In the ZIRA area, the depth to the top of the Callovo-Oxfordian across this zone varies from 340 m to over 530 m, and the thickness of the layer itself varies from 140 m to 160 m.

The absence of fractures in the investigated zone, the overall very low permeability, the absence of preferential flow paths, the favourable geochemistry (reducing environment, low solubility of radionuclides) are important elements in the safety case that allow the evaluation of transfer through the host formation as diffusion-dominated transport for those radionuclides that are in solution and not strongly sorbed. Any activities (e.g. excavation) or evolutions (e.g. desaturation-resaturation, heating, chemical interactions) that may have an impact on this must be well understood and taken into account.

In addition, these water transport properties of the clay host rock (diffusion-controlled flux rates) limit near field desaturation during operation in ventilated access tunnels and disposal drifts. They also limit resaturation after drifts and tunnels have been closed. This also has implications on the mechanical properties. In addition, due to the very low permeability of the host formation, the only expected interaction with overlying formations is related to access shafts and access ramps. Any impact on surrounding aquifers due to excavation and operation will need to be monitored in order to meet the water environment protection regulations.

The lateral homogeneity of this clay host rock may be used, among other things, to justify that the evolution of any given underground structure is representative of the evolutions of similar structures. Therefore, monitoring of any given representative structure should also provide reasonable insight into the evolution of similar structures, provided construction protocols and materials used are identical or sufficiently similar.

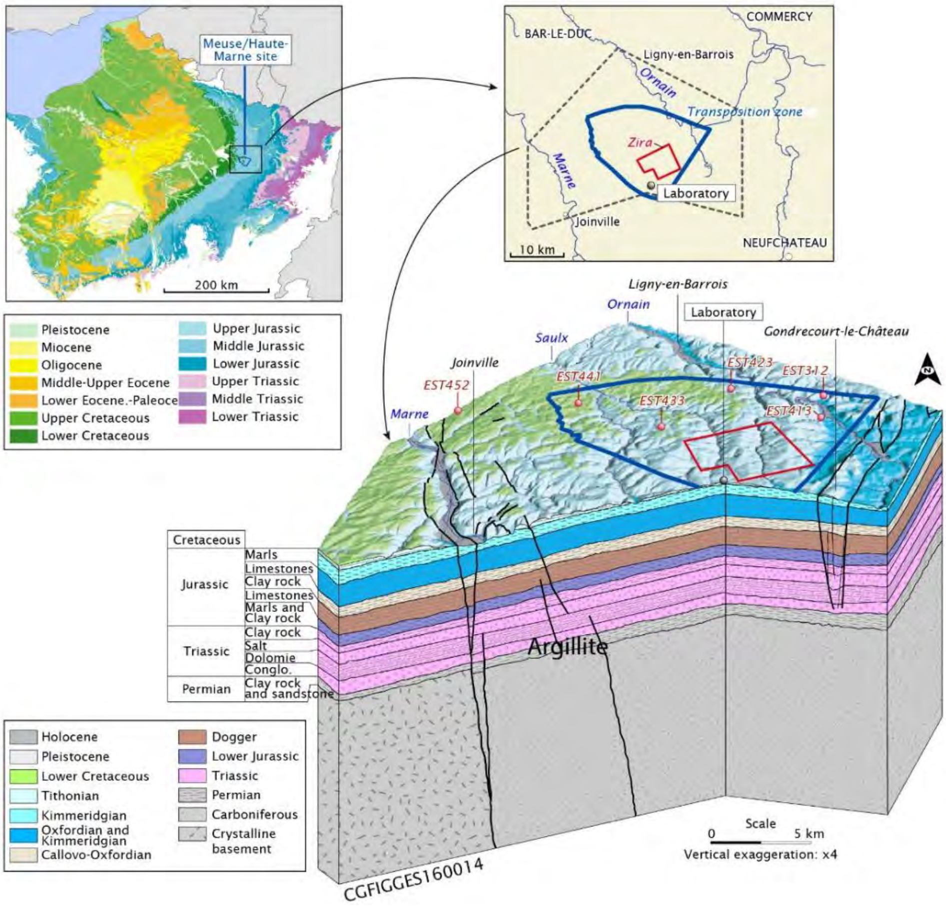


Figure 7: 3D GEOLOGICAL BLOCK DIAGRAM OF MEUSE / HAUTE-MARNE SITE

3.2 The EBS

A distinction is made between a disposal section for moderately exothermic HLW (HA0 in French) and disposal sections for highly exothermic HLW (HA1/HA2 in French). The design of these sections and their disposal cells differs in the moderate heat release from the waste, which allows higher disposal density and by the disposal schedule. A pilot industrial zone will be built well before the operation phase and will contain a small number of moderately exothermic waste cells. This pilot industrial zone will allow a feedback. Additional progress with regard to knowledge and technical demonstrations can offer greater prospects of optimisation as part of the incremental development of Cigéo.

The design options and requirements defined for the HLW disposal cells and disposal sections in order to contribute to the accomplishment of the Cigéo safety functions are described below.

Each HLW disposal cell of Cigéo is blind with respect to the rest of the underground facility in order to limit water flows between the underground facility and the overlying formations via the surface-bottom connections after closure.

The small diameter structure group includes all HL waste disposal cells. These horizontal disposal cells will not be ventilated. A cylindrical envelope/sleeve of non-alloy steel provides mechanical stability. The inner diameters of the disposal cells will be approximately 70 cm. These disposal cells are illustrated in the following figure. This structural component responds to the requirements and allows the emplacement and potential retrieval of the waste disposal package: Its resistance to corrosion – at a minimum during the century scale operation phase – is ensured by its design and by placing the sleeve in a low-corrosion environment. The latter is achieved by the presence of a material between the clay rock and the sleeve contributing to a low corrosion speed and by preventing air exchange with the access galleries, thus providing for an anoxic environment.

It should be remembered that the limitation of the release of the radionuclides contained in the HLW waste is based in the first place on a low weathering rate of the vitrified waste. The weathering rate depends on the inherent characteristics of the glass and on the physicochemical environmental conditions in the HLW disposal cell, in particular the water properties (pH…) and the core temperature of the glass matrix when the water reaches the waste, which depends on the durability of the disposal overpack leak tightness. Andra is consequently designing the HLW disposal cell to support the durability of the disposal overpack initially and then, after loss of overpack leak tightness, the slow dissolution of the glass and the precipitation of most of the radionuclides.

The disposal overpack is protected by giving to the sleeve the highest possible mechanical durability, taking into account scientific uncertainties, technological limits and economic factors; this delays any contact between the sleeve and the disposal overpack during the operation phase. The overpack is also protected by avoiding a chemically-corrosive environment for both the overpack itself and the sleeve.

Like the disposal overpack, the sleeve is made of low-carbon unalloyed steel; this material withstands the mechanical stresses applied by the clay rock, and has a predictable long-term corrosion mode that avoids any risk of galvanic corrosion between sleeve and overpack.

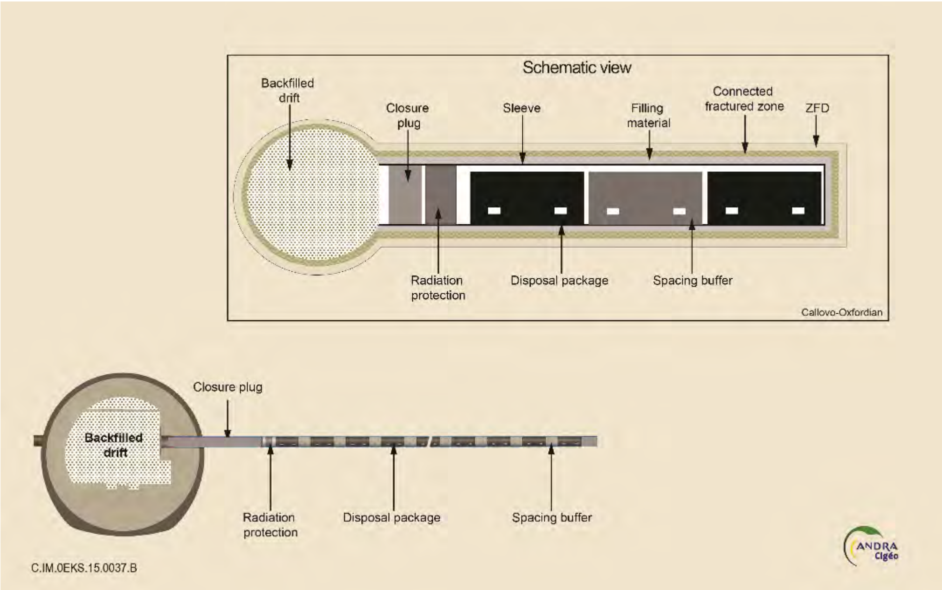


Figure 8: **SCHEME OF THE HLW DISPOSAL CELL DESIGN**

Thermal processes

At the level of the disposal cell (internal and near field), the thermal head in near field is reached during the period of operation: on the basis of established design, the maximum temperatures are reached between about 5 to 10 years depending on the type of HLW disposal cell.

After 100 years (HA0) to a few hundred years (HA1 / HA2), the temperature in a disposal cell is broadly homogeneous: it is around 35 °C in a moderately exothermic disposal cell, and from 50 to 80 °C in a highly exothermic disposal cell and in near field.

Hydraulic processes

In the post closure short term, the exothermicity of HLW results in a temperature increase which implies, particularly in clay host rock at the centre distance between cells, an increase in pressure of the pore water during its thermal expansion (up to 10-12 MPa). The favourable properties of the clay host rock are preserved.

In parallel, but also in the longer term, conditions become anoxic and corrosion rates are then low. This phenomenon produces hydrogen, which prevents total resaturation of the disposal cell during several tens of thousands of years at least.

Mechanical processes

In situ mechanical loading of the sleeve was investigated on reduced and full scale HLW cell demonstrators drilled in the Meuse/Haute-Marne URL. All the measurements led to an anisotropic loading whether with or without cement grout in the annular space between the sleeve and the rock. This behaviour is govern by the anisotropic extent of the excavation induced fractures network around the cell. The resulting radial bending of the sleeve leads to its ovalization, which can reach 1% of the diameter after 5 years. Convergence rate is decreasing with time and an extrapolation over 100 years leads to a maximal diameter variation of about 1.5%. During this period, overpacks are only subjected to a non damaging external hydrostatic pressure.

Chemical processes

To control the functioning of a HLW disposal cell, the most chemical important process is the corrosion of metallic components such as the sleeve and the overpack between 100 and 1000 years and the glass dissolution after 1000 years.

Synthesis of processes with time for disposal components

The different processes are synthetized in the following scheme.

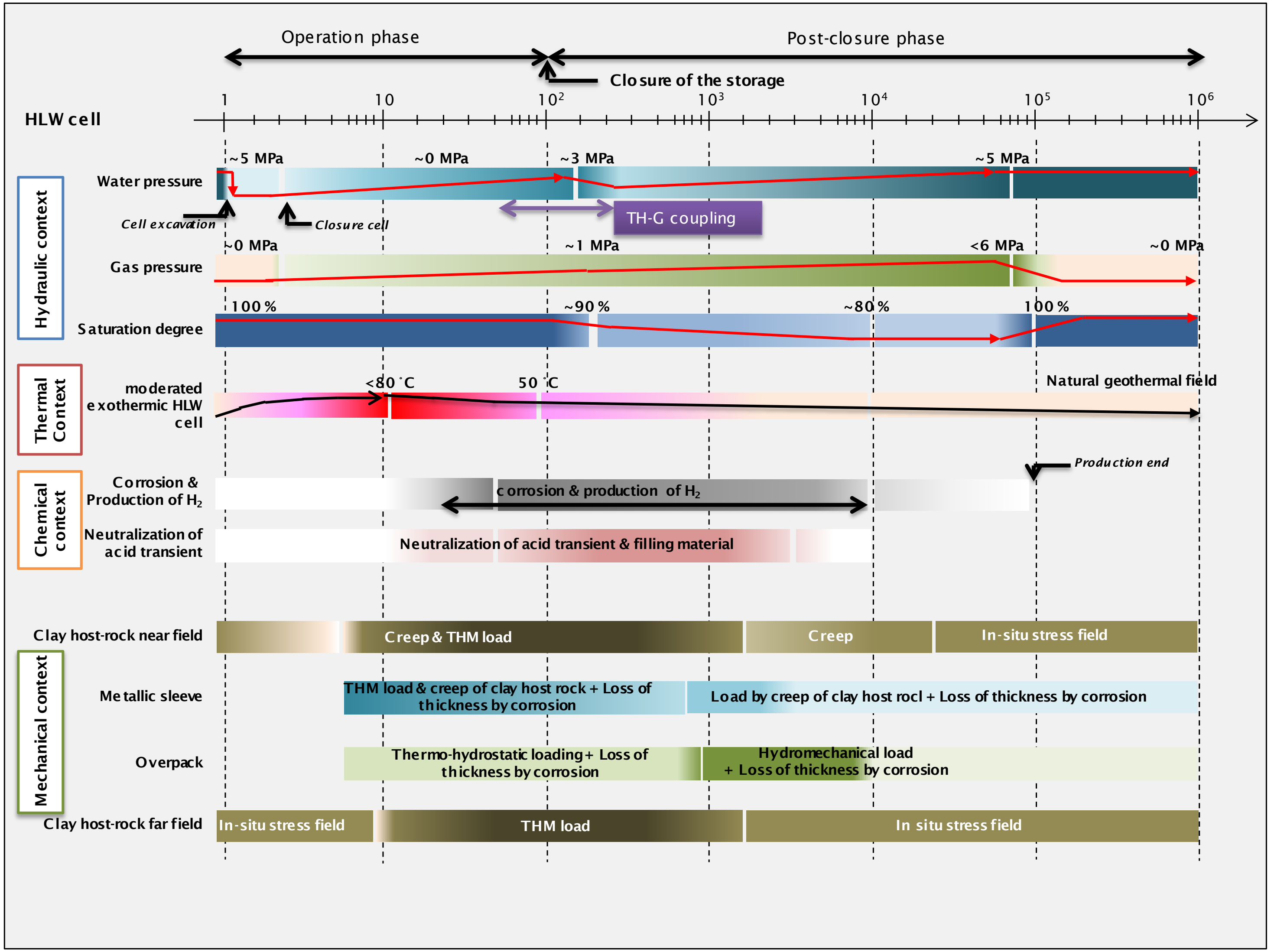


Figure 9: SCHEME OF THMC PROCESSES WITH TIME FOR DISPOSAL COMPONENTS OF A HLW DISPOSAL CELL

4 Monitoring objectives and strategy

The IAEA Specific Safety Requirements SSR-5 (IAEA, 2011a) 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.

4.1 A regulatory framework

This monitoring system also needs to answer to legal expectations expressed, in particular:

- in the 2006 Planning act on radioactive waste management and the 2016 act on transparency and safety,
- in the French Safety Guide, which recommends that Andra develop a monitoring program to be implemented at repository construction and conducted until closure, and possibly after closure, with the aim to confirming prior expectations and enhancing knowledge of relevant processes,
- in Environmental laws, asking to establish an environmental reference state consistent with the importance of the industrial project,
- during public debates, during conferences and seminars conducted to define the reversible governance…

To achieve these objectives, a global strategy including the waste package controls, surveillance of disposal structures and the surface environment is developed by Andra as part of the Cigéo project. This calls for the development and emplacement of a system of waste package controls and for a dedicated monitoring system.

In, 2016, Andra submitted a document explaining the different safety options: «safety options dossier" for the Cigéo project to the French regulator ASN. This sets out the chosen objectives, concepts and principles for ensuring the safety of the facility. The dossier gives Andra the possibility of getting advice from ASN in preparation for the license application on the operation and post-closure safety principles and approach.

Today the regulatory framework about monitoring is under discussion between Andra and regulator.

4.2 The disposal monitoring strategy

For post-closure safety and evaluation of retrievability conditions, the objectives of monitoring are the following ones:

- Check the capability to retrieve waste packages
- Check that post-closure safety is ensured as expected
    - Control the normal evolution domain of the repository system during the operational period
    - increase confidence in the understanding of processes affecting long-term safety.

5 Monitoring parameters identification

5.1 Andra's method for selecting the parameters to be monitored

The method chosen by Andra, to define its needs in terms of processes and parameters to be monitored, analyzes for each component of the repository:

- Safety functions
- Phenomenological processes in link with safety functions
- Quantification of phenomenological processes in link with safety functions
- Selected indicators/parameters of phenomenological processes in link with safety functions
- Monitoring apparatus/technology
- Data management

This method for selecting the monitoring parameters differs slightly from that proposed under Modern2020, in particular as regards the starting point and the steps dedicated to the processes.

5.2 The starting point for testing the workflow proposed in Modern2020

The objective of task 2 withinModern2020 work package (WP) 2 is to test the methodology for selecting parameters to be monitored as developed within Task 1 of WP2. As mentioned above, this method is slightly different from the one developed and used by Andra. Still for the purpose of assessing and refining Modern2020 workflow, Andra tested the workflow to identify parameters in a HLW disposal cell.

To test the Modern2020 workflow, Andra began the analysis from a set of global phenomenological processes without any consideration of safety. This made it possible to test all the steps of the workflow. Starting from important processes for the safety would not have allowed testing all the stages of the workflow, in particular steps PRO2 and PRO3 (cf. process level of the workflow).

The set of phenomenological processes was defined from the Andra's analysis called PARS (phenomenological analysis of repository situations).

The construction, provision of equipment, gradual operation and gradual closing of a disposal facility or repository initiate various phenomenological processes. They are complex, often coupled and may persist from a few hours to a few hundreds of thousands of years. Many physical processes are involved at multiple spatial scales:

- Thermal (T);
- Hydraulic-gas (H);
- Mechanical (M);
- Chemical (C);
- Radiological (R).

The phenomenological analysis of repository situations (PARS) corresponds to the group of THMCR processes affecting the repository/disposal and its geological environment from the operating phase until up to the very long term period. It is the evolution judged the most probable in the current state of scientific knowledge without any safety considerations.

The processes for HLW disposal cells are the following ones:

- Heat production by HLW;
- Time dependant deformation of the clay host-rock;
- Thermo-hydraulic-gas transient;
- Oxydation of the clay host-rock;

- Corrosion of metallic components.

These processes concern 4 main components: clay host-rock, atmosphere in the disposal cell, sleeve and overpack.

5.3 Cigéo test case: evaluation of the Modern2020 screening methodology

All the processes occurring in an HLW disposal cell and determined under the PARS methodology were used to test the workflow proposed by Modern2020.

The first step in the workflow is to distinguish important processes with respect to the safety and / or retrievability condition of radioactive waste storage packages. Modern2020 is not addressing operational safety requirements even though the retrievability functions can be closely linked to those of the operation (protection of the worker, among others).

Andra has decided to illustrate each part of the workflow with the example of the corrosion process.

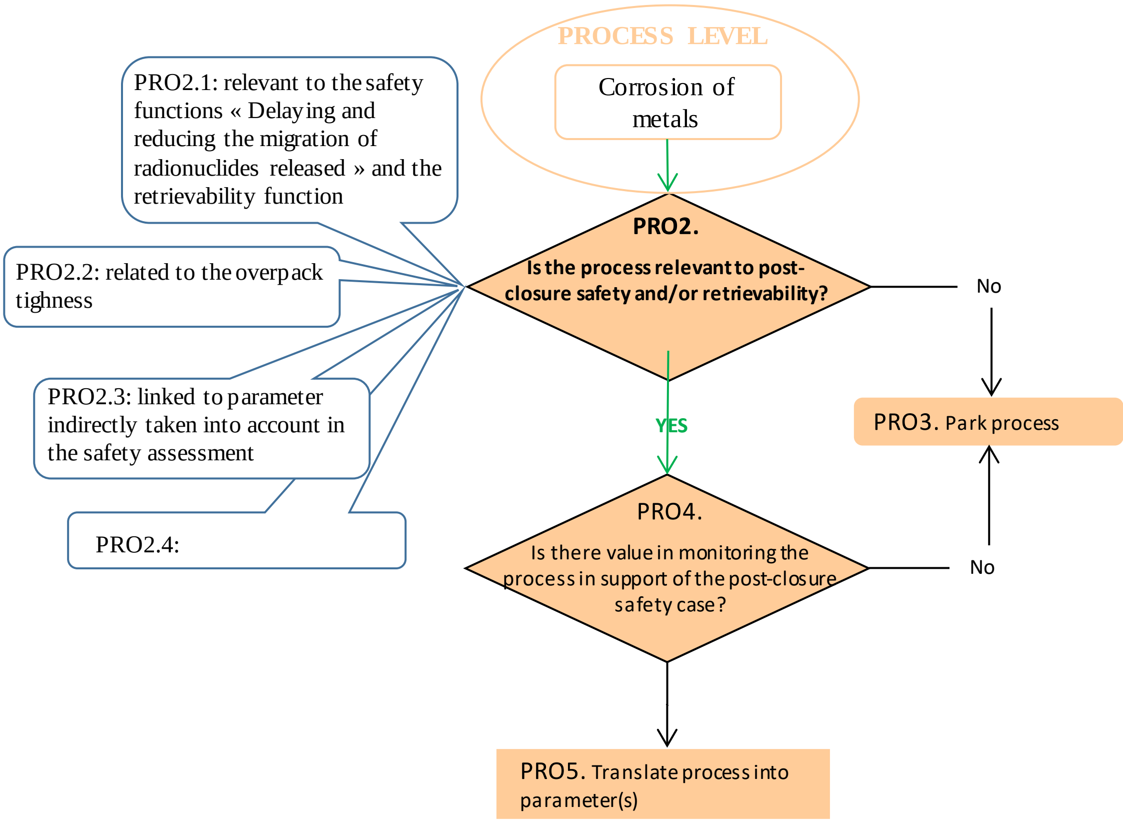


Figure 10: EXAMPLE OF ANSWERS TO PRO2 FOR ONE PROCESS IN THE CASE OF THE HLW DISPOSAL CELL

Andra finds the associated sub-questions very useful to answer to the PRO2 step.

- PRO2.1: Is the process related to one or more safety functions of any element of the repository system?
- PRO2.2: Is the process related to any safety function indicator?
- PRO2.3: Is the process linked to a parameter modelled in the safety assessment that has a significant impact on system performance (dose/risk)?
- PRO2.4: Is the process related to system performance that could lead to a decision to retrieve waste or otherwise reverse the disposal process?

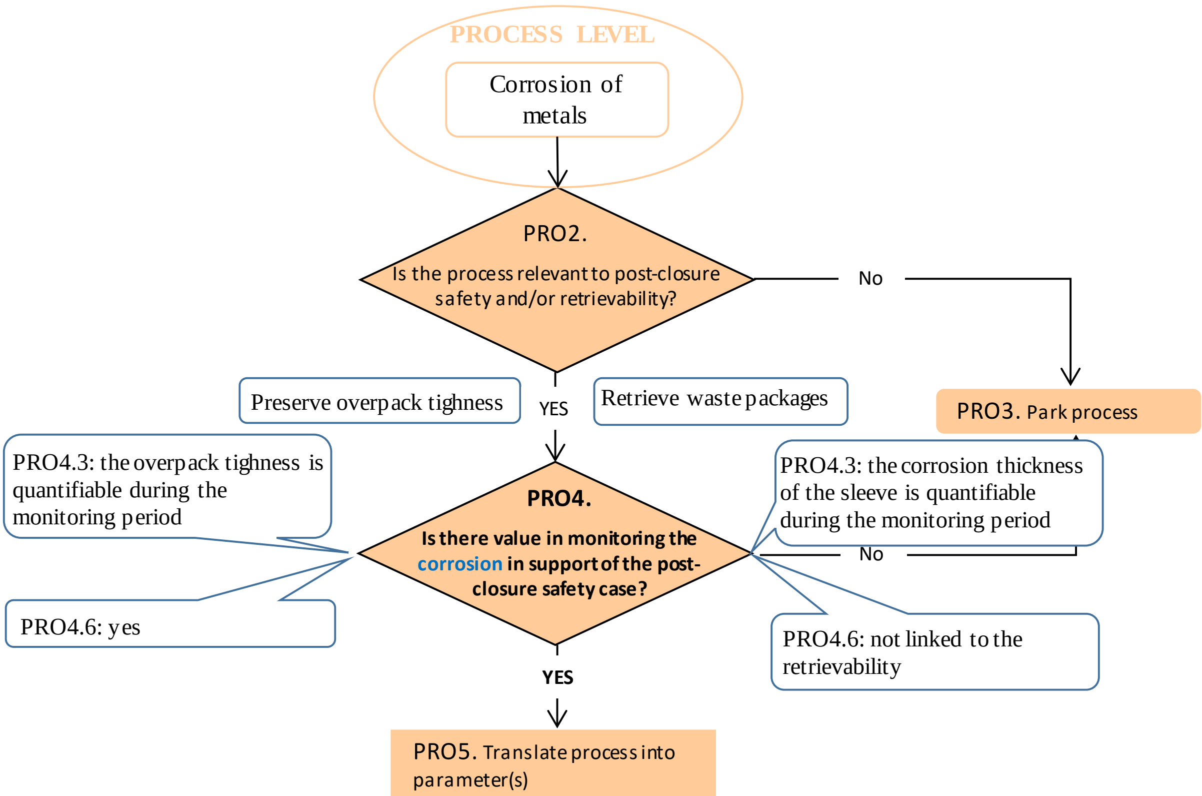
The analysed processes are not all directly linked to a parameter modelled in the safety assessment: they may be used indirectly because they are already taken into account in the design requirements, the architecture. The post-closure safety is first based on the favourable characteristics of the Callovo-Oxfordian and a suitable architecture (upper and lower thicknesses of intact rock, intrinsic properties: hydraulic conductivity, diffusion coefficients ...).

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

To answer this question, which is mainly based on an expert opinion, additional questions are proposed associated with the parameter selection workflow. These questions are:

- PRO4.1: 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);
- PRO4.2: 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)?
- PRO4.3: Could the changes to the repository system resulting from the process be quantifiable during the monitoring period?
- PRO4.4: Could any uncertainty that would be addressed by monitoring the process be more readily addressed by changes to the repository design?
- PRO4.5: Could monitoring the process support repository design improvements?
- PRO4.6: Could monitoring the process result in greater system understanding that would be incorporated in a periodic update to the post-closure safety case?

Here again, the sub-questions are important, especially PRO4.3 which allows to exclude certain non-quantifiable processes during the monitoring period.



<u>Andra remarks after use of this workflow step:</u> The sub-questions are of significant help.

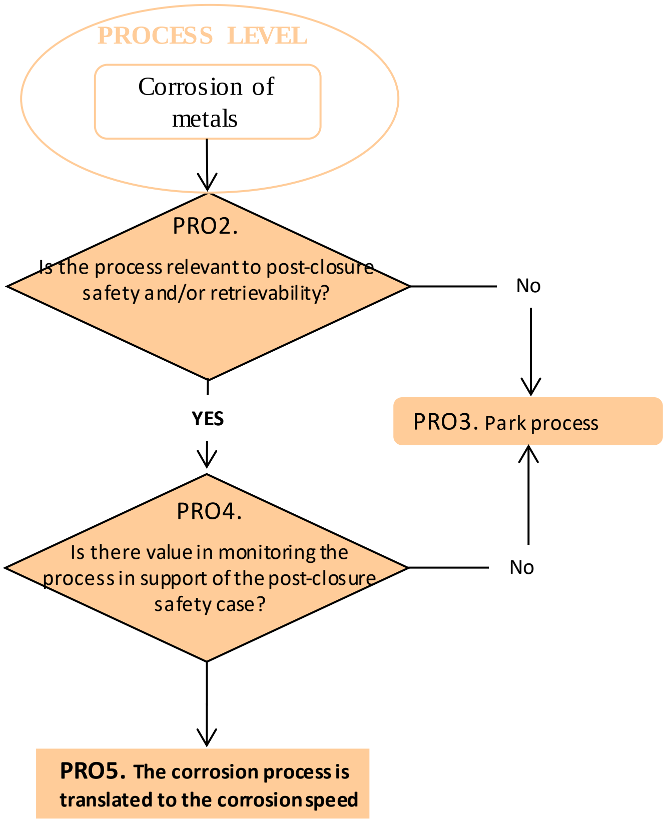
Between PRO2 and PRO4, there is not anymore consideration of retrievability process. PRO 4 is only looking at the value of monitoring for post closure safety.

Comment on PRO4.1: The aim of monitoring is not to reduce uncertainty on repository performance but to confirm the trend.

Comment on PRO4.3: Monitoring period for the disposal cells is around 100 years. Changes could not be observed for all selected processes.

The next step PRO5 is to define parameters associated with each process.

Regarding the example of the corrosion process, the first associated parameter is the corrosion speed of the overpack.



Andra remarks after use of this workflow step:

The parameters associated to the same process must not be decoupled for the rest of the analysis, as this may reduce the representativeness of the measurements and the quality of the process monitoring.

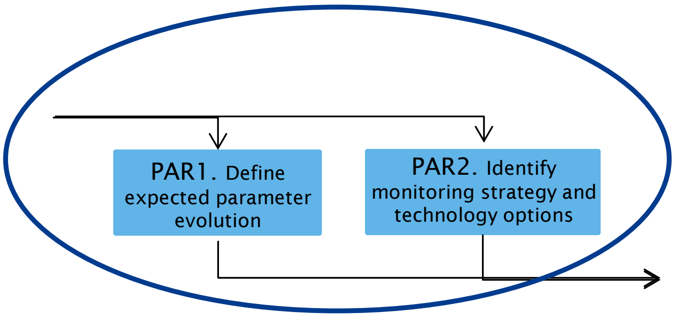
The choice of monitoring technology and its location (subsequent step) depend on the component to be monitored.

The selected parameters in link with post-closure functions or retrievability function are summarised in the following table, before any consideration of feasible technology.

Phenomenological process	Function (post-closure safety or retrievability)	Sub-function	Phenomenological process in link with a component and function	Selected parameter

Heat production by HLW	Preserve favourable properties of the clay host rock	Limit thermal and thermos-mechanical disturbances	Thermal evolution of the near field clay host rock	Temperature of the clay host rock
			Thermal induced pressurization of the clay host rock	Effective stress of the clay host rock
		Limit thermo-hydraulic disturbances	Thermal evolution of the disposal cell	Temperature at the surface of overpack
			Thermal induced pressurization of the clay host rock	Pressure in the clay host rock
TH gas transient	Retrieve waste packages		Generation of H_2 in the disposal cell	H_2 concentration
	Preserve favourable properties of the clay host rock	Limit thermo-hydro-gas disturbances	Generation of H_2 in the disposal cell = no relevant during the operation period	
	Restricting the release of radionuclides and immobilising them in the repository	Protecting the waste from water	Corrosion of the overpack	Corrosion cinetic
Time dependant deformation of the clay host rock	Retrieve waste packages		Metallic sleeve deformation	Sleeve displacement
	Restricting the release of radionuclides and immobilising them in the repository	Protecting the waste from water	Metallic sleeve deformation	Thermo-mechanical load on sleeve
	Preserve favourable properties of the clay host rock	Master the long-term mechanical evolution	Mechanical evolution of the clay host rock	Clay host rock creep
Corrosion of metallic components	Restricting the release of radionuclides and immobilising them in the repository	Protecting the waste from water	Corrosion of the sleeve	Corrosion cinetic
	Restricting the release of radionuclides and immobilising them in the repository	Protecting the waste from water	Corrosion of the overpack	Corrosion cinetic
Oxidation of the clay host rock	Restricting the release of radionuclides and immobilising them in the repository	Protecting the waste from water	Neutralization of the acid transient by the filling material	pH of the water within the disposal cell

The next step PAR1 concerns the definition of the expected domain of parameter evolution. In the text of the workflow, it is specified that it is necessary to model the performance of each parameter.



Andra remarks after use of this workflow step:

The notion of parameter must be well defined. It is necessary to define a couple {parameter, component} linked to a process to follow.

At this stage of the analysis, it does not seem necessary to have a modelling of the evolution of each parameter. Limit requirements or orders of magnitude may be sufficient to go to the next steps.

The following part of the workflow focusses in strategy issues and technology solutions.

In terms of global strategy of monitoring, Andra has decided to provide at the start of the operation of the geological repository for an industrial pilot phase in order to back up the underground laboratory tests and confirm the following points during actual operations and in the associated conditions. There are also general principles in the choice and use of the monitoring technologies, whatever the parameter is to be monitored.

For example, during the industrial pilot phase, direct measurements of parameters, non-destructive methods, redundancy of systems, and the least amount of human intervention possible could be emphased.

It seems to us that this step should be removed. A possible modification is proposed in figure 27 the step PAR2 becomes the step TEC2. The notion of monitoring strategy is discussed if no technology is available in the conditions of the disposal facilities.

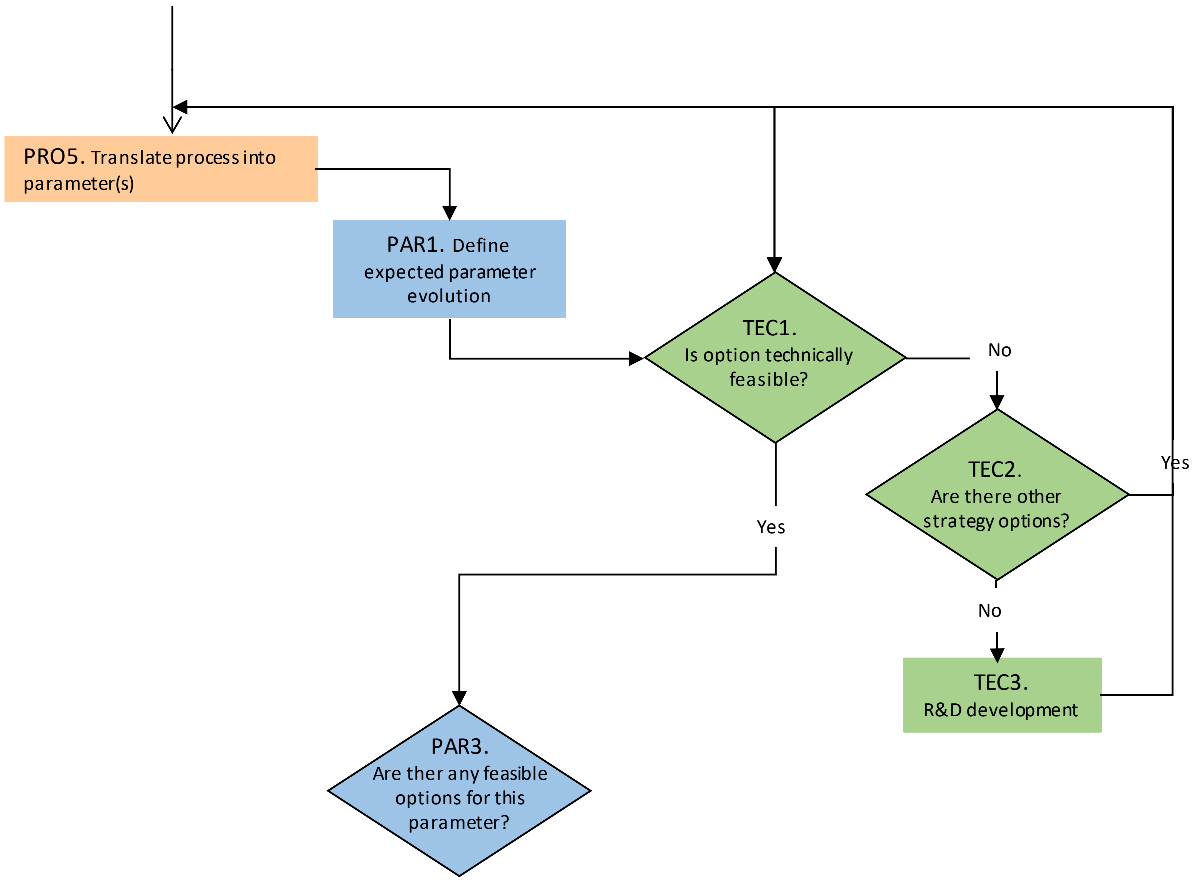


Figure 11: PROPOSITION OF WORKFLOW MODIFICATION FOR THE STEP PAR2

<u>Andra remarks after use of this workflow step:</u>

It would be relevant to define a step which emphasizes the global monitoring strategy and which may constrain the technological options and a step on monitoring strategy applied to a process or a parameter acquired by a technology.

The step dedicated to parameter monitoring strategy seems to be better placed once the feasible technologies are listed.

In the next step TEC1, based on current state-of-the art technology, the possible known and/or tested technical solutions constrained by the general surveillance strategy are considered with regard to the following sub-questions:

- 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?

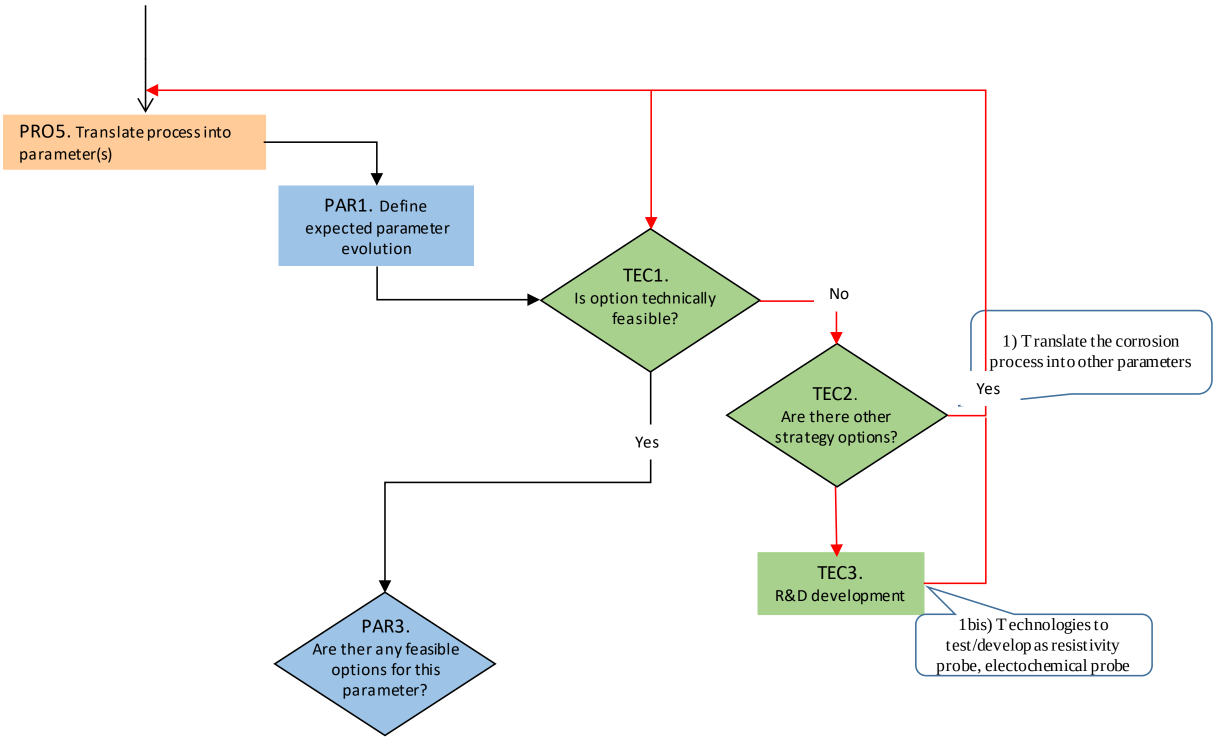
This step may reveal a lack of available technology to measure a parameter. For example, the measurement of the corrosion speed is not directly possible taking into account the constraints of the disposal cell. According to the workflow, foreseen technology to monitor corrosion should be kept aside.

With the added step TEC2 allowing to adapt the strategy and to go back to the translation into parameters, it becomes possible to propose another feasible technology.

Several options are possible: translate the corrosion process in other parameters like the loss of mass of metal coupons or environmental condition measurements to check that the corrosion is generalized and to evaluate the associated corrosion cinetic.

In the case of the overpack corrosion, getting back to PRO2 allows to translate the process in indirect parameters as environment conditions and thickness of the HLW overpack. The objective is not here to access to the corrosion speed but to condition domains representative of a type of corrosion.

In this case, sensors exist for environmental conditions and thickness of the overpack measurements.



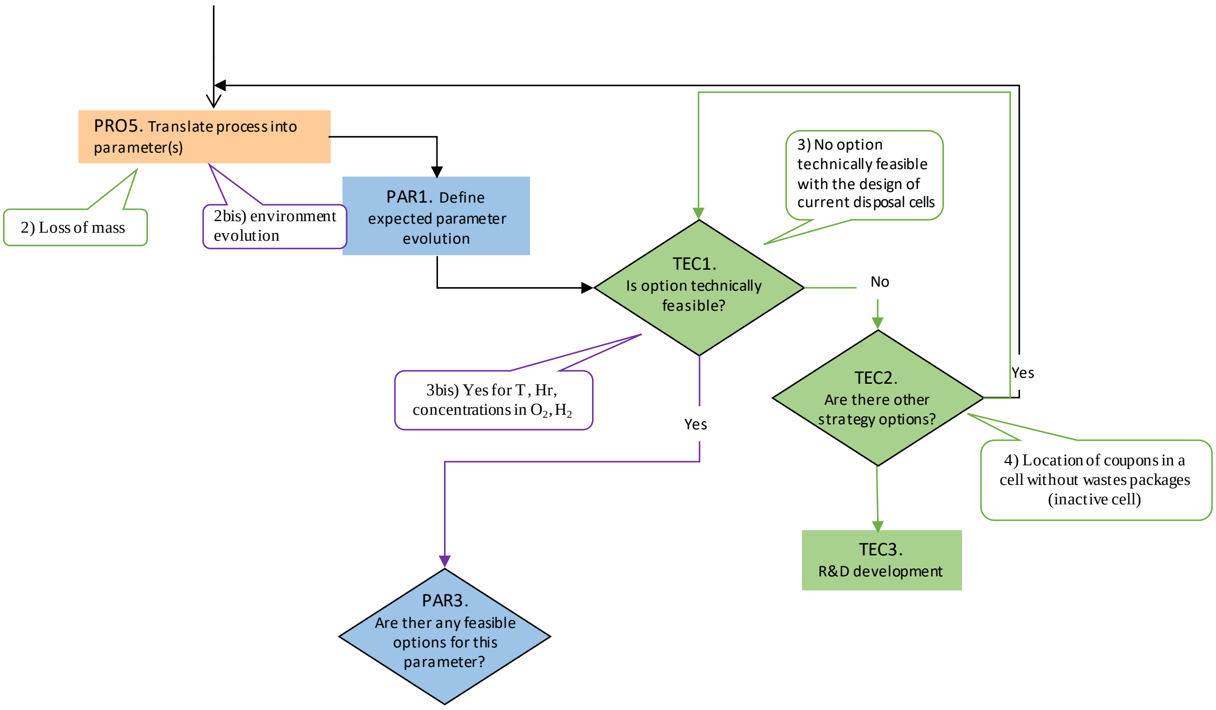
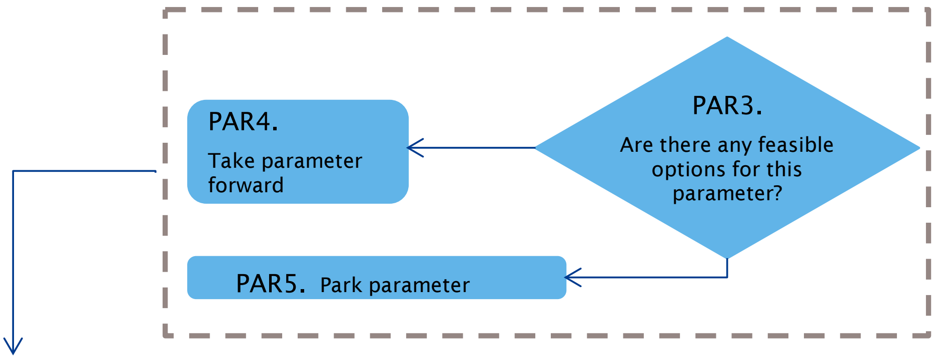


Figure 12: USE OF WORKFLOW MODIFICATIONS TO PROPOSE OTHER WAY TO MONITOR THE CORROSION PROCESS

> Andra remarks after use of this workflow step:
>
> At this stage, it would be necessary to allow a link to the strategy. If there is no feasible technology in the disposal conditions, it is important to be able to modify the measurement strategy if necessary (indirect measurement, design evolution…).
>
> For all parameters selected in this test case, a technology option has been proposed associated to a strategy option.
>
> The question of the implementation feasibility with the design of the component should be better emphasized, for example as a sub-question of TEC1.

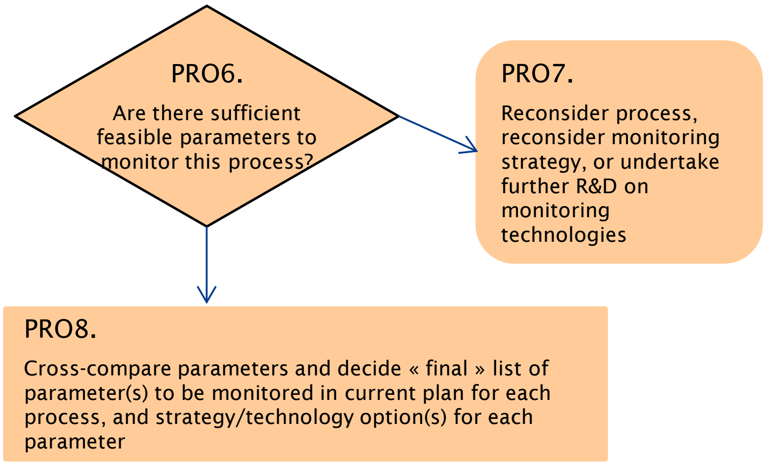
The next stage {PAR3, PAR4 and PAR5} allows checking that it exists a feasible option for the monitored parameter.



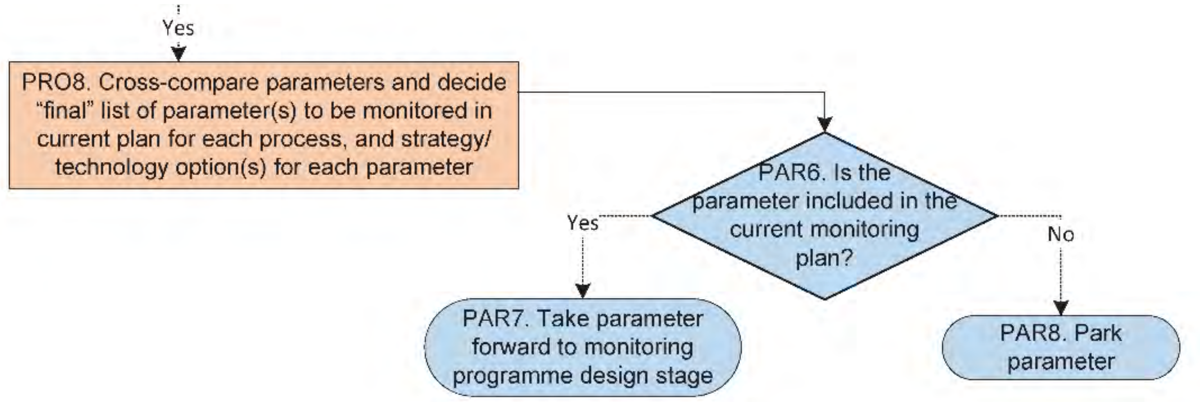
At this step, there is a little misunderstanding. Taking into account the previous step, there is at least one feasible technology for the selected parameter.

The technology options as results of the present test case are summarized in the following table.

Parameter	Component	Reasoning for monitoring parameter	Technology option for monitoring as results of the present test case
Temperature	Disposal cell / near-field rock	Relevant to post-closure safety and retrievability (information about possible rock deformation).	Monitored directly in some cells using Pt probe and/or optical fibre sensors.
Porewater pressure	Near-field rock	Relevant to post-closure safety (information about thermal induced pressurization of the clay host rock)	Monitored directly using vibrating wire or optical fibre piezometers.
Confining pressure	Total pressure on cell sleeve	Relevant to demonstrating retrievability of the disposal packages (information about the mechanical load acting on the cell sleeve)	Monitored directly in some cells, using optical fibre sensors.
Displacement	Cell sleeve	Relevant to demonstrating retrievability of the disposal packages (information about the deformation of the sleeve)	Monitored directly in some cells using optical fibre sensors and 3D scan.
Strain	Cell sleeve	Relevant to demonstrating retrievability of the disposal packages (information about the deformation of the sleeve)	Monitored directly in some cells, using optical fibre sensors.
Hydrogen concentration	Cell atmosphere	Provides information about the cell atmosphere as data for the retrievability of the disposal packages and about the environment conditions of corrosion	Monitored directly in some cells using LiDAR and/or thermal gas conductivity and/or gas density and viscosity measurements.
Oxygen concentration	Cell atmosphere	Provides information about the cell atmosphere, as data for the retrievability of the disposal packages and about the environment conditions of corrosion.	Monitored in some cells using LiDAR.
Relative humidity	Cell atmosphere	Provides information about the corrosion of sleeve and overpack, which is relevant to demonstrating retrievability of the disposal packages and to post-closure safety (environment conditions).	Monitored in some cells using capacitive sensor (based on an electrical capacitor).
Porewater pH	Near-field rock	Relevant to post-closure safety (information about the neutralisation of the filling material)	Monitored in some cells (based on pH meter)
Thickness	Cell sleeve	Relevant to demonstrating retrievability of the disposal packages.	Monitored in some cells using corrosion coupons.
	Overpack	Relevant to post-closure safety.	Monitored in some cells using corrosion coupons.
Corrosion rate	Cell sleeve	Relevant to demonstrating retrievability of the disposal packages.	Monitored indirectly in some cells using electrical resistance probes and mass loss of coupons.
	Overpack	Relevant to post-closure safety.	Monitored in some cells using electrical resistance probes and mass loss of coupons.



With respect to the next step PRO8, the comparison could eliminate some redundant parameters. However, the decision depends on the general monitoring strategy and the location of each parameter measurement. Temperature for example is a key parameter to follow many processes. This parameter can be measured at different locations depending on the process to follow. It may be decided at this stage to use a single sensor and at only one location. However, it may also be decided to keep several measurement means in different components or with redundant technologies. For this cross-comparison, the parameters need to be linked with the associated process and the measurement location.



PAR 6: is the parameter included in the current monitoring plan?

For Andra, it is “yes” at this stage

<u>Andra comments:</u>

Andra doesn’t understand completely the wording of the sentence. Andra suggests to delete “current”.

Some sub questions could be envisaged to PAR 6 regarding especially the cost.

6 Conclusion

Andra considers the screening methodology quite useful to structure and justify the final parameters to include in a monitoring plan.

Nevertheless, Andra considers that the screening methodology could be updated considering the specific points:

Retrievability

Parameters in relation to retrievability could be better considered in the workflow.

Link between strategy & technology

The actual wording of the PAR2 and TEC1 could be confused and should be modified. The workflow should better consider that the monitoring strategy could be revised if there is not suitable/feasible technology. This revision may consider other (indirect) parameters or other types of cells to monitor.

Appendix D: ANSICHT Test Case (DBETEC)

Contents

Executive summary

The aim of this report is test the applicability of the screening workflow developed during task 2.1 of the project. The development of the Modern2020 Screening Methodology is motivated by a desire to develop a justified and needs-driven monitoring programme. The development of this kind of monitoring programme is a major motivation for DEBTEC to participate in this task. The use of a structured screening approach would allow to explain in a comprehensible and transparent way why, how, and to what extent repository monitoring is intended to be performed taking into consideration technological possibilities and limitations.

In the frame work of the German ANSICHT project a repository concept as well as a backfilling and sealing concept has been developed for potentially suitable clay formations in Germany. The sealing concept consists of different types of engineered barriers like emplacement borehole seals and drift and shaft seals. For testing the screening methodology of these barrier types, the emplacement borehole seal, has been selected as an example and thus as the ANSICHT test case.

Prior to going through the screening workflow those processes have been selected which potentially have an impact on the performance targets and thus on the safety function of the seal. To identify these processes the site specific FEP catalogue has been used. This list of processes has been used as a starting point for the parameter screening. By going through the screening process the following main findings have been listed:

- It seems not appropriate to go through the whole screening workflow process by process but going through it step by step considering all selected processes at each individual step in parallel.
- The first half of the screening process was found to work well. In view of the first bullet point, we proposed a few changes of the supplementary guidance questions which in general we found to be quite helpful with regard to justifications.
- In the second half of the screening process we think there are a few overlaps needing clarification, especially in terms of transparency to external viewers (e. g. stakeholders).
- For the rest of the screening work flow, we think a re-arrangement of boxes, additional links, and a new PAR4 box might be helpful.
- In particular, the contents of the PRO7 box should be revised because on the one hand it mixes up the three levels of processes, parameters, and technology and on the other hand it may question identified processes which seems not appropriate.
- A visually more restrictive division between the three levels 'process level', 'parameter level', and 'technology level' should be strived for. This would make the illustration more transparent.

As a result of the screening test, we propose a revised workflow to address the findings mentioned above for discussion (Fig. 0.46). The outcome of the screening process is a final parameter list for monitoring the emplacement borehole seal. According to this list a monitoring concept has been developed and the corresponding system requirements been stated based on simulations of the parameter evolutions.

Finally, the monitoring concept has been linked to decision making by the development of decision sequences, explicitly identifying decision points in time and responsibilities. Considerations about confidence building complement the performed work.

1 Introduction

The focus of the Modern2020 Project is monitoring during the operational period in support of demonstration of post-closure safety. Aspects of monitoring after final closure are for consideration by the responsible organisation. It is an implicit principle of the Screening Process that any monitoring after full closure of a repository would be a continuation of monitoring prior to full closure. Therefore, the process that is developed here is equally applicable to all phases of monitoring. Closure entails that deposition is completed and galleries are backfilled. Once monitoring is put in place during the operational period it is up to the responsible organisation and its regulatory framework to decide on discontinuation.

Monitoring programmes based on developed safety cases are at different levels of development. Preliminary parameter lists exist for the Cigéo and Olkiluoto repositories. For the other programmes, preliminary parameter lists will to some extent be developed within Task 2.2.

The general objective of Task 2.2 is to test the methodologies for screening monitoring parameters identified and developed in Task 2.1. Specific objectives are:

- Describe specific objectives for monitoring the barrier system in different national programmes, based on generic objectives for monitoring identified in the former MoDeRn project.

- Identify the parameters that should be monitored in practical (implementable) programmes by using screening methodology from Task 2.1.

- Describe the expected evolution of the disposal system during the monitoring period, as it relates to the monitoring parameters identified.

The approach used will depend on the national programme, and may include consideration of safety cases during the operational phase, safety function indicators and/or FEPs.

It will be relevant to develop a link between EBS (Engineered Barrier System) monitoring results and the decision making processes during the operational phase of repository implementation. Specifically, the work in Task 2.2 shall for different national programs elaborate on how results from the monitoring of the EBS might be utilised to support operational decision and provide support to stakeholders. This will feed into Task 2.3 to identify and develop methodologies and tools to for the decision making process.

2 System description

With the restart of the site selection for a high-level waste (HLW) repository in Germany different types of host rocks, especially clay, are in the focus. During past years the research activities in argillaceous rocks in Germany have been significantly intensified.

In the framework of the ANSICHT project a safety assessment methodology for a high-level waste repository in clay formations in Germany was developed (Jobmann et al. 2017a and 2017b). This was done by a project team consisting of Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Federal Institute for Geosciences and Natural Resources (BGR) and DBE TECHNOLOGY GmbH. In the ANSICHT project, the idea was to use generic geological models showing typical clay formations and adjoining rocks situations in Germany. Exemplarily, for different boundary conditions in Germany, two generic geological models, typical for potential clay sites in Northern and Southern Germany, were developed.

The project is important for the German scientific community in the field of the high-level waste disposal, and it is in line with the new site selection process in Germany, which at the first stage considers different host rocks equally eligible for the final disposal of high-level waste and spent fuel (HLW/SF) (Deutscher Bundestag 2013).

The repository concept and especially the sealing concept have been taken as the ANSICHT Test Case for MODERN2020.

2.1 EBS/Host rock system

At the begining of the ANSICHT project, results from former investigations of BGR were available regarding potentially suitable clay formations in Germany (Hoth et al. 2007). In this study, clay formations have been selected based on criteria defined by the „Arbeitskreis Auswahlverfahren Endlagerstandorte" (AkEnd 2002). The results are shown in Fig. 0.1. The areas identified to be potentially suitable are marked in green. Since the clay formations in Northern and Southern Germany are significantly different, it was not possible to represent all aspects in one representative geological model. Therefore, the development of two different site models was necessary. These two site models are illustrated in Fig. 0.2.

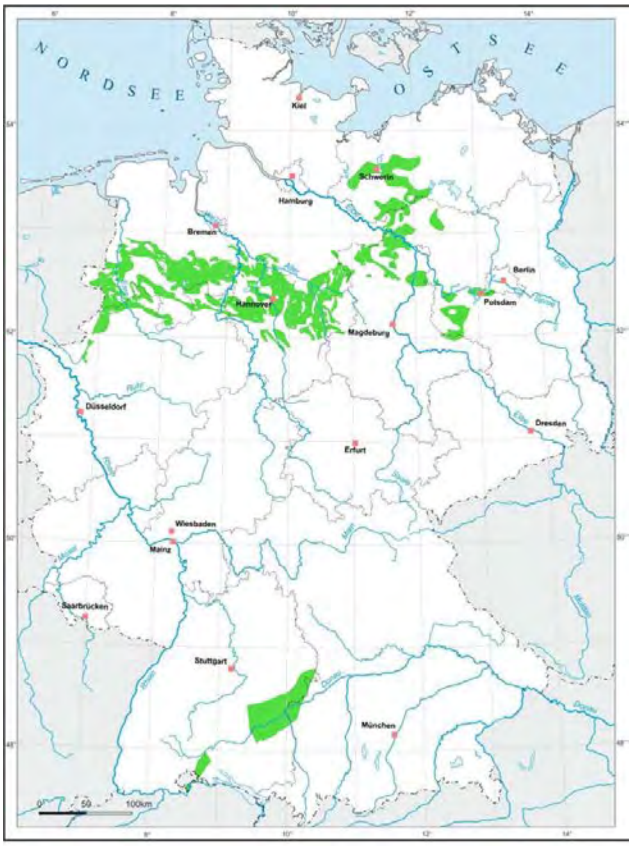


Fig. 0.1:

Areas of potentially suitable clay formations in Germany (Hoth et al. 2007)

2.1.1 Generic geological site models

A sound basis for a system analysis is a 3D geological site model. For this, two generic geological models for Northern and Southern Germany (Model NORTH and SOUTH) are built up in 3D with defined model units as shown in Fig. 0.2 (Reinhold et al. 2013, Reinhold et al. 2016). The model units represent relatively homogenous formations, which can regionally be well characterised. The data basis like position, depth, bedding or lithologic, hydraulic, and petrophysical properties for the units were derived from published data of the exploration industry on oil, gas, salt and other natural resources (Jahn & Sönnke 2013, Jahn et al. 2016). For every model unit representative values have been selected as input data to numerical model calculations (Nowak & Maßmann 2013, Maßmann 2016). Because the available published data for German clay rocks is insufficient, assumptions derived from comparable geological units are taken into account. These assumptions are based on the findings from international site investigation programs, for example in the context of repository projects in Switzerland and in France.

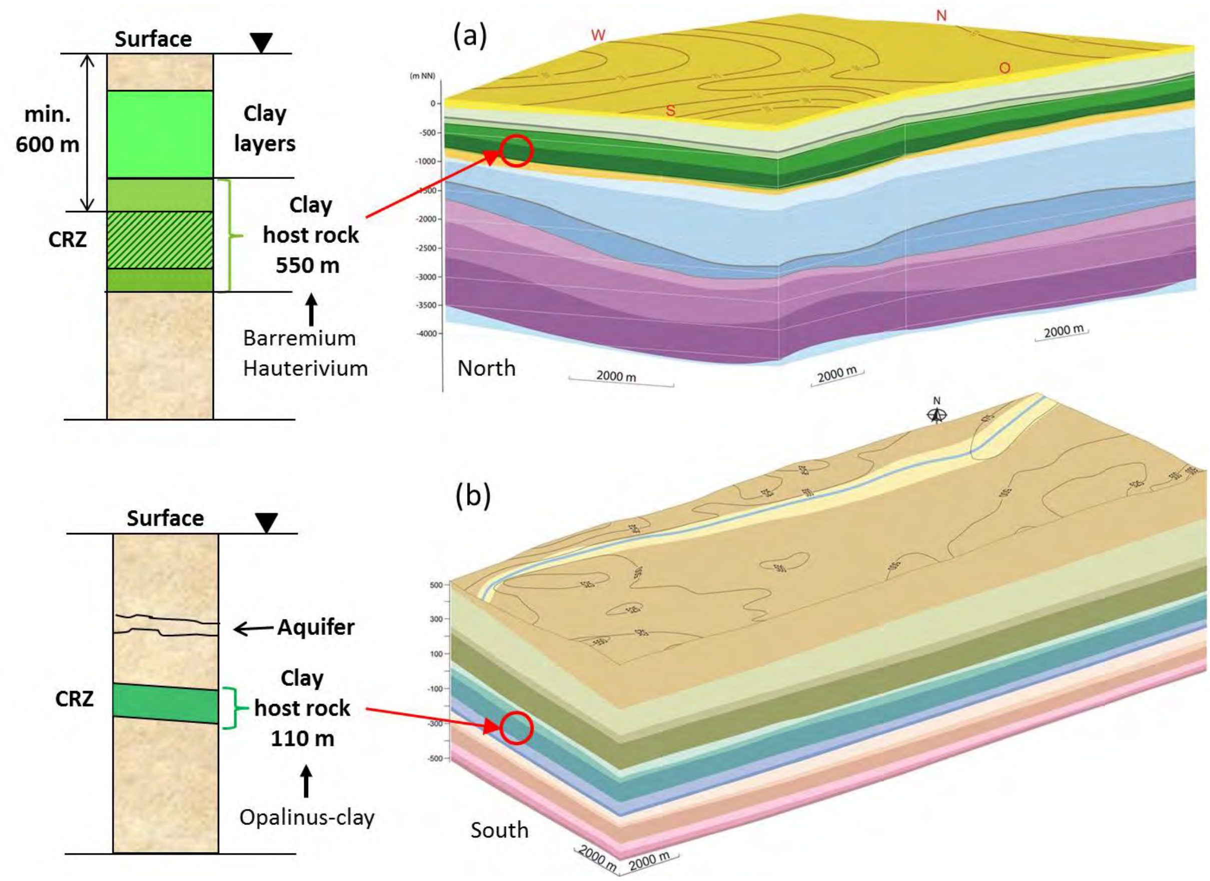


Fig. 0.2: 3D geological sections (right) illustrating the model units of the repository site models North (a) and South (b) as well as simplified geological profiles (left) illustrating the availability of clay layers at the different model sites.

The representative parameters include average values and bandwidths. The parameter collection includes mineralogic and geochemic, petrographic, mechanic, thermal and hydraulic parameters. In a second step, certain parameters are selected out of a bandwidth for numerical simulations which are used to demonstrate the integrity of the geologic barrier.

The model NORTH represents a typical situation in the North German Basin where potential host rock formations are bedded in a suitable depth under 600m below ground surface (Reinhold et al. 2013). The reference region and the surrounding generally is structured in a crystalline basement, a cover of

sedimentary rock and quaternary sediments. The generic 3D model contains 14 units from the basis Zechstein until the Quaternary (Fig. 0.2).
Salt domes or active fault zones are excluded from the model to assume a representative position. The size of the model is 70 km^2. The Barremian & Hauterivian formation in the Lower Cretaceous represent the host rock formations. The host rock formations consist of claystones and clayey marl and subordinate micritic lime marl. The hydrogeologic conditions contain a surficial groundwater reservoir of low salinity in quaternary sediments and several deeper aquifers with high salinity water in the Rhätsandstein, Aalensandstein and Hilssandstein (Reinhold et al. 2013).

The geological model SOUTH is situated in the north alpine Molasse Basin (Reinhold et al. 2016). The region is structured in a crystalline basement, a cover of mesozoic sedimentary rock, molasses sediments and quaternary sediments. The generic 3D model contains 16 units from the basis Muschelkalk until the Quaternary (Fig. 0.2) Active fault zones are excluded from the model. The model regards an area of about 140 km^2.

The Opalinus clay of the Middle Jurassic is defined as host rock formation and consists of claystones which show a low variability in facies and lithology. It is slightly inclining and the surface of the formation lies between 500–700m below ground surface. The hydrogeological conditions contain a near-surface groundwater reservoir in quaternary sediments and several deeper aquifers in the Upper Muschelkalk, Stubensandstein and Upper Jurassic. The model unit of the Upper Jurassic comprises strong dolomitized and karstified limestones.

2.1.2 Repository concept

The emplacement level of the repository shall be completely surrounded by the host rock and excavated at a depth between 600 and 800m to avoid any adverse impact from the surface (e.g. during ice ages). The emplacement strategy must be compatible with the thickness, the characteristics and the extent of the host rock. To reduce disturbance and to re-establish the properties of the host rock, the volume of excavations will be minimized. Operations will be carried out in retreating mode, which means that an emplacement field completely filled with waste packages will be backfilled immediately with swellable material, sealed, and abandoned (Lommerzheim & Jobmann 2015). The repository will consist of two shafts and one emplacement level with an infrastructure area, drifts for mine work, waste transport, and ventilation and emplacement areas (Fig. 0.3).

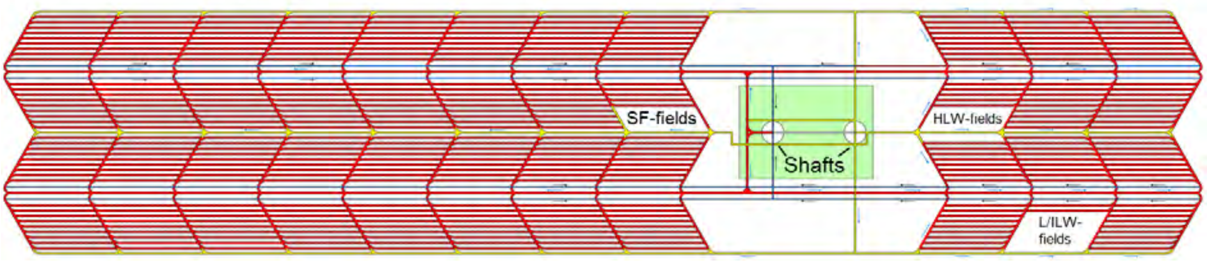
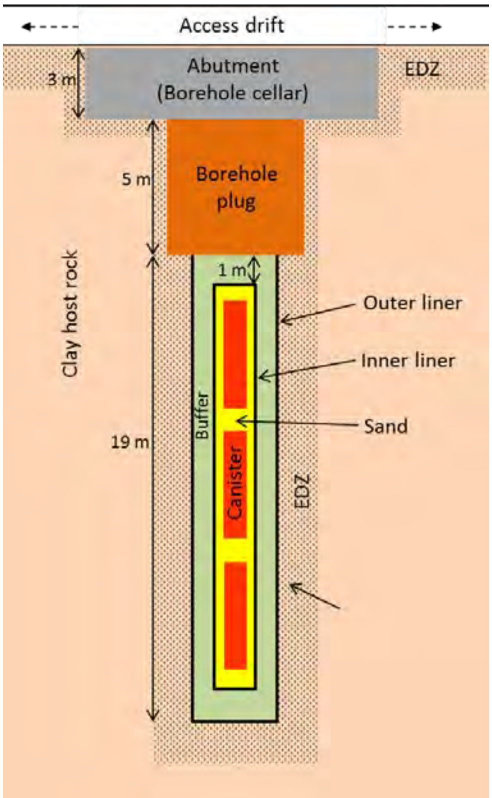


Fig. 0.3: Repository design (Borehole disposal, model NORTH) with two shafts, infrastructure area (green) and emplacement areas (red; left: for spent fuel, right: waste from reprocessing).

The general layout is based on former designs developed by Pöhler (2010) that consider radiological and non-radiological areas, a corresponding air ventilation system, and the transport logistics for parallel work of mining and radioactive waste transport. The emplacement areas dimensions are based on design calculations and arranged in a modular way. The disposal strategies include either vertical borehole or horizontal drift emplacement depending on the available thickness of the host rock. The footprint of the repository mine for the drift emplacement concept is nearly 50% larger than that of the repository mine with vertical borehole emplacement (11.2 km^2 vs. 7.6 km^2).



These disposal strategies consider the Safety Requirements (BMU 2010), which stipulate that retrievability has to be ensured during the operational period and for a period of 500 years after repository closure. Retrievability options are currently being investigated in a parallel R&D project called ERNESTA (Herold 2016). For the thick Lower Cretaceous clay formations in the model NORTH the option of vertical borehole emplacement (Fig. 0.4) has been analysed (Lommerzheim & Jobmann 2015).

Fig. 0.4:
Principle design of an emplacement borehole in the site model NORTH (Lommerzheim & Jobmann 2015).

The access drifts to the emplacement boreholes will have a length of 400m and will contain 13 boreholes for heat-generating waste or 20 boreholes for non-heat-generating waste each. The depths of the boreholes will be 27m. To ensure the stability of the borehole during emplacement and to ensure retrievability, each borehole will be equipped with an external and an internal liner. Three canisters will be inserted in the internal liner and the remaining void volume will be filled with sand (Fig. 0.4). The space between the inner and the outer liner will be filled with a compacted clay buffer. Each borehole will be sealed with a bentonite plug and an overlaying concrete abutment.

Because of the limited thickness (110m) of the Opalinus Clay in the repository site model for Southern Germany, a drift emplacement concept has been favoured for this region (Jobmann & Lommerzheim 2016). The emplacement drifts have a length of 400m and POLLUX® casks will be placed on beddings of highly compacted clay with a spacing of 23m (Fig. 0.5). The remaining void volume will be filled with clay (reprocessed mined rock). The MOSAIK® containers for structural elements of spent fuel (SF) assemblies will be disposed in emplacements chamber that will be backfilled with concrete.

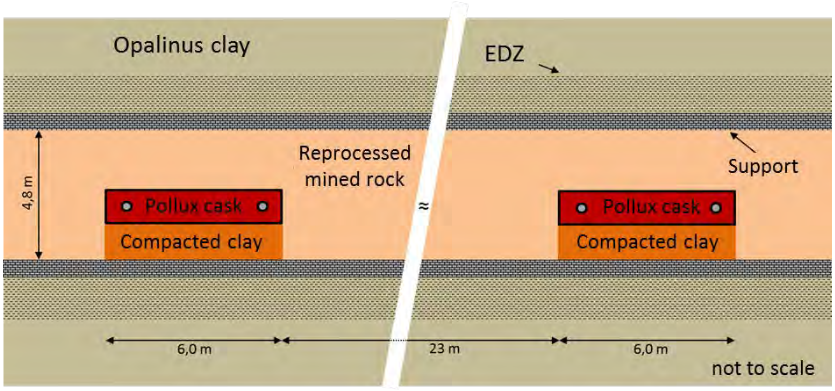


Fig. 0.5:
Scheme of drift emplacement in the site model SOUTH.

2.1.3 Backfilling and sealing concept

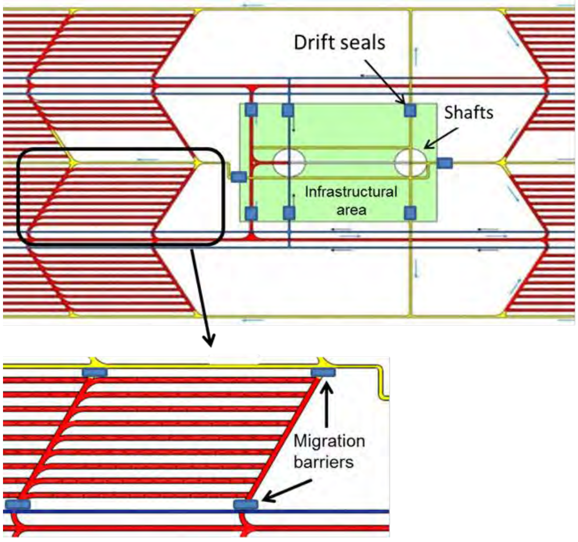
In the framework of the backfilling and sealing concept a conceptual design of the geotechnical barriers is developed (Jobmann et al. 2017b). Referring to the repository concept the sealing concept consists of four (NORTH) and three (SOUTH) plugs which are complementary. These barriers are

- shaft seals
- drift seals (infrastructural area)
- migration barriers (emplacement fields)
- emplacement borehole seals (only NORTH) and exploration borehole seals

In addition to these plugs, the backfill in the drifts will act as a barrier as well but at later times after the evolution of its properties has reached a stationary state.

The shaft sealing system consists in principle of two modules named lower and upper seals. The lower module is assumed to be at the boundary of the CRZ while the upper module is located next to aquifers to minimize a down flow of freshwater to the lower module as much as possible to keep the hydro-chemical system stable.

The drift seals in the NORTH and SOUTH concept are slightly different. Seals for emplacement boreholes as shown in Fig. 0.4 are only present in the NORTH concept because of the chosen borehole disposal option. They act as a very first barrier in case of a canister failure. The SOUTH concept can be seen as a further development of the NORTH concept which was developed first. In the SOUTH concept both types of drift seals are additionally equipped with an asphalt/bitumen element (Jobmann & Lommerzheim 2015). Fig. 0.6 gives an overview of drift seal locations and shows a principle sketch of the sealing system. The disposal drifts are reached via the main drifts and access drifts which are backfilled.



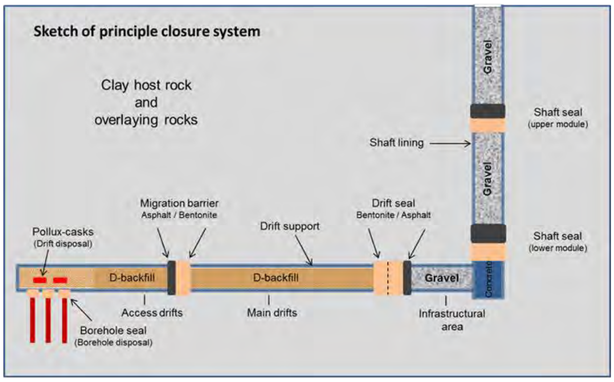


Fig. 0.6: Schematic overview of the principle sealing system (Jobmann et al. 2017b)

Since the drift support is not dismantled, the backfill cannot take over the sealing function at early times but at later times only. As long as the drift support is not corroded, it can act as a preferential pathway for potentially contaminated fluids. After corrosion of the cement phase the mechanical support diminishes and the remaining material will be compacted between the converging rock and the swelling pressure of the backfill. The final permeability of this area is still unknown. The gravel backfill in the infrastructural area is intended to act as a temporary gas reservoir.

At both ends of the access drifts at the interface to the main drifts so-called migration barriers are build which are smaller than the large drift seals at the interface to the infrastructural area (Fig. 0.7). In this barrier an asphalt element is located in direction to the disposal field. The asphalt element immediately takes over its sealing function right after installation. This is necessary because the adjacent bentonite element may need a few decades to develop its full sealing ability and thus to ensure that the sealing function of the barrier is available at early times. In case of instantaneous failure of a canister the sealing is ensured. Both elements will be kept in place by concrete abutments.

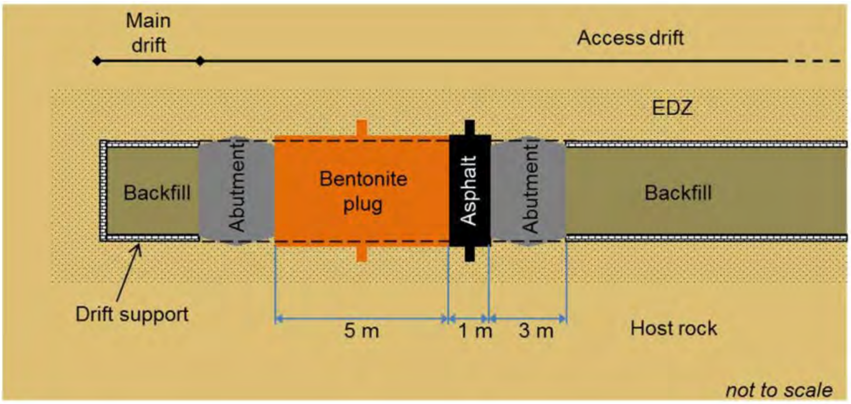


Fig. 0.7:

Principle design of a migration barrier separating the access drifts and the main drifts (Jobmann et al. 2017b)

Prior to implementation of the two sealing elements the most disturbed part of the EDZ will carefully be taken out. As an optional element small slices will be implemented in both seal areas to further reduce fluid movement within the EDZ in axial direction. Currently this is still seen as an option since the effectiveness of these seal slices is still to be demonstrated. The bentonite seal will be built using highly compacted blocks consisting of Ca-bentonite as the reference material (Engelhardt et al. 2011, Müller-Hoeppe et al. 2012). The asphalt element will as well be built by using prefabricated cold blocks. Afterwards these blocks will be made monolithic by using pressure and temperature (Kudla et al. 2009). After saturation of the bentonite the asphalt will be squeezed due to the swelling pressure improving the cohesive connection between the asphalt and rock surface.

In the larger drift seals at the infrastructural area the asphalt element is located in direction to the shafts and thus outwards (Fig. 0.8). The reason is that due to the immediate sealing ability of the asphalt, the early inflow of fresh water from upper groundwater levels is avoided and the hydro-chemical conditions are kept undisturbed. Analogously to the smaller drift seals the asphalt element provides time for the bentonite elements to fully develop their sealing capacity.

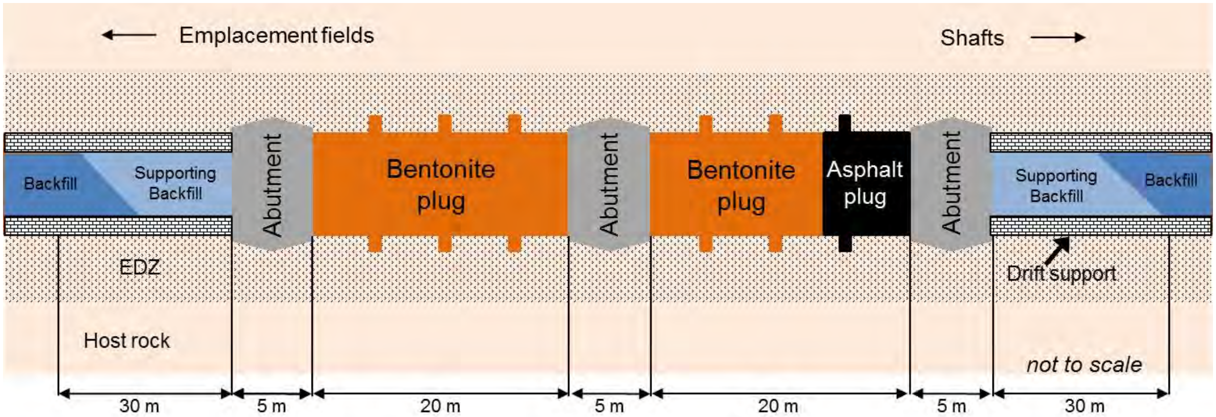


Fig. 0.8: Conceptual design of the drift seals separating the main drifts from the infrastructural area.

For both repository site models concepts for shaft sealing systems have been developed. Both conceptual designs consider two different seal modules for the upper and the lower part of the shafts. The lower modules are intended to be implemented in the host rock and the upper modules will be installed in the overlaying rock. The main function of the upper modules is to avoid an early inflow of fresh groundwater and thus to avoid a disturbance of the hydro-chemical conditions down in the host rock. The lower modules shall in conjunction with the borehole and drift seals avoid a fluid migration out of the repository at later times. As an example the shaft sealing system for the repository site model NORTH (Fig. 0.9) is described below (Jobmann et al. 2017b).

The bottom of the shafts and the access area to the underground drift system will be filled by a gravel column. On top of this gravel column the lower seal module will be implemented which mainly consist of a bentonite sealing element embedded between two filter sections and supported by a concrete abutment below to guarantee low settlements. The bentonite element is seen as the long-term sealing element. The short-term seal above the bentonite will be a bitumen filled gravel column. The element is located in an rock area where bituminous clays are present.

The upper seal module is designed for the depth range between 200 m and 350 m below the earth's surface. The area was chosen because the seal then separates two aquifers and avoids water exchanges. The abutment below is located in the layer called Hedbergellenmergel. This lithological unit is assumed to have higher rock strengths due to the high carbonate content and is thus beneficial for locating a concrete abutment. The conceptual design of the upper module is similar to the lower one.

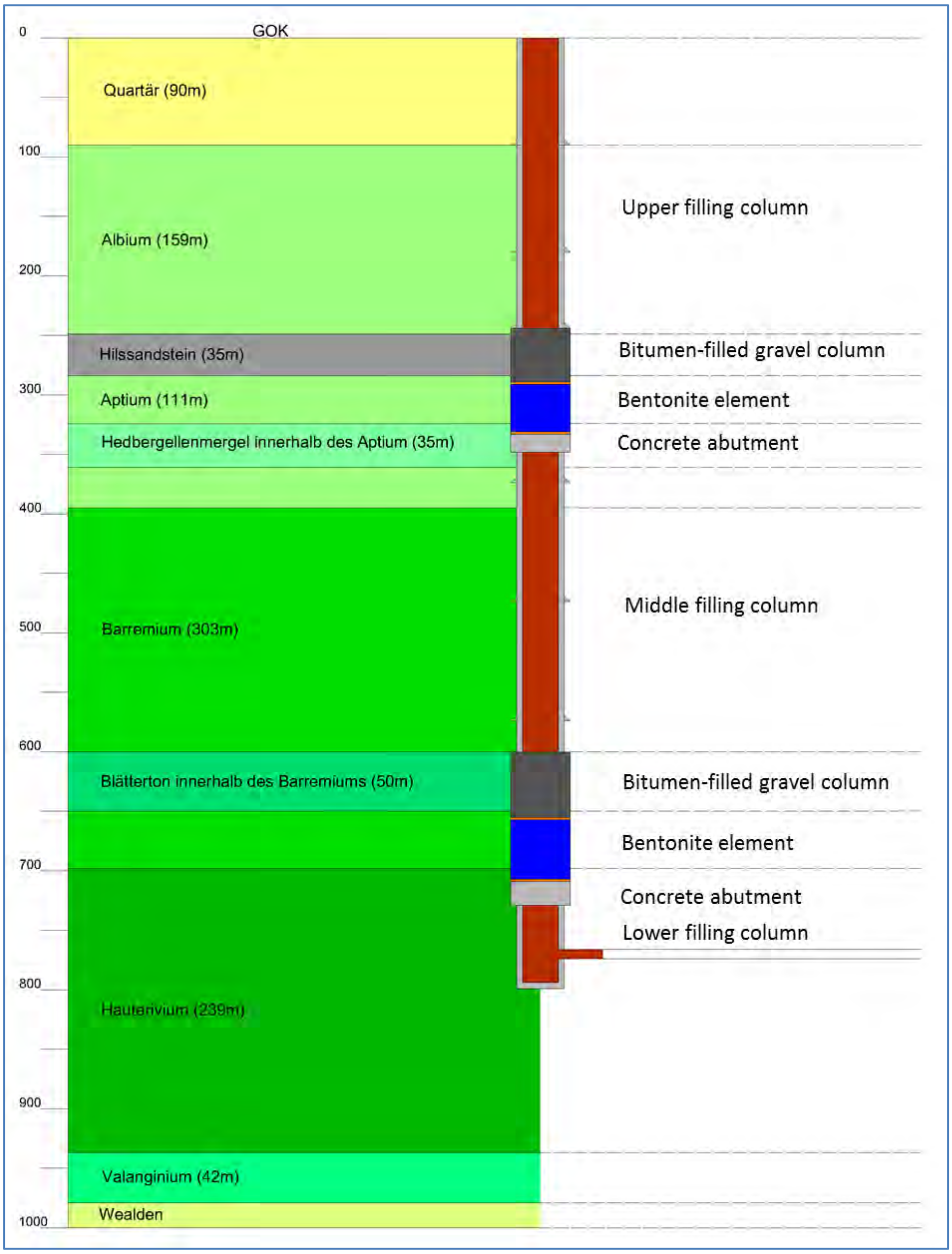


Fig. 0.9: Conceptual design of the shaft sealing system for the repository site model NORTH (Herold et al. 2016b)

2.2 Expected behaviour of EBS

As an example, the repository site model NORTH has been selected and the seal of the vertical emplacement boreholes have been chosen to demonstrate the development of a monitoring concept for engineered barriers. To simulate the behaviour of the seal, numerical models have been developed able to calculate the THM response to the emplacement of heat generating waste for the first 150 years.

In order to investigate the fluid pressure build-up, the duration of water saturation and the temperature evolution at the borehole seal, the model of one drift with one emplacement borehole sealed with bentonite plug and excavation damaged zone (EDZ) around the borehole in one emplacement field was considered. In the borehole, three waste canisters and metal liners that contribute to the gas generation are emplaced (Fig. 0.4). The gas production due to corrosion of metal leads to pressure build-up in the repository and therefore, to possible barrier damage and to contaminant transport. Hydrogen is the main component of the gas, resulting from the corrosion of metal containers. The generated heat causes thermal expansion of rock and pore fluids and hence, leads to higher pressures and possible occurrence of macroscopic fracturing. The gas production and heat rates for one borehole were estimated and presented in Fig. 0.10 (Burlaka 2016, Rübel 2016). Three-dimensional two-phase flow simulations have been performed regarding flow of water and hydrogen in the simplified drift model.

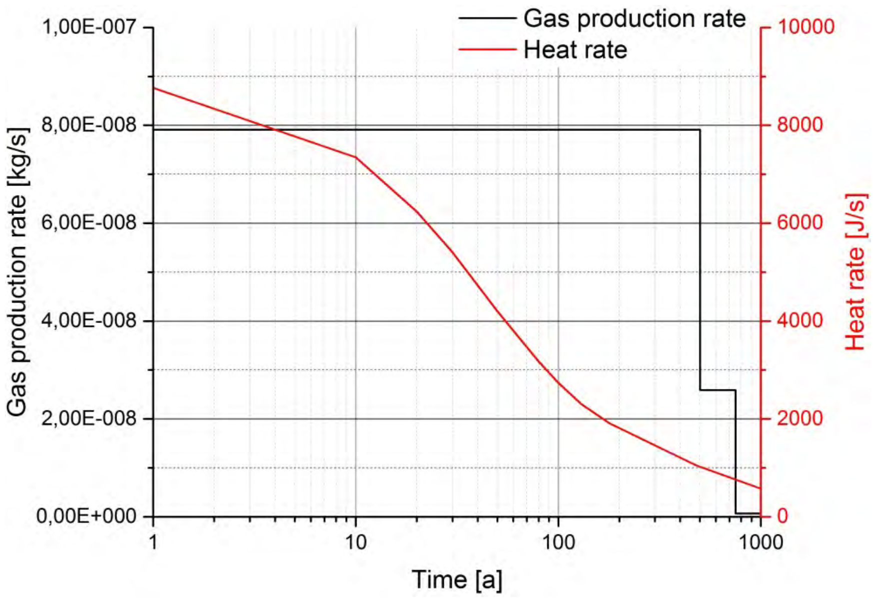


Fig. 0.10:
Gas production and heat rates estimated for one borehole

Methods and materials

The computer code TOUGH2 (Pruess et al. 1999) and its graphical interface PETRASIM (Thunderhead Engineering 2010) have been used. Equation-of-State module EOS5 was applied to simulate two-phase flow of hydrogen and water. The EOS5 module was developed to investigate the behaviour of groundwater systems in which hydrogen releases are taking place.

In the model, one drift comprises emplacement, access and main drifts and has a length of 1140 m and cross section of 40 m^2. Borehole and sealing plug have lengths of 22 m and 5 m, respectively. The thickness of EDZ is considered of 0.5 m. Model domain consists of 130548 grid blocks, 584 m width, 1260 m length and 500 m height (Fig. 0.11). Fig. 0.12 shows mesh discretization in the borehole area. Bottom, middle and top of the sealing plug were taken as observation points in the simulations. As a boundary condition, a fixed hydrostatic pressure is assumed at the upper and lower boundaries of the simulation model (Fig. 0.11). The rock mass is initially completely water saturated with imposed hydrostatic pressure, while the drift, borehole and the sealing plug are considered 45 % water saturated and at atmospheric pressure. Since in EOS5 module gas is assumed to be hydrogen, the gas saturation in the repository corresponds to saturation of hydrogen. The modelling concept considers that intermediate storage time is twenty years and initial temperature is 35°C in the repository and host rock.

Relative permeabilities of two phases and capillary pressure are represented by van Genuchten function (Mualem 1976, van Genuchten 1980). Gas entry pressure for the clay and the EDZ was calculated according to (Jahn & Sönnke 2013).

$$P_0=5.6\cdot 10^{-7}\cdot k^{-0.346}$$

Intrinsic and flow property parameters in materials used in simulations are given in Table 1.

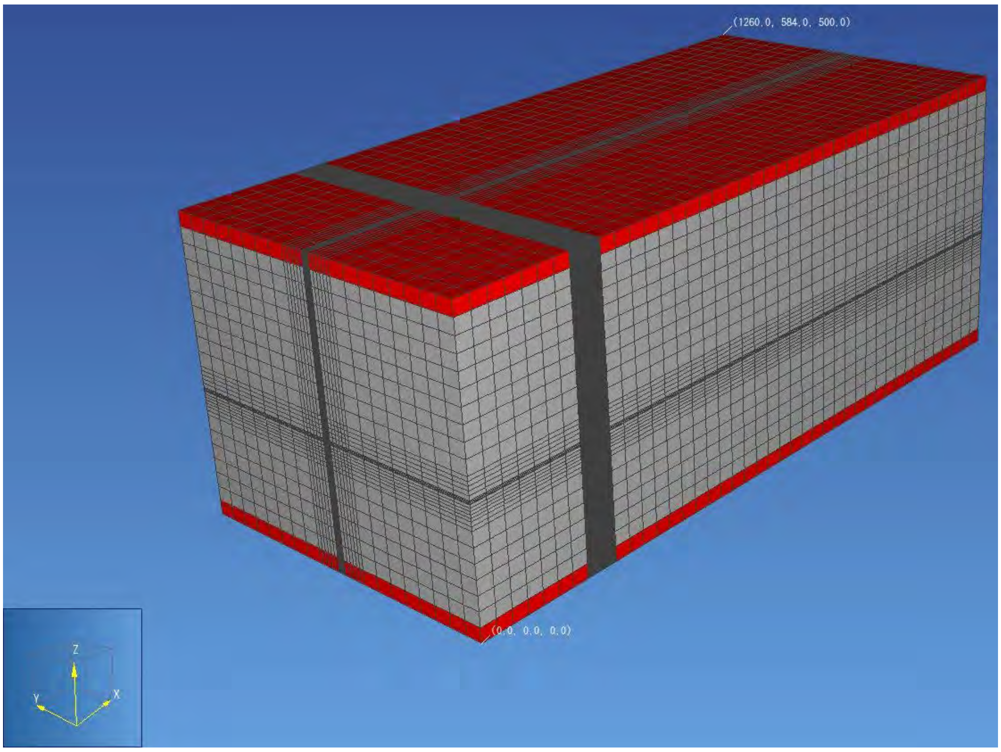


Fig. 0.11: Model domain with colour coded boundary conditions regime. Fixed state is presented in red.

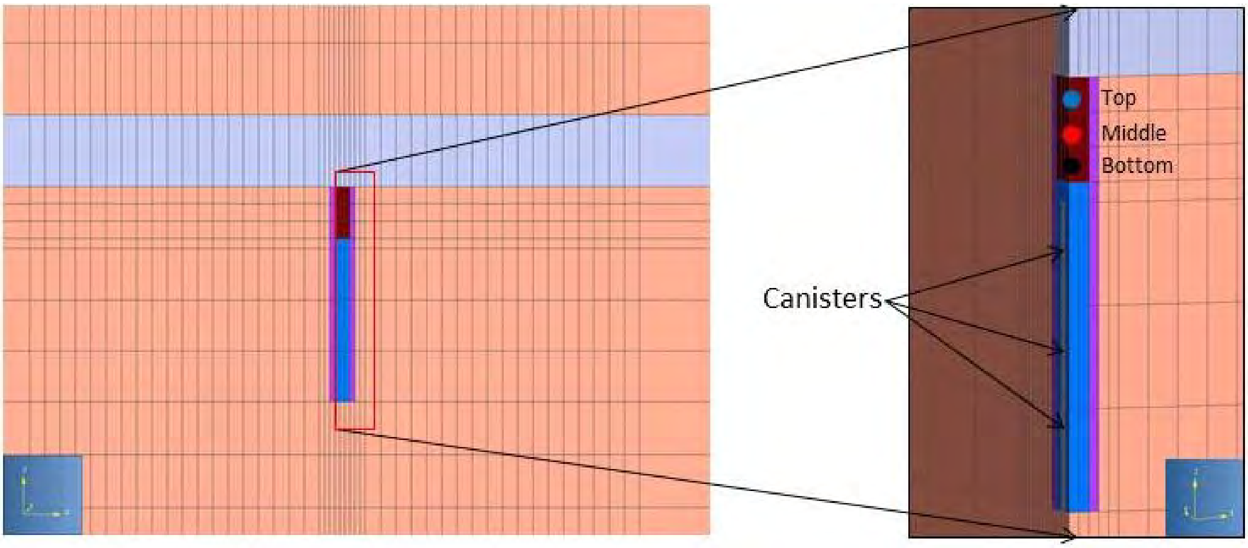


Fig. 0.12: TOUGH2 mesh discretization in borehole area with enlarged mesh of emplacement borehole with canisters. Black, red and blue circles are observation points in sealing plug.

Table 0.1: Intrinsic and flow parameters of the materials used in the simulations after Nowak & Massmann (2013) and Yildizdag et al. (2008).

Material	Colour in model	Permeability [m²]	Porosity [-]	Wet heat conductivity [W/(m·K)]	Gas entry pressure, P_0 [MPa]	Water retention curve shape parameter, λ [-]	Maximum capillary pressure [MPa]
Clay		horizontal: 10^{-19} / vertical: 10^{-20}	0,05	2	2,1	0,55	10
EDZ		10^{-18}	0,05	2	1	0,55	10
Backfill in drift		10^{-15}	0,20	2	0,1	0,55	7,41
Sealing plug		10^{-19}	0,36	1,6	0,3	0,363	2
Buffer in borehole		10^{-17}	0,36	1,6	0,3	0,363	9
Steel (supposed to be corroded)		10^{-15}	0,001	10	-	-	-

Results

To investigate the influence of gas production and heat generation on pressure build-up and water saturation in the sealing plug, four cases have been considered:

- with gas production and with heat generation
- without gas production and with heat generation
- with gas production and without heat generation
- without gas production and without heat generation

Fig. 0.13 shows the results for first two cases up to 200 years. The pressure gradient is observed in sealing plug from the bottom to the top independent on the presence of gas production. Due to coming gas and heat from canisters the highest pressure is observed at the bottom of sealing plug and exceeds the hydrostatic pressure when gas production is considered (Fig. 0.13 upper graph). The gas generation leads to the higher pressure and appearance of free remaining gas phase in the sealing plug (Fig. 0.13 lower graph). Due to significant decrease of the heat rate after ten years (Fig. 0.10) and hence, decrease of thermal expansion of rock and pore fluids, the drop of pressure is observed up to 50 years. Without heat production, pressure remains steady from 10 to 50 years and then increases. Pressure increase in sealing plug after 50 years corresponds to complete water saturation of the drift by this time (see Fig. 0.14) and therefore, results from additional pressure due to water inflow through the drift.

Desaturation of the sealing plug is occurred when gas generation is considered (Fig. 0.13 lower graph). To explain this phenomenon, simulations using permeability of sealing plug of 10^{-16} and 10^{-17} m^2 with gas and with heat generation have been performed and results were compared with results of simulations using initial permeability of 10^{-19} m^2 (Fig. 0.14). Sealing plug is fully water saturated after five years, when permeability is 10^{-16} m^2, and small desaturation occurs only after 80 years, when permeability is 10^{-17} m^2. Higher permeability of plug leads to gas escape through the borehole seal and hence to water saturation of sealing plug. Pressure in the plug exceeds the hydrostatic pressure only in case of a permeability of 10^{-19} m^2.

Results of simulations only with heat generation reveal that initially located gas in repository is dissolved and sealing plug is completely water saturated after ten years (Fig. 0.13 lower graph).

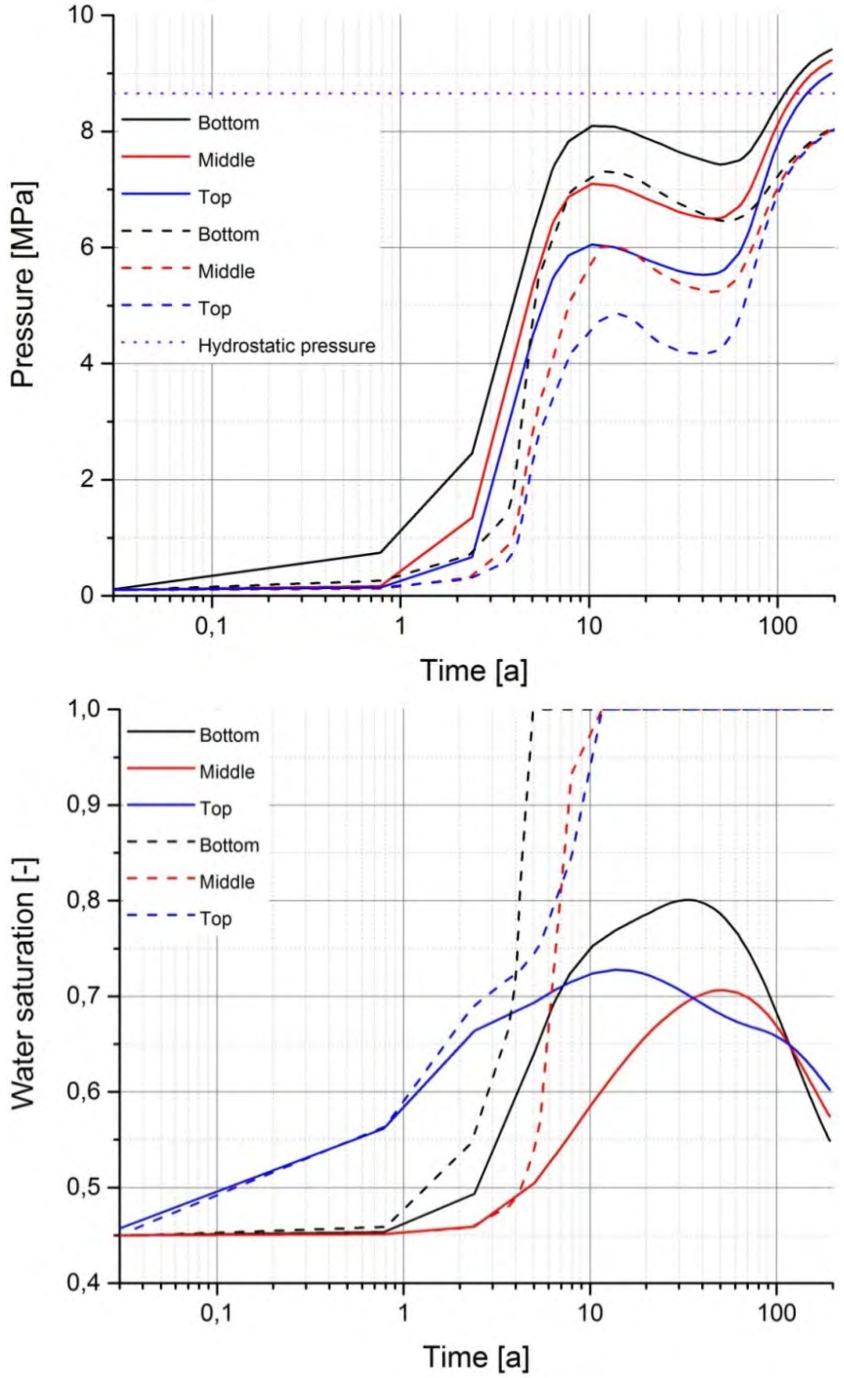


Fig. 0.13: Pore pressure build-up (up) and water saturation (down) at the bottom, middle and top of sealing plug with gas and with heat production (solid line) and only with heat generation (dashed line).

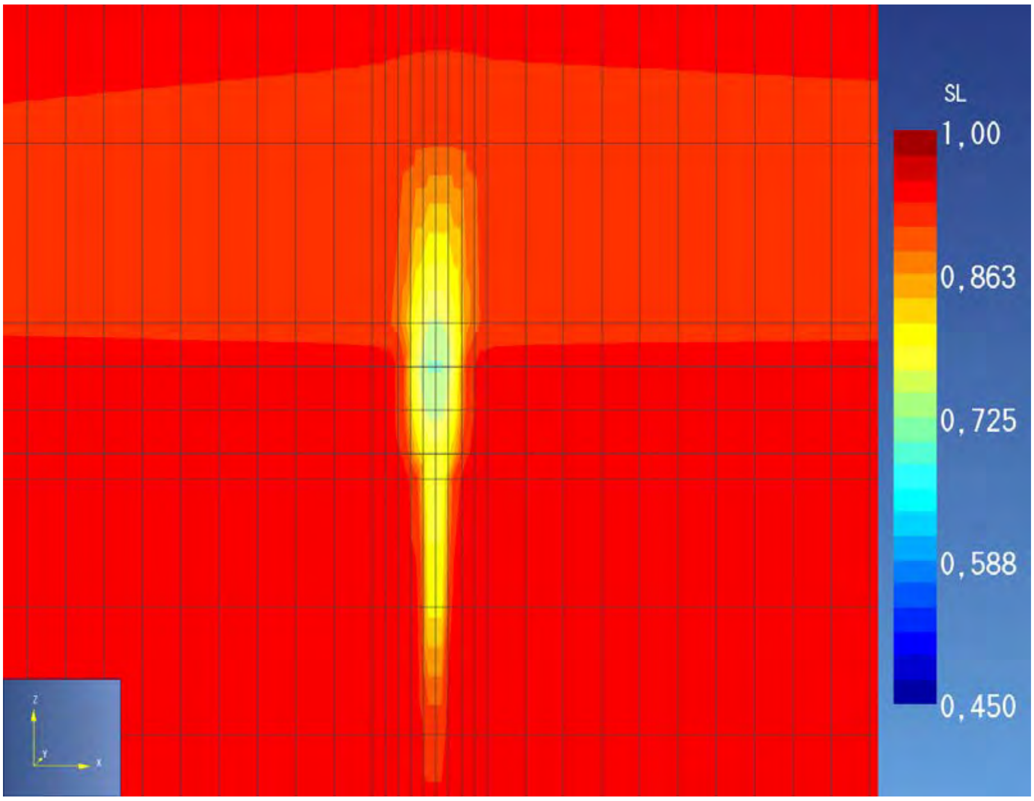


Fig. 0.14: Water saturation distribution in borehole area and in the drift after 50 years, when gas production and heat generation are considered

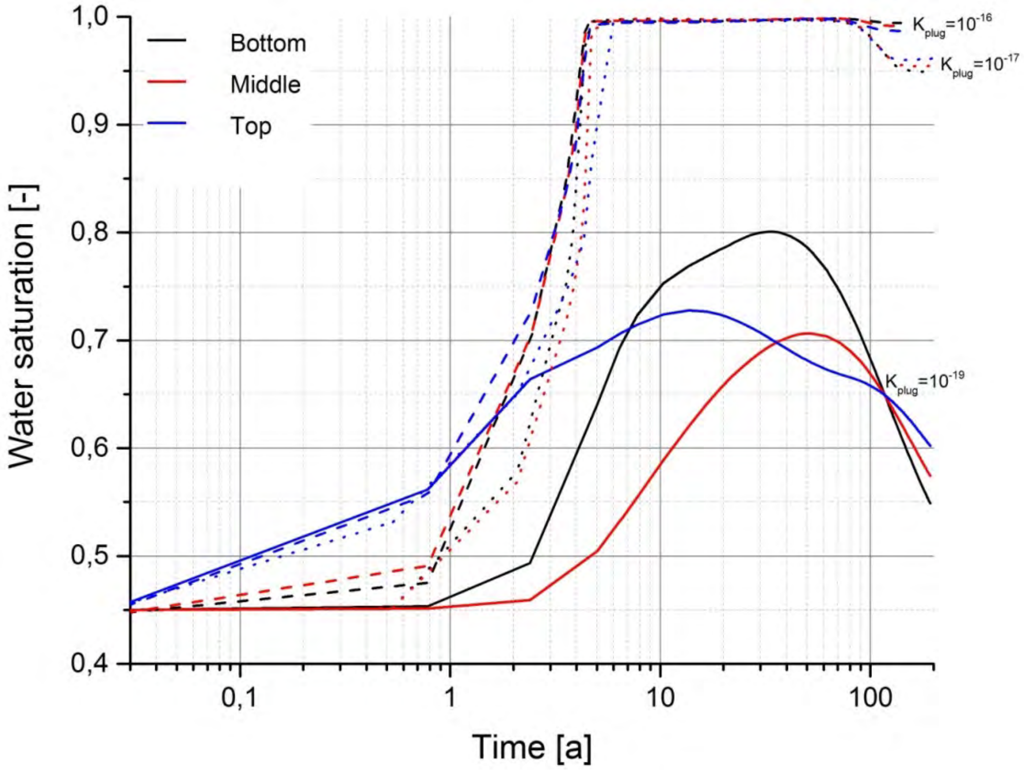


Fig. 0.15: Water saturation at the bottom, middle and top of sealing plug with gas and with heat production, where permeability of sealing plug is 10^{-19} (solid line), 10^{-16}(dashed line) and 10^{-17} (dotted line) m^2.

The temperature increase during first 10 years (Fig. 0.16) corresponds to high heat rate at this period of time (Fig. 0.10). The highest temperature of 67 °C was reached at the bottom of sealing plug. Temperature distribution in borehole area after ten years is shown in Fig. 0.17.

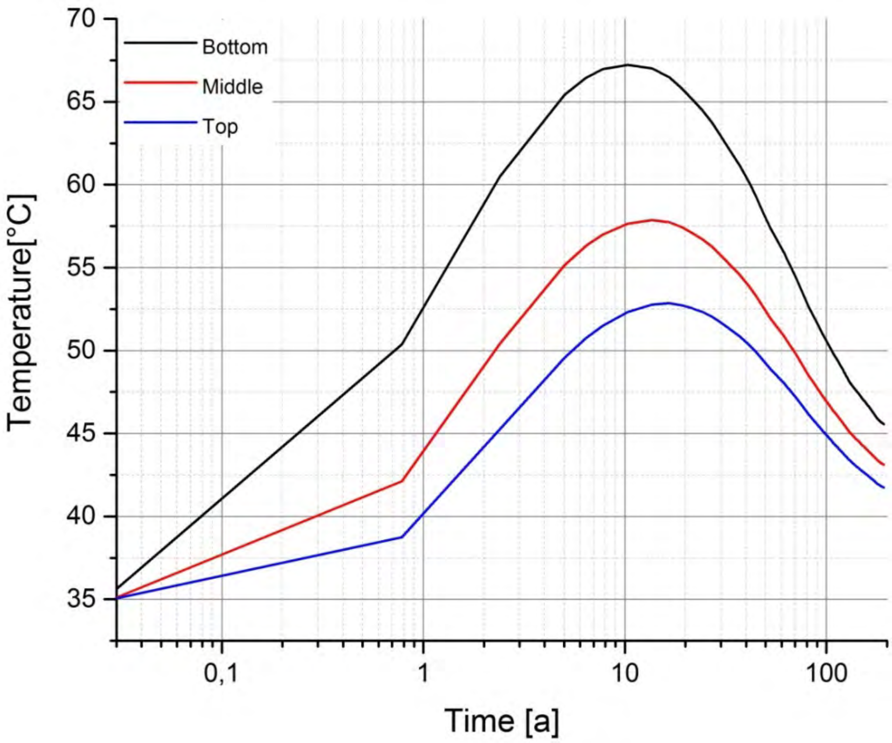


Fig. 0.16: Temperature evolution at the bottom, middle and top of the sealing element

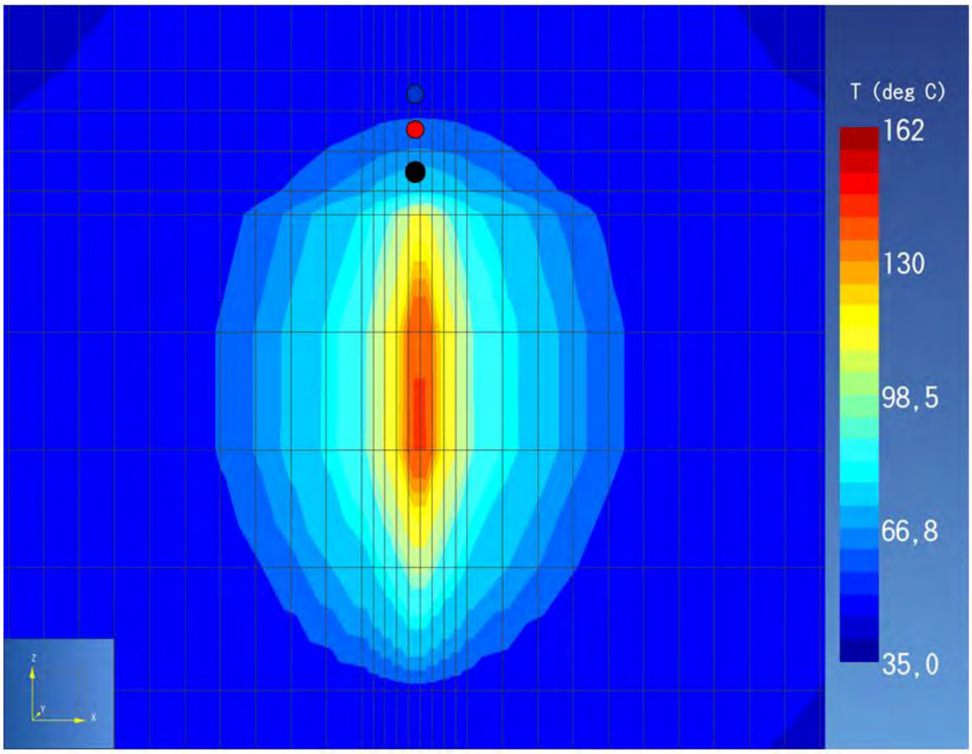


Fig. 0.17: Temperature distribution in the borehole area after 10 years. Bottom, middle and top of the sealing element assigned as black, red and blue circles, respectively.

To study influence of heat generation, results of simulations without heat and without gas production were compared with results of simulations only with heat generation. It was observed, that heat production leads to higher and faster pressure build-up at the borehole seal (Fig. 0.18 upper graph). Such increase is caused by thermal expansion of material and pore fluids due to generated heat. Water saturation of the seal takes longer without gas and heat production as when heat generation is considered, since heat reduces viscosity of the water and hence accelerates fluids flow. In simulations without gas generation and without heat production, pressure remains steady for few decades. Such behaviour corresponds to complete water saturation in the sealing plug by this time (Fig. 0.18 lower graph). Afterwards pressure increases again due to pressure induced from the water inflow from the drift. The same observation can be made in case only gas production is considered, albeit pressure is higher and exceeds the hydrostatic pressure after 110 years.

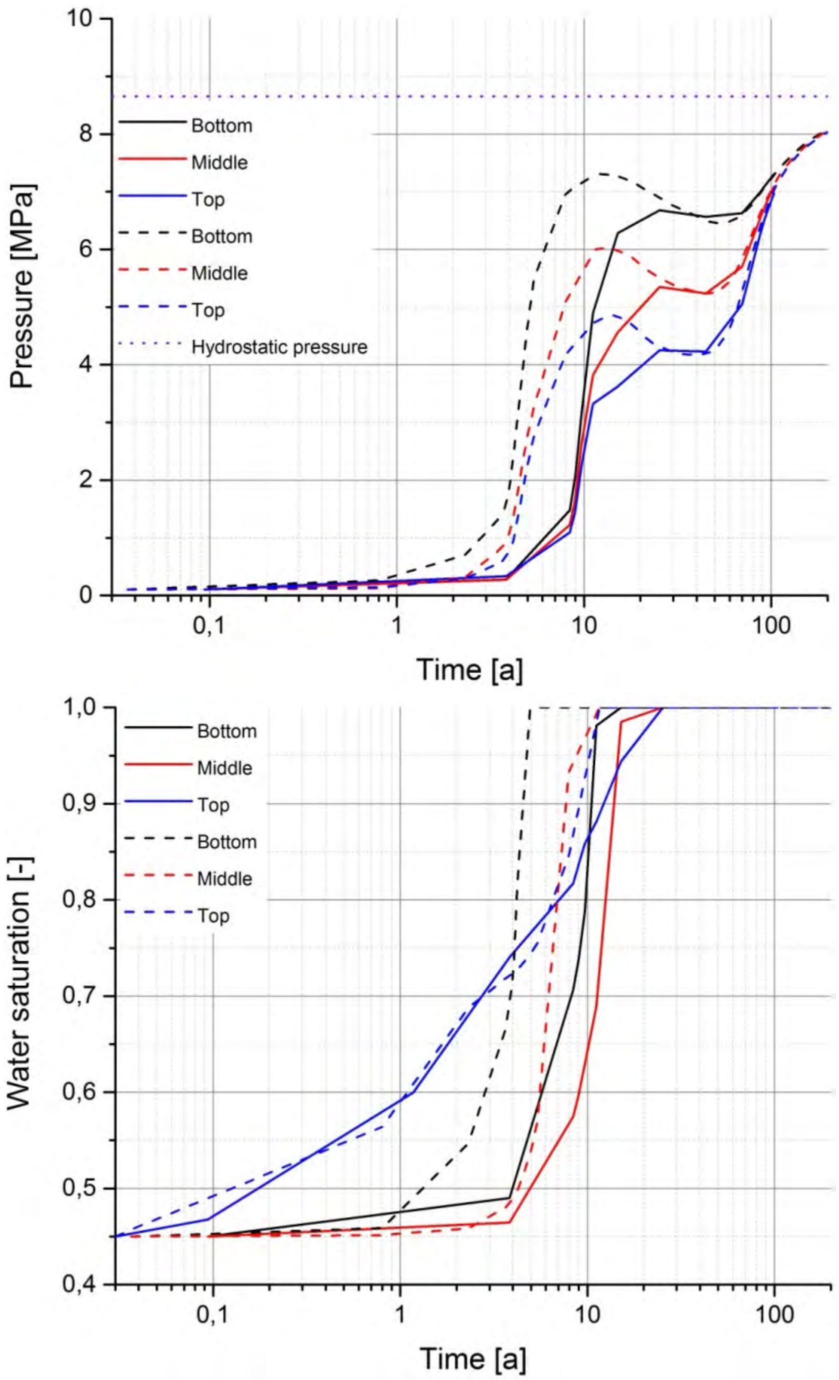


Fig. 0.18: Pore pressure build-up (up) and water saturation (down) at the bottom, middle and top of sealing plug without gas and heat production (solid line) and only with heat generation (dashed line).

To study the influence of the EDZ on water saturation in the sealing element in the presence of gas production, the permeability of the EDZ was set to 10^{-17} and porosity was increased from 0.05 to 0.1, but the results of the simulations reveal that the influence of the EDZ is limited.

The mechanical evolution of the plug has been simulated applying the FLAC3D code using a similar model geometry. The resulting mechanical pressures in vertical and radial direction are shown in Fig. 0.19 and Fig. 0.20. The pressures are plotted for observation points at the bottom, in the middle, and at the top of the bentonite sealing element as indicated in the included model graph.

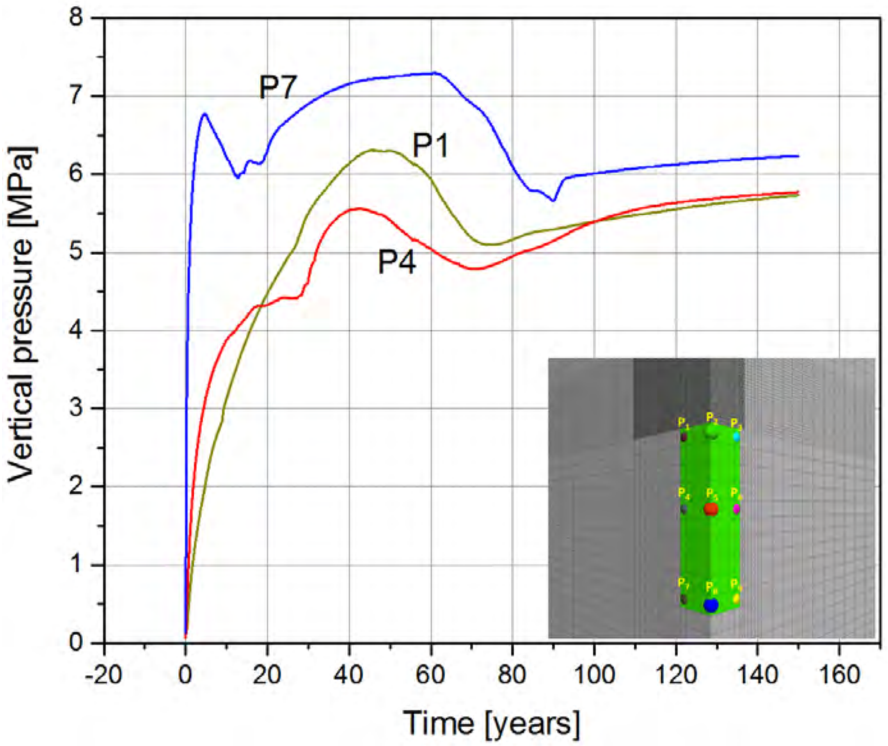


Fig. 0.19:

Evolution of vertical pressures in the sealing element

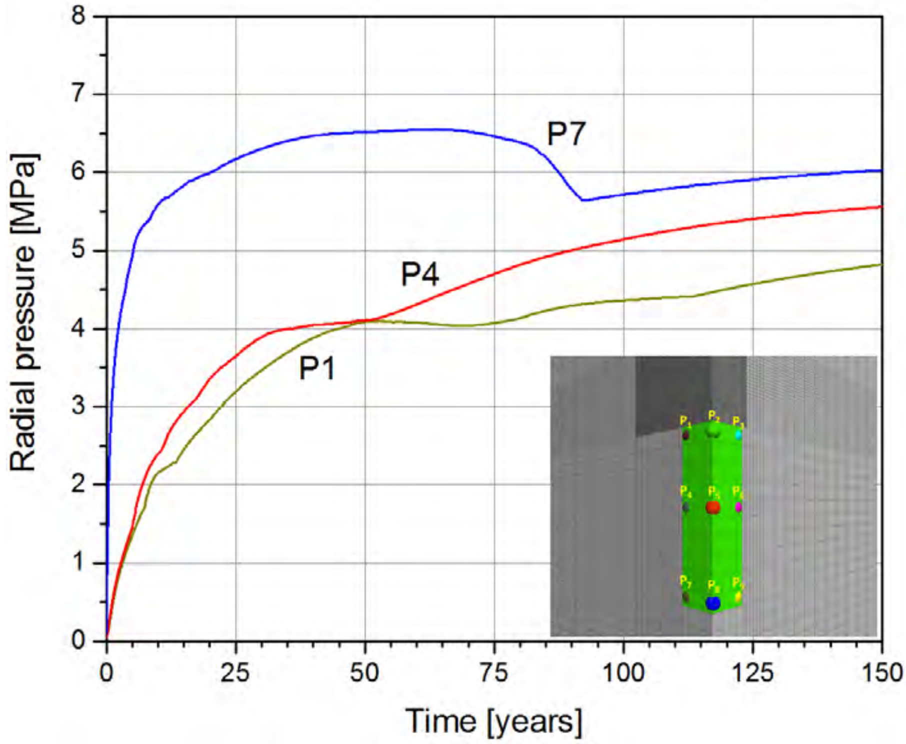


Fig. 0.20:

Evolution of radial pressures in the sealing element

The modelling results regarding the vertical displacement of the abutment are shown in. Fig. 0.21. The performance target of the abutments says that its displacement shall not exceed 3% of the length of the sealing element. The simulation yields a vertical displacement of less than 4 cm after the assumed monitoring period of 150 years. The shape of the curve suggests that even after extrapolation the vertical displacement will hardly exceed a value of 5 cm on the long term. Since 3% corresponds to a value of 15 cm the safety margin seem to be large enough to cover uncertainties.

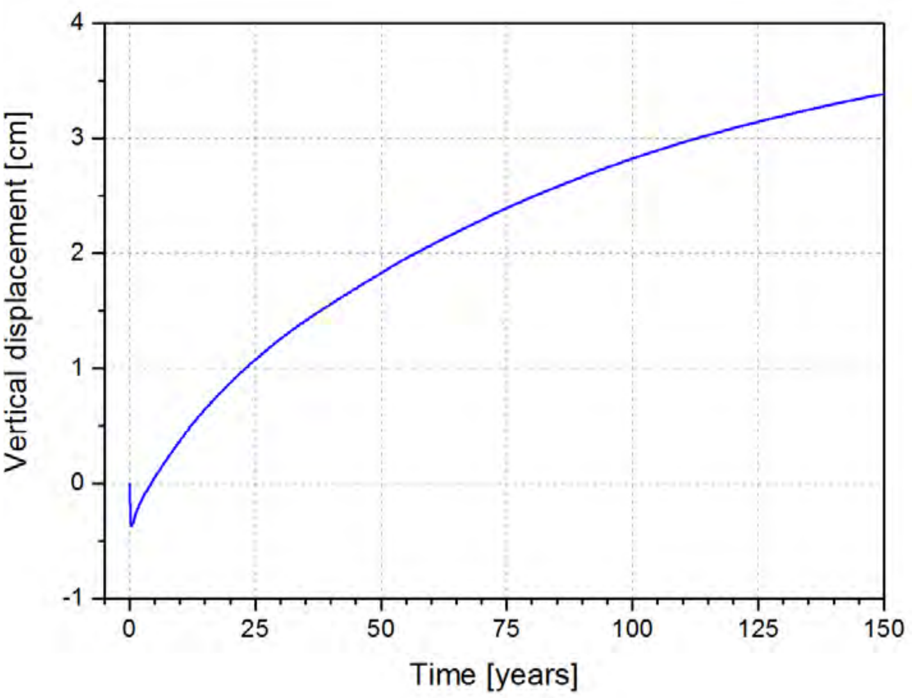


Fig. 0.21: Vertical displacement of the abutment due to pressures from the sealing element

Conclusions

The gas production leads to higher pressures exceeding hydrostatic pressure (after 110 years) and to remaining free gas phase, when permeability of sealing plug is10^{-19} m^2. With increasing permeability of sealing plug to 10^{-16} m^2, gas is completely dissolved and after 5 years the borehole seal is fully water saturated, and pressures are not over the hydrostatic pressure. Heat generation leads to earlier and faster water saturation of the sealing element and causes a pressure decrease due to significant decrease of the heat rate after ten years and then increases after 50 years, while in the simulations without heat generation, instead of a decrease the pressure remains stable. Intrinsic properties of the EDZ, such as porosity and permeability don't have any influence on fluid pressure build-up and water saturation of the sealing element.

The mechanical pressures do neither lead to an inadmissible vertical displacement of the abutment above the sealing element nor to a radial pressure which exceeds the minimum principle stress in the host rock and thus crack building is avoided.

The simulation results are used to determine the necessary measurement ranges of sensors to be embedded in the sealing element and the abutment.

Previous modelling studies indicated limited influence of gas production in the repository site model SOUTH due to the low gas generation rate (Burlaka, 2016) and therefore, only the gas production rate in the model NORTH was considered. Two simplified model configurations of the repository have been used for three-dimensional two-phase flow simulations to study the impact of gas and heat production on the duration of water saturation and the fluid pressure build-up in the access drift and in the drift plug for the first 200 years. One model comprises only one emplacement drift and the other one a complete emplacement field with 9 emplacement drifts. In both models, 17 canisters were considered as gas and heat sources in each emplacement drift. The access drift is directly connected with the emplacement drift and sealed versus the main drift with a plug. In all drifts, a tunnel lining and an excavation damaged zone (EDZ) are implemented. The EDZ is subdivided into three layers to represent a permeability gradient in the EDZ between the drift and the rock. The plug consists of two abutments with an asphalt and bentonite sealing element in between. The principle layout of the model of the repository is presented in Fig. 0.22. To represent a complete emplacement field, volume factors were used to consider the total volume of 9 emplacement drifts. The gas production rate of each canister was multiplied by 9 to represent the total gas production in the emplacement field. The gas production and heat rates for one borehole estimated for the repository concept NORTH (Burlaka 2016, Rübel 2016) are shown in Fig. 0.10.

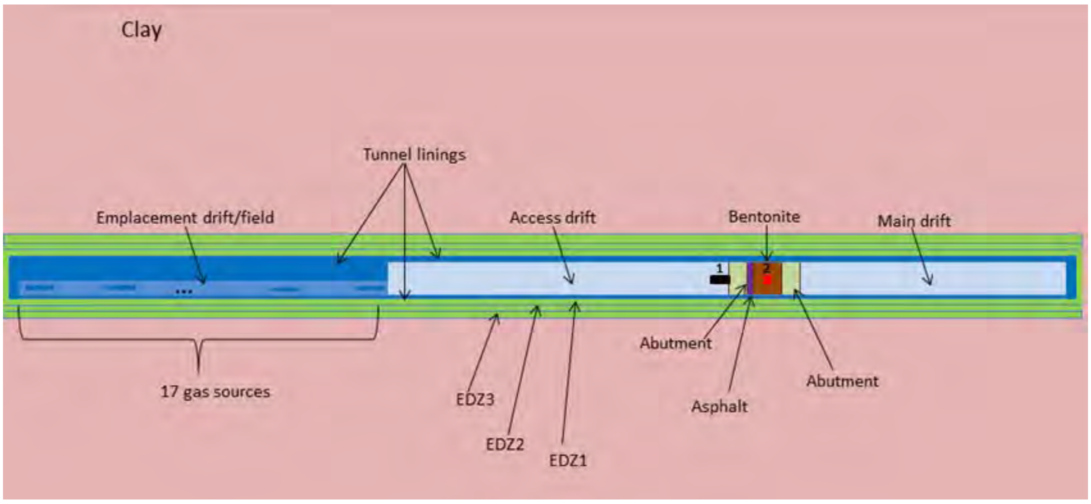


Fig. 0.22: Principle layout of the repository model

Methods and materials

The TOUGH2 module EOS5 was used to simulate two-phase flow of hydrogen and water (Pruess et al. 1999). The model domain is 1650 m long, 584 m wide, and 500 m high, and the mesh consists of 188160 rectangular elements. An enlarged mesh of the plug area is shown in Fig. 3. The black and red cells (see Fig. 0.22 and Fig. 0.23) were taken as observation points in the simulations corresponding to one element in the access drift and one in the bentonite plug. The emplacement drift has a length of 420 m and a cross-section of 20 m^2, while the access and main drifts are 390 m long and have a cross-section of 40 m^2.

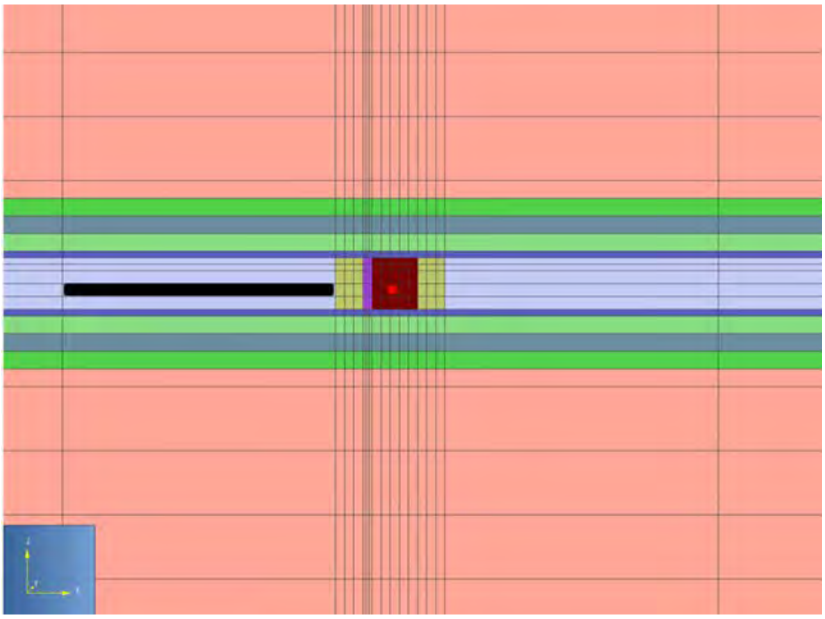


Fig. 0.23: Enlarged mesh of the plug area in the xz plane. The black cell corresponds to the observation point in the access drift and the red one corresponds to the observation point in the bentonite element.

The initial water saturation conditions are: 100 % in clay and in asphalt, 95 % in EDZ, 80 % in tunnel linings, 20 % in abutment, 45 % in the drifts, in canisters (gas and heat sources), and in the bentonite element. The initial pressure in the rock mass is distributed in accordance with the hydrostatic pressure gradient, while the other model elements are at atmospheric pressure. The initial temperature is 35°C in the repository and in the host rock. The capillary pressure and the relative permeabilities of the two phases are represented by the van Genuchten function (Mualem 1976, van Genuchten 1980). The gas entry pressures for the clay and the EDZ were calculated according to Jahn & Sönnke (2013).

$$P_0=5.6\cdot 10^{-7}\cdot k^{-0.346}$$

Characteristic material parameters for the simulations are given in Table 1.

The EDZ was subdivided into three zones with different material parameters (Table 0.2). The thickness of each EDZ layer is 2 m.

As a boundary condition, a fixed hydrostatic pressure is assumed at the upper and lower boundaries of the simulation model (Fig. 0.24).

Table 0.2: Material properties and parameters of capillary pressure used in the simulations

Material	Permeability [m²]	Porosity [-]	Wet heat conductivity [W/(m·K)]	Gas entry pressure, P_0 [MPa]	Water retention curve shape parameter, λ [-]	Maximum capillary pressure [MPa]
Clay	horizontal: 10^{-19} / vertical: 10^{-20}	0.05	2	2.1	0.55	10
Tunnel linings	10^{-15}	0.15	2	0.087	0.55	10
EDZ1	10^{-16}	0.15	2	0.19	0.55	10
EDZ2	10^{-17}	0.1	2	0.43	0.55	10
EDZ3	10^{-18}	0.077	2	1.0	0.55	10
Backfill in drift	10^{-15}	0.2	2	0.1	0.55	7.41
Bentonite plug	10^{-19}	0.36	1.6	0.3	0.363	2
Asphalt	10^{-23}	0.01	2	-	-	-
Abutment	10^{-17}	0.15	2	0.15	0.55	10
Gas source (steel is supposed to be corroded)	10^{-15}	0.001	10	-	-	-

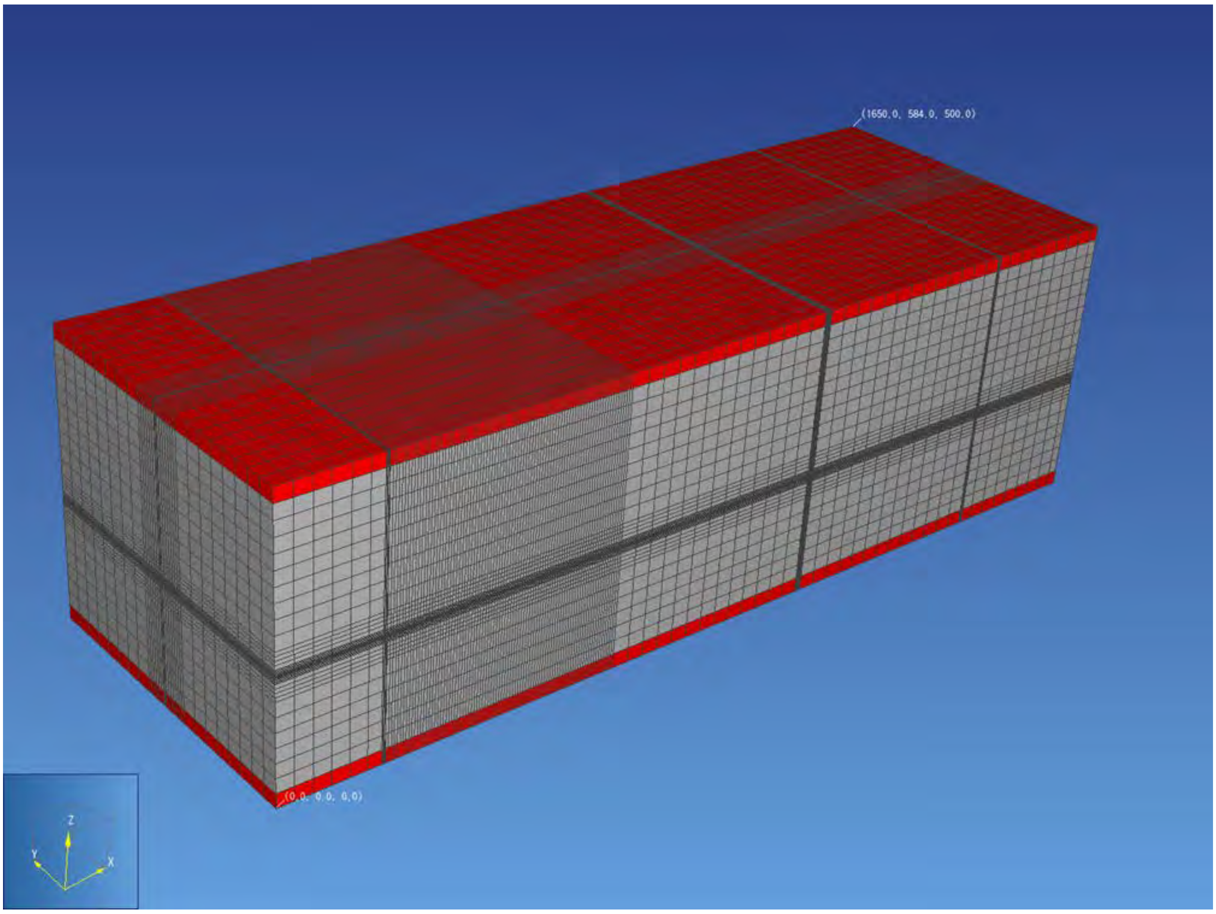


Fig. 0.24: Boundary conditions of the model: The red zones indicate constant hydrostatic pressure and the grey zones represent no flow boundary conditions

Results

The model considering one emplacement drift

To study the impact of heat generation on the fluid pressure build-up and the duration of water saturation in the access drift and in the bentonite element, simulations considering gas and heat generation and simulations considering gas generation only were carried out.

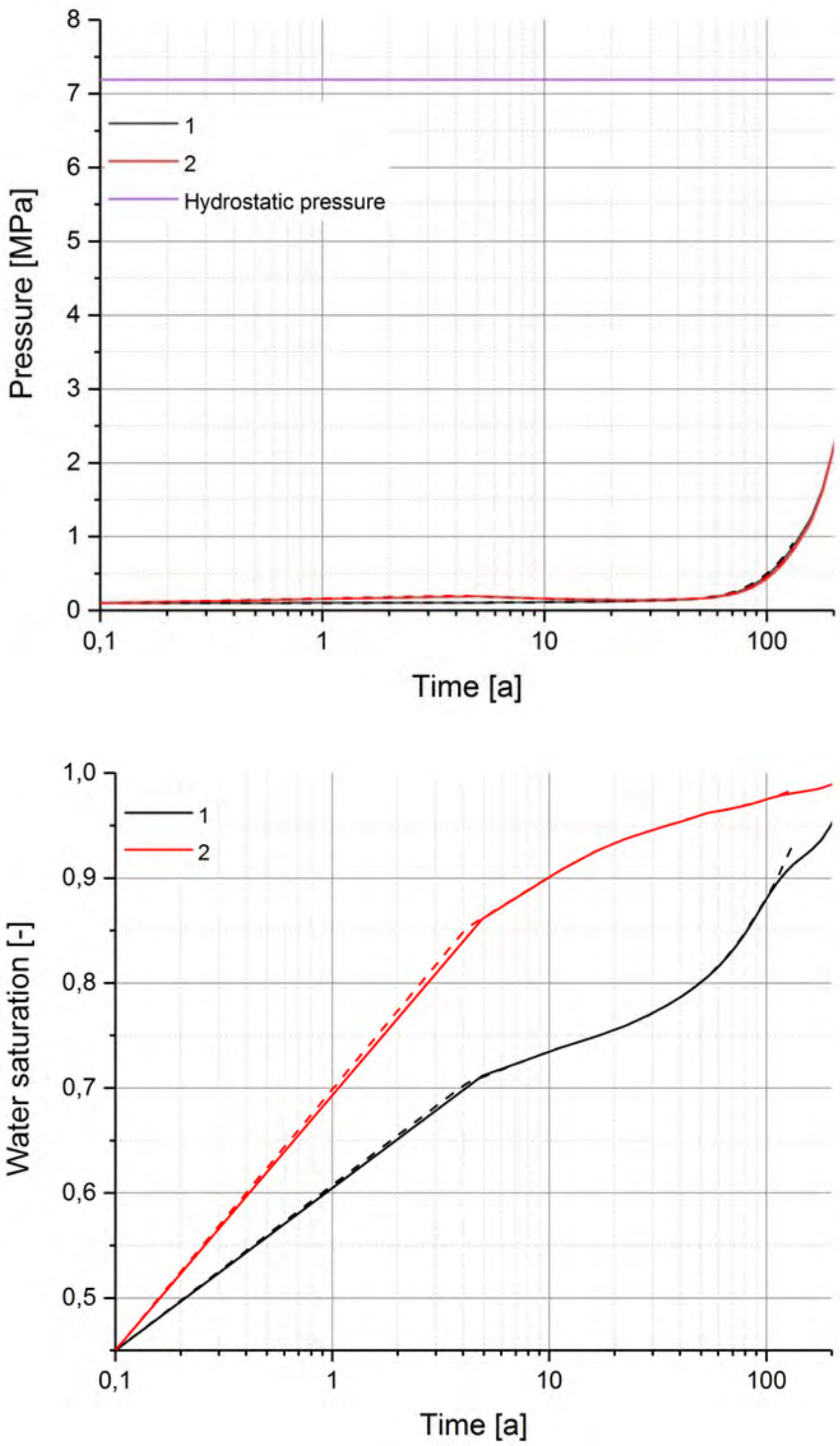


Fig. 0.25: Pore pressure build-up (top) and water saturation (bottom) in the access drift (1) and in the bentonite element (2) with hydrogen and heat generation (dashed line) and with hydrogen production only (solid line) considering one emplacement drift

The results of the simulations reveal that the influence of heat generation on the pressure build-up as well as on the water saturation is very limited (Fig. 0.25), since the temperature change after 200 years in the access drift and in the bentonite element is negligible (0.001 °C). In the access drift (dashed black curve in Fig. 0.25 lower graph), water saturation with the presence of heat increases slightly faster after

115 years, which is mainly due to the reduced fluid viscosity and hence, accelerated fluid flow compared with the case without heat (solid black curve in Fig. 0.25 lower graph).

The water saturation in the access drift (black curves in Fig. 0.25 lower graph) takes longer than in the bentonite element (red curves in Fig. 0.25 lower graph) due to the increasing amount of gas coming from the canisters in the emplacement drift. Impermeable asphalt, which is placed in front of the bentonite element, hinders the penetration of gas into the bentonite.

The pressure in the access drift and the bentonite element equally increases due to the pressure equilibration imposed by the pressure of the surrounding rock mass, and reaches 2.2 MPa after 200 years (Fig. 0.25 upper graph).

The model considering the emplacement field

In the model considering the emplacement field, the heat generation was neglected since its impact was found to be very limited. Thus, the simulations were carried out only with gas production and without gas production.

The results are shown in Fig. 0.26. In the presence of gas, pressure increases drastically faster (solid lines in Fig. 6 upper graph) and achieves 5.2 MPa after 200 years. The gas pressure response in the access drift and the bentonite element is similar irrespective of the presence of gas.

When gas production is considered, a free gas phase is formed (15% gas saturation) in the access drift (black solid line in Fig. 0.26 lower graph) due to the large amount of coming gas from the emplacement field, while in the bentonite element (red solid line in Fig. 0.26 lower graph) water saturation stays constant (only 3% gas saturation) after 90 years. Such a difference between water saturation in the access drift and the plug is caused by the influence of the impermeable asphalt element placed in front of the bentonite element. The asphalt element prevents the penetration of gas from the emplacement field into the bentonite. Hence, gas inflow into the bentonite element can occur through the EDZ only (Fig. 0.27).

This shows an important function of the asphalt element, which allows the bentonite element to saturate with water without being disturbed by the free gas phase. Thus, the evolution of the full swelling pressure and the full sealing capabilities can be achieved.

To investigate the influence of permeability of the bentonite element on the duration of its water saturation and pressure build-up, simulations using permeabilities of the bentonite element of 10^{-17}, 10^{-18} and 10^{-19} m^2 with gas generation were performed. The results of the simulations are shown in Fig. 0.28. The results indicate that the permeability of the bentonite does not influence the water saturation evolution in the access drift and the pressure build-up in the access drift and in the bentonite plug (pressure build-up not plotted). With decreasing permeability from 10^{-17} m^2 down to 10^{-19} m^2, water saturation in the bentonite element takes longer during the first 35 years. After reaching about 95% water saturation, it increases simultaneously independent of the permeability of the bentonite element.

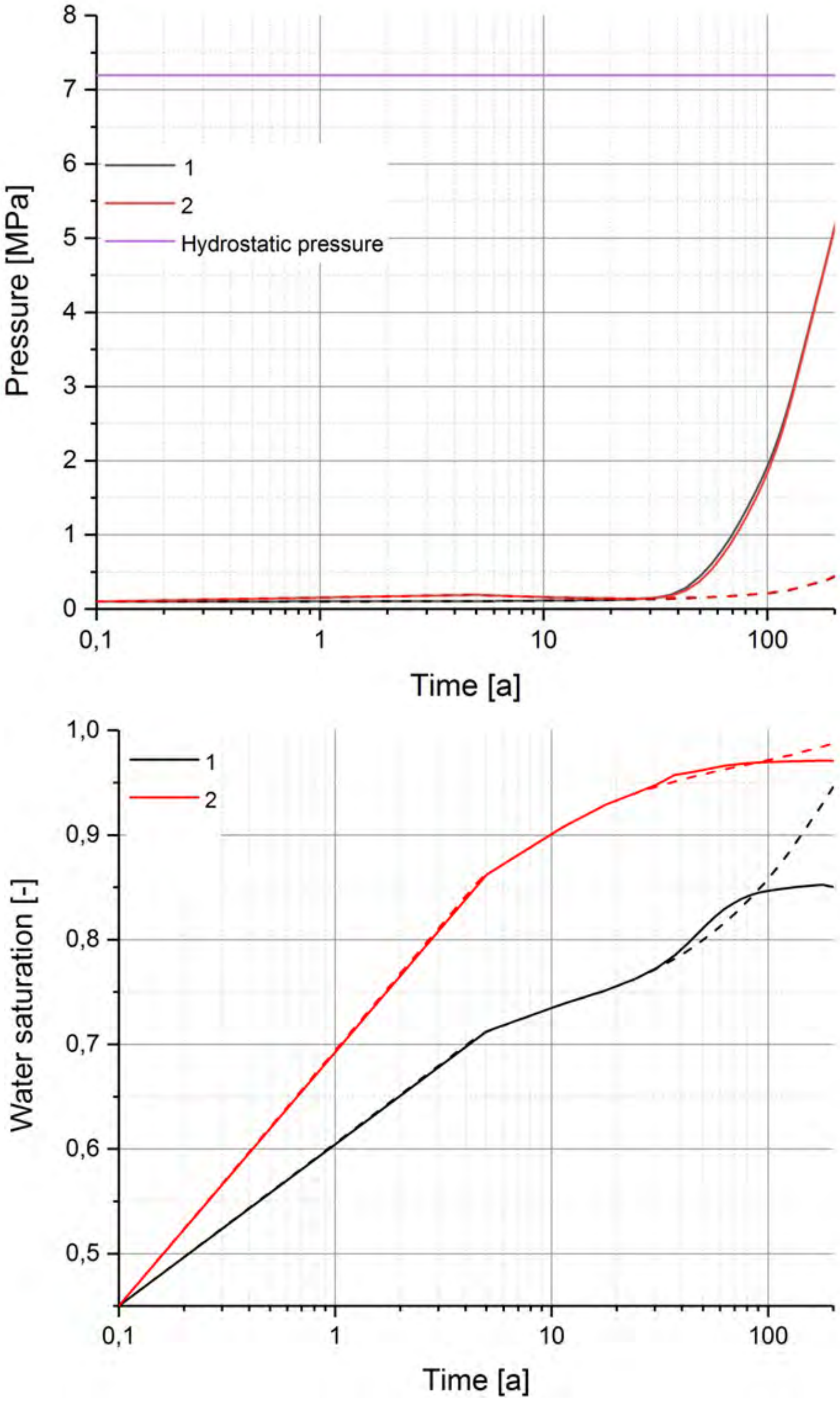


Fig. 0.26: Pore pressure build-up (top) and water saturation (bottom) in the access drift (1) and in the bentonite plug (2) with hydrogen generation (solid line) and without hydrogen production (dashed line)

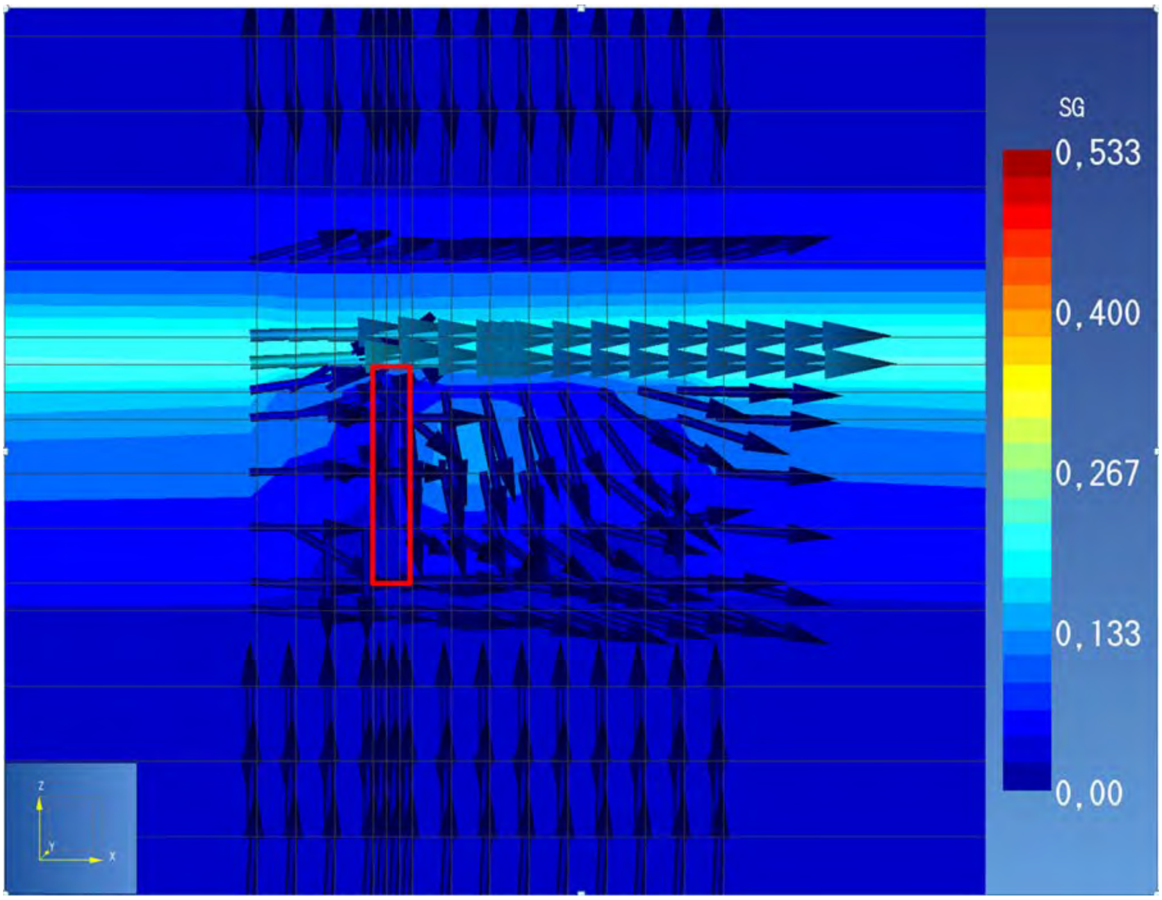


Fig. 0.27: Gas saturation distribution after 90 years in the drift plug in the area of access and main drifts with arrays of gas flow. Asphalt area marked in red

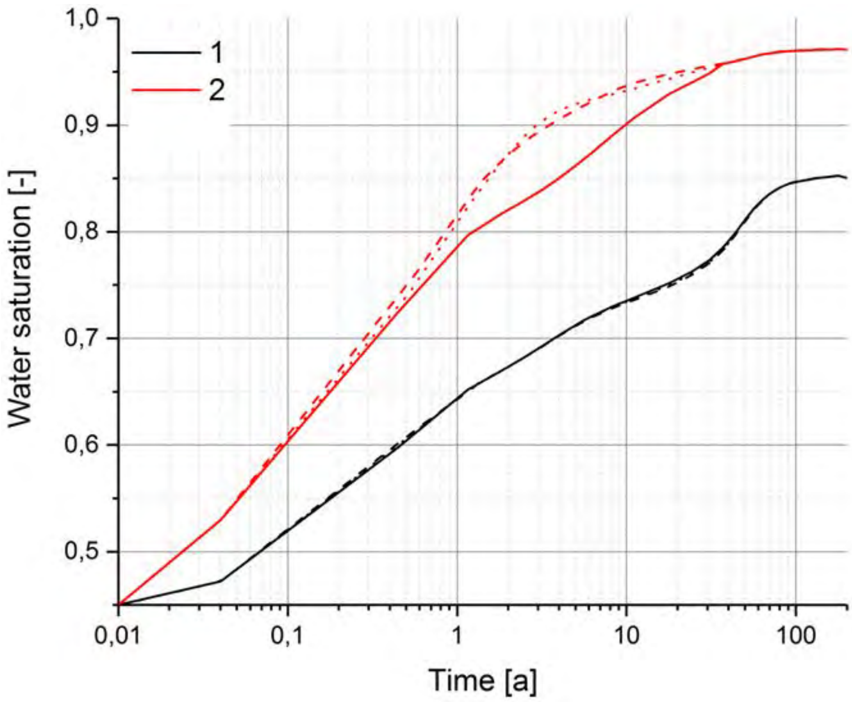


Fig. 0.28: Water saturation in the access drift (1) and in the bentonite plug (2) with gas production, where permeability of sealing plug is 10^{-19} (solid line), 10^{-17}(dashed line) and 10^{-18} (dotted line) m^2

Conclusions

The results of the simulations show that the influence of heat generation on the pressure build-up and duration of water saturation in the access drift and the bentonite element is very limited. Increasing the gas production rate from one emplacement drift to the rate from emplacement field leads to a higher pressure (from 2.2 MPa to 5.5 MPa after 200 years) and formation of a free gas phase in the access drift and the bentonite element. In all simulations, the pressure build-up is similar in the access drift and in the bentonite element. Gas inflow into the bentonite can occur through the EDZ only, because the impermeable asphalt element prevents penetration of gas coming from the emplacement field. With the low permeability of the bentonite element of 10^{-19} m^2, its water saturation takes longer compared with higher permeabilities of 10^{-17} and 10^{-18} m^2, albeit only during first 35 years. After this period, the water saturation evolution is similar. The permeability of the bentonite element has no influence on the pressure build-up in the access drift and in the bentonite itself and on the water saturation evolution in the access drift.

3 Monitoring objectives and strategy

Within the scope of the MODERN2020, a monitoring concept for repositories in clay formations in Germany, especially for the EBS, is to be developed taking into consideration the current German regulatory framework. As already mentioned in section 2.2 the repository site model NORTH has been selected as an example and the seal of the vertical emplacement boreholes have been chosen to demonstrate the development of a monitoring concept for engineered barriers.

3.1 Regulatory framework

3.1.1 Safety Requirements

With regard to the German Safety Requirements for the disposal of heat generating radioactive waste released by the German Ministry for the Environment in September 2010 (BMU 2010), a monitoring concept has to be part of the license application. In particular the Safety Requirements stipulate that:

- A monitoring and evidence preservation programme must be used during emplacement operations, decommissioning, and for a limited period after closure. This is to verify the assumptions and statements of the safety analyses and the safety case (This includes the EBS).
- In particular, the monitoring programme should record the general host rock behaviour in the repository environment and especially the rock's THM-response to the heat released by the radioactive waste.
- Baseline monitoring as well as recording activity concentrations in the groundwater, the soil, surface waters and in the air shall be part of the overall monitoring programme.
- Any significant deviations from statements and assumptions in the safety case should be evaluated with regard to their safety relevance.

3.1.2 Repository commission report

In July 2013 the German government released a new law for the site selection for a repository for high-level radioactive waste (Deutscher Bundestag 2013). At the same time a commission was founded for a period of two and a half years called "Commission for the disposal of high-level radioactive waste". The task of this commission was to define a fair and transparent procedure for the siting of a repository in Germany including a description of the complete disposal route and the repository phases. The final report describing the results of this commission was delivered at the end of 2016 (Endlagerkommission 2016). Monitoring plays an indispensable role when it comes to transparency, observation of repository evolution and decision making about stop or proceeding the disposal operation. In the following section statements about monitoring made by the commission are summarized.

3.1.2.1 General statements about monitoring

In view of the repository construction phase is was stated that a backfilling and sealing concept as well as a monitoring concept should be part of the license application for the repository construction. The monitoring concept shall consider monitoring activities that have to be started right from the beginning and those activities which are to be started at later times. Monitoring activities to be started right from the beginning shall be described in detail while monitoring activities intended to be started later can be described on a conceptual level. But in any case the concept has to point out whether installation requirements for monitoring equipment have to be considered during for example excavation activities or other technical measures in order to avoid any negative impacts on a later monitoring.

In the beginning of the operational phase of the repository the option should be considered whether to start with a test phase by filling only a few emplacement boreholes or drifts including backfilling of the corresponding drifts. During this test phase the evolution of the nearfield could be observed by suitable monitoring systems. Depending on the monitoring results it can be discussed and decided whether to continue in the same way, to change the procedure or to retrieve the waste.

In general, during the operational phase of the repository the monitoring concept shall be checked versus the state of the art of science and technology on a regular basis, e. g. every ten years in parallel with the

safety case re-evaluation as stipulated in the Safety Requirements. This shall be performed for ongoing monitoring measures as far as possible and for those monitoring systems planned to be installed in the near future.
From today's viewpoint it is assumed that after all emplacement fields have been filled the access to the repository, that means the shafts and the main drifts connecting the emplacement fields will not be closed right away. Instead, an observation period or pre-closure phase should be foreseen prior to final closure for evaluation purposes. During this pre-closure phase the following options shall be considered:

- decision for final closure
- fix a time span for the observation period and evaluate the monitoring results continuously
- or decision for waste retrieval

In view of the post closure phase, from the technical point of view a final update of the monitoring concept shall be considered based on the current state of the art technology and final installations are to be performed. Finally, the goals for a possible post-closure monitoring shall be re-evaluated as well.
After final closure of the repository the remaining issues are the monitoring activities and the result interpretation as well as the documentation and the information transfer to future generations.

At the time being it is idle to think about how this has to be organized in the future. The only thing one can and should do is to tell future generations that from today's point of view it seems reasonable to continue monitoring activities and that for these activities a responsible organization would be necessary including the responsibility for documentation and information transfer. The remaining goal for post-closure monitoring would be the confirmation that no unexpected repository evolution would question the passive safety.

3.1.2.2 Framing of monitoring by the repository commission

In their report the commission distinguished between 'Process Monitoring' and 'Repository Monitoring'

The term 'monitoring' comprises continuous and periodical tracking of previously defined parameters and the assessment of the results taking into account the respective requirements or changing boundary conditions or assessments. Monitoring provides transparency about the actual situation of the disposal process in all its phases as well as about the geological conditions at the repository site. This transparency allows early detection of unexpected evolutions and possible failures, and thus early learning and correction. Furthermore, transparency can build public confidence and – especially in the repository region – increase confidence in the processes and actors involved. In radioactive waste disposal, two kinds of monitoring need thus to be distinguished:

a) Process monitoring: Accompanying monitoring of the entire process up to the completion of a repository including all decision making processes and all relevant changes (political changes, new scientific findings etc.) as well as assessment of results in view of next steps. The commission considers this to be a process monitoring that is independent of but complementary to the key players (waste producers, regulatory body, operators) and different from the process organization the players have to demand of themselves as self-controlling system.

b) Repository monitoring: Accompanying monitoring of a potential or then real repository site regarding the existing geologic and hydrogeological conditions and their changes as well as regarding the state of the emplaced waste. Repository monitoring will primarily be carried out by the operator and the regulatory body; i.e., by key players in radioactive waste disposal that are directly obliged to critically monitor their actions in terms of a self-controlling system.

Both kinds of monitoring are central elements of final disposal as a learning process. This leads to interfaces between the procedure of participation, the structure of the regulatory body, and the commitment to a self-analyzing system but also with the necessity and orientation of future research and technology development.

Process monitoring

To the current understanding, the German Bundestag (*German Federal Parliament*) is to start the process to search for a repository site that offers best possible safety in 2017. Until emplacement starts, many decades will have passed, until closure it may even be more than a century. The extremely long duration of the entire process necessitates that the process itself be subject to accompanying monitoring as well as periodic and critical assessments, in order to optimize the procedure in terms of quality, time, and contents. Process monitoring; i.e., accompanying observation of and reflection on the process route, must start already at the beginning of the selection process because here, the course for the coming decades will be set. Likewise, the related necessary structures need to be created early on.

Process monitoring should at least comprise the following aspects:

regular reflection on the state of the procedure and assessment against self-imposed targets; if necessary, modification of the targets and of the designated time periods

regular assessment of the institutional situation: operator, structure of the regulatory body, supervisory body, transparency, etc.

Contemplation of the steps and formats provided for in the participation procedure in order to detect confidence problems and week points of participation early on

during the search for a suitable site: for all eligible sites, contemplation which parameters can be monitored or are to be monitored

regular assessment whether the approach to site investigation and exploration as well as the designated technology is state of the art both on a national and on an international level

regular survey of the state of knowledge regarding monitoring (e.g., new monitoring technology)

Effective process monitoring requires access to all relevant data. The commission believes that it is one of the responsibilities of the public advisory board to demand process monitoring in methodically adequate and transparent form, to accompany the selection of methods, to supervise the implementation, and to take care that the results are analyzed in a proper way. In view of the duration of the site selection process, which will take many years, process monitoring is essential for an optimized implementation of the procedure.

Experience from the past decades has shown that the techniques in mining and in the exploration of deposits (especially oil and gas) are constantly being further developed. For example, seismic investigation methods (3D seismic) and drilling methods (deflected boreholes up until horizontal) are available already today, which allow gathering high-quality data without essentially impeding the barrier function of the host rock in a potentially containment providing rock zone. In the site selection process, the optimization potential derived from the expected technical development can also open up potentials for optimizing the selection process in terms of time. When defining the exploration programs for phases 2 and 3, the organization responsible for the project must thus take into account the state of the art in science and technology, in order to carry out the exploration measures without unnecessary impairment of the barrier function of the host rock, without unnecessary space consumption, and without unnecessary impairment of the environment.

As a decision about the exploration and monitoring methods that will be used in the future cannot be made at this point in time, process monitoring must ensure that the then existing state of the art in science and technology will be applied for the site investigation based on the then required data for the assessment of the potential sites. The geologic and technical data that will have to be gathered in the respective phase will be determined by the respective repository concept, among others.

3.1.2.3 Repository monitoring

The aim of repository monitoring is to systematically monitor the state of the geologic formation, of the hydrogeologic conditions and of the waste as well as to monitor the impact of the repository in its various phases on the environment. This means that in the various phases of disposal and at various points in time, various methods of monitoring will be applied.

Permanent monitoring of the repository system, of its components, and of its environment throughout the process serves to detect undesirable developments or unexpected evolutions at an early state in order to be able to draw respective conclusions and to be able to apply corrective measures (in extreme cases, this includes retrieval or recovery of the radioactive waste). It also serves to optimize the respective next geotechnical process steps; e.g., the design of the various sealing constructions, and to review the assumptions and information that are the basis of the safety analyses for the construction and operation of a repository and for the post-operational phase.

It has to be defined which parameters are to be monitored at which location, as this impacts the design of the monitoring technologies (sensors and data transmission to the surface). These should be at least those parameters hat are relevant to the safety considerations; e.g., relating to the effectiveness of the geologic and the technical barriers. The monitoring parameters can only be defined after possible repository sites and the related repository designs have been selected (phase 3); a detailed definition can only be prepared after a final decision for a site has been made.

Monitoring has to find a compromise between the endeavor to monitor the safety-relevant parameters as completely as possible and the fact that build-in sensors/measuring devices and their cables; e.g., for data transmission from inside a sealed drift, create possible weak points for water intrusion. This conflict will be intensified if monitoring is to be continued after sealing of the entire repository mine. At this point, there is a conflict of objectives: On the one hand, incomplete sealing may be a weak point in safety. On the other hand, monitoring can mean a safety gain in case of unexpected evolutions. This conflict in objectives will be resolved or at least diminished in the future when technical developments for wireless data transmission that today are still in the research and development stage will entail new monitoring possibilities.

In order to be able to interpret the observations in an as comprehensive as possible temporal frame, monitoring of the geologic formation needs to start already with the selection of sites for underground exploration. This will gather information on the initial state of the system, against which the data that will be gathered in the course of the further evolution of the repository system can be compared. In order to be able to detect future up-lift or lowering processes, it is necessary, for example, to implement permanently safe geodetic points of reference for measuring the ground surface as a first measure after a site for underground exploration has been selected.

When creating underground facilities (first for exploration and after a decision for a site has been made, for the construction of the repository), further monitoring devices will be installed and operated; e.g., to monitor stress states and their evolutions or to monitor the formation of potential water pathways. The emplacement of waste will entail additional and other monitoring activities regarding the waste packages and their emplacement surroundings. When closing emplacement areas and when eventually closing the repository, decisions about the installation of measuring devices to gather specific data (e.g., about the temperature development, about water inflow, gas generation or radionuclide release into the near field) but also about the transmission of data to the surface will have to be made. Monitoring of closed areas has a time limit that corresponds to the lifetime of the devices used. Thus, indirect monitoring (e.g., of the ground surface, of the groundwater in the overburden or of the planned outer border of the containment providing rock zone) will gain in importance in the long-term monitoring of the repository site.

During the entire process, repository monitoring is thus continuously further developed in parallel to the disposal stages. At different points in time, a variety of information will be accumulated that will have to be assessed and analyzed regarding its significance for the safety of the repository. Based on the information gathered from monitoring, the continuous functional efficiency of a repository system can be demonstrated during the various phases of its construction and operation, which in turn can strengthen the confidence in the correctness of the decisions made. Repository monitoring is thus also a technical/scientific basis for decision-making to identify errors and defects. In this connection, standards need to be developed in order to be able to differentiate which deviations from the expected values are to be considered as faults that necessitate the application of corrective measures.

Active repository monitoring is necessary at least until the point in time where – from a design point of view – it is impossible to recover the waste containers. It is not possible to stipulate methods for this long-time monitoring. However, we must demand already today that repository monitoring in all phases must be based on the state of the art in science and technology available at the time and that a target-oriented further development of the methods to monitor the safety of a repository be supported. Furthermore, as a final point for monitoring cannot be defined, it is to be expected that a society that is informed about the existence of the repository will want to monitor the repository site and/or the surrounding protected assets (e.g. surface, groundwater) in the long term. Which methods will be applied, must be seen in the future. When it comes to preventive documentation, the related fundamentals can be handed over to future generations.

3.2 Repository monitoring strategy of DBETEC

DBETEC's framing of repository monitoring comprises the definition of what monitoring is all about, high-level goals to be achieved by a suitable monitoring concept, and a monitoring strategy considering the German regulatory framework and the European view on repository monitoring established during several European projects.

3.2.1 Definition of monitoring

As a definition of repository monitoring, the definition developed by the MoDeRn consortium is assumed to be comprehensive and applicable. The MoDeRn Project defines the term 'monitoring' in the context of geological disposal of radioactive waste as (White 2013):

> *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.*

3.2.2 Goals of repository monitoring

The motivation of repository monitoring and in particular of the engineered barrier system (EBS) is to get continuous information about the evolution of important repository components. The clay host rock is assumed to be the main barrier for radionuclide migration. But even the best host rock cannot fulfil the containment requirements if the man-made access routes to the underground facilities are not sealed in a suitable manner. Engineered barriers need to be installed in the underground drifts and shafts able to fulfil the containment requirements in a similar quality as the host rock itself. Repository monitoring is seen as a tool which shall, to the extent possible, provide information whether the containment requirements can be met. Thus, high-level goals to be achieved by a suitable monitoring concept are defined as:

- The monitoring concept has to be consistent with the current German regulatory framework.
- The concept shall be based on the 'Monitoring Workflow' that was developed during the European MoDeRn project (NDA et al. 2013a).
- The concept shall allow to the extent possible the verification whether the identified performance targets (PT) for the geotechnical barriers, also referred to as safety function indicators (SFI), can be met.
- The concept shall allow to the extent possible the verification whether the integrity of the host rock or the containment providing rock zone is not endangered.
- The monitoring concept shall be developed as a 'process concept' which explicitly includes learning effects during the whole operational phase. The 'process concept' shall be structured by milestones.

- Monitoring results shall be included in decision sequences as basic information, especially for the successive implementation of new seals and the associated monitoring systems to be installed.
- The monitoring concept shall be designed in such a way that – taking into account the emplacement concept or the sequence of emplacement – it is possible to assess the possibilities and limits of post-closure monitoring already during the operational phase.
- The monitoring concept shall be updated at least every 10 years in parallel with the required update of the safety case.

3.2.3 Strategy for repository monitoring

As explained in chapter 2, the emplacement option of the repository site model NORTH is vertical borehole emplacement. The repository layout consists of 45 emplacement fields plus infrastructure part with 2 shafts (see Fig. 0.3). Each emplacement field comprises 9 emplacement drifts with 11 vertical emplacement boreholes each. According to the backfilling and closure concept, emplacement starts in the field farthest from the shaft.

When a borehole is completely filled, it will be sealed with a plug consisting of a sealing element and an abutment to keep the sealing element in place. The part of the emplacement drift above the borehole will be backfilled (Fig. 0.29). This corresponds to a repository design where repository backfilling and sealing takes places continuously and successively during the entire operating phase of the repository. The monitoring concept has to be adjusted to the operating processes.

One specific aspect that has to be considered in order to determine the duration of the monitoring activities is the evolution of the repository. The monitoring programme is to be understood as a continuous learning process that is to be used to collect information that may help the repository operator, the regulator, and future generations to make decisions in the course of the repository evolution. In order to successfully implement a monitoring programme in a repository, a learning or process concept that consists of all measures necessary to collect, evaluate, transfer, and implement lessons learned related to the monitoring activities has to be defined and developed as part of the monitoring programme.

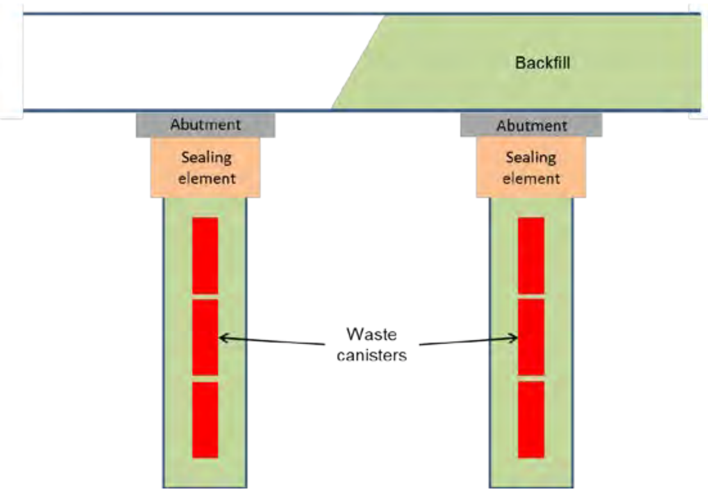


Fig. 0.29:
Sketch of the operational procedure of backfilling the emplacement drifts.

The basic idea for the development of a monitoring concept is to select representative components of the repository for monitoring purposes. The recommended approach for implementing the monitoring programme in a repository is to initially select specific emplacement fields, specific emplacement boreholes, and specific seals for the installation of monitoring equipment and to perform the monitoring activities. These specific components will be referred to as 'Monitoring Fields' (MF), 'Monitoring Boreholes' (MB) and 'Monitoring Seals' (MS). The experience gained from the initial monitoring activities in the first MF, MB, and MS will allow to refine the knowledge of the operator about implementing and evaluating the monitoring systems (e.g. durability, adequate measurement locations, reliability etc.), about analysing and interpreting the data obtained, and about understanding the behaviour of the repository and its barriers. The results shall continuously be collected and analysed in a regular manner by the responsible staff and institutions. The evaluation results are intended to be used to increase the quality of the monitoring systems and its implementation in the next selected repository components for monitoring in order to improve the monitoring efficiency and therefore the monitoring concept in general. As a first approach and with regard to the repository concept and facility design (cf. Fig. 0.3), six emplacement fields have been selected as representative (Fig. 0.30).

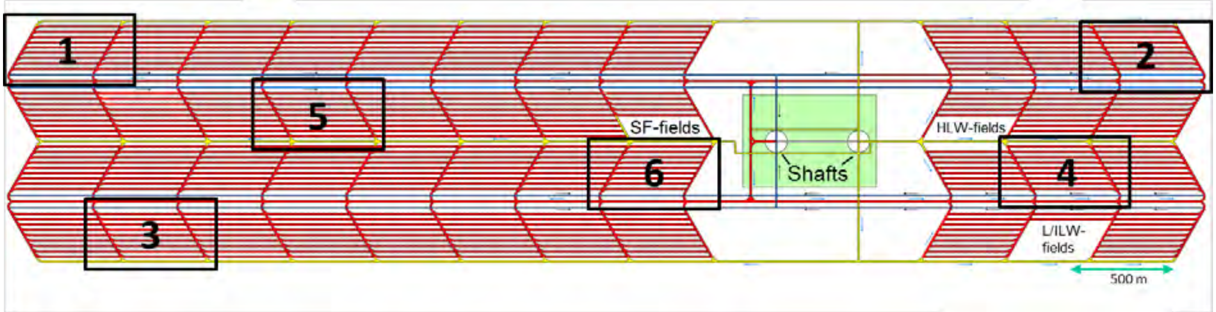


Fig. 0.30: Potential arrangement of monitoring fields in a repository (the assigned number indicates the order in which the monitoring activities will be implemented).

In order to benefit from the experience gained in previous monitoring activities, the process will start by installing the monitoring equipment at the first monitoring field [1]. This monitoring field will be the outermost one in the emplacement area planned for the disposal of the spent fuel canisters. This field will be the first one to be filled and thus offers the possibility of maximizing the available time for monitoring during the operational period of the repository. The same argument is valid for monitoring field [2]. This field is the outermost emplacement field in the area planned for the disposal of reprocessing waste. According to the safety requirements each emplacement field has to be sealed against the rest of the underground openings as soon as possible. This allows obtaining monitoring data out of an already backfilled and sealed emplacement field during the operational period of the repository and thus getting some kind of “post-closure” information.

During the monitoring activities, the results will be recorded properly, and before starting the monitoring activities at the next monitoring field [3], a standardized review statement of the monitoring activities implemented at field [1] and [2] will be produced and evaluated. This evaluation point is seen as a milestone. The results of this evaluation will be used to decide whether the monitoring concept needs to be updated and/or improved, thus determining the monitoring strategy and approach to be followed in the next disposal field. This approach allows to minimize errors and to increase the knowledge of the operator and the regulator. Currently it is being discussed whether an involvement of public/lay stakeholders in the evaluation process at this milestone would help getting acceptance and increase the confidence of stakeholders.

After the monitoring activities at field [3] have started, the monitoring activities at field [1] and [2] will of course continue. It is important to implement continuous long-term monitoring activities and to collect long-term monitoring data, which can be helpful to better understand the long-term behaviour of the barriers of the repository and thus, to determine the most suitable monitoring strategy to be followed during the post-closure phase of the repository. If the lessons learned from monitoring during several decades in the operational phase of the repository render obvious that further monitoring would not provide significant added value, the monitoring activities may be stopped.

Fig. 0.31 gives an overview of the arrangement of monitoring boreholes in monitoring field [1] together with the first migration barriers intended to be monitored as well.

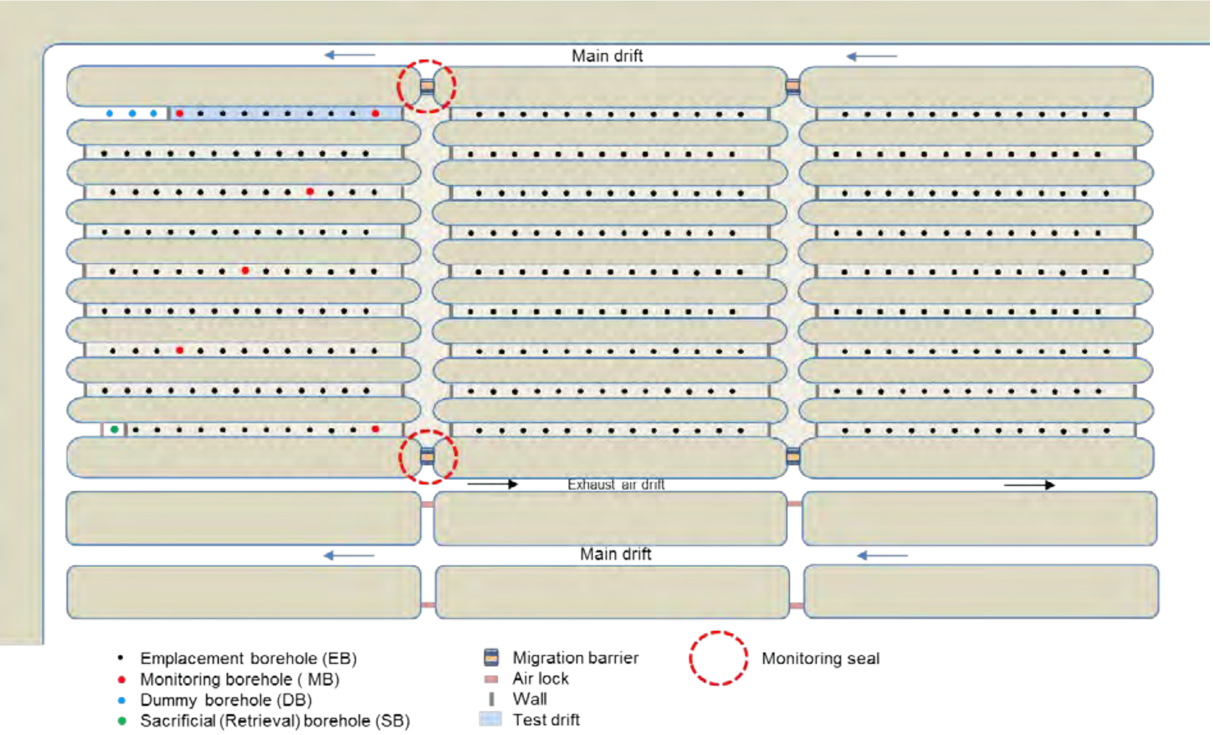


Fig. 0.31: Potential arrangement of monitoring boreholes in monitoring field [1] and the first monitoring seals.

The monitoring fields 4 and 5 are located in the central areas of the two emplacement areas for spent fuel and high active reprocessing waste. They will experience the highest temperature and thus the highest THM impact of all the fields. Monitoring field 6 is assumed to be the last one to be filled and the distance to one of the shafts is the most shortest one which represents the critical path when it comes to the evaluation of the tightness of the backfilled and sealed underground openings.

Currently, the implementation of so-called “Dummy Boreholes (DB)” is being discussed. The idea is to implement three dummy boreholes in the very first monitoring field (MF1) as illustrated in Fig. 0.31 by the three blue dots in the outermost drift. The use of electrical heaters in the very first three boreholes, as shown in Fig. 0.32, would allow testing the complete emplacement procedure, especially the plug implementation without risk of exposure to radiation. The three plugs will be instrumented to monitor the plugs' long-term behaviour under heat load, fluid inflow and rock convergence. Easy access to the monitoring equipment to check or update sensing and/or transmission units used for data acquisition will be possible. These dummy systems can be used to evaluate the monitoring system and the plug evolution and to develop improvements for future installations in plugs of boreholes filled with real waste. How these monitoring results fit into the evaluation and decision sequences is explained in chapter 6.

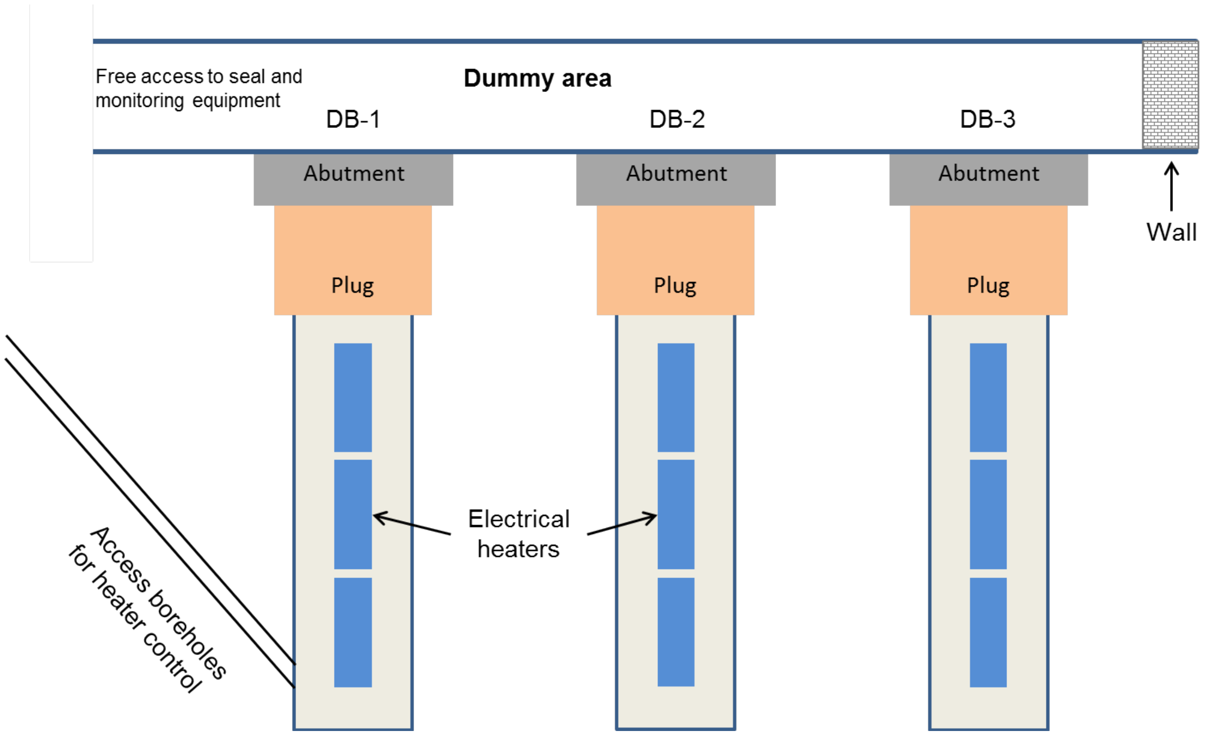
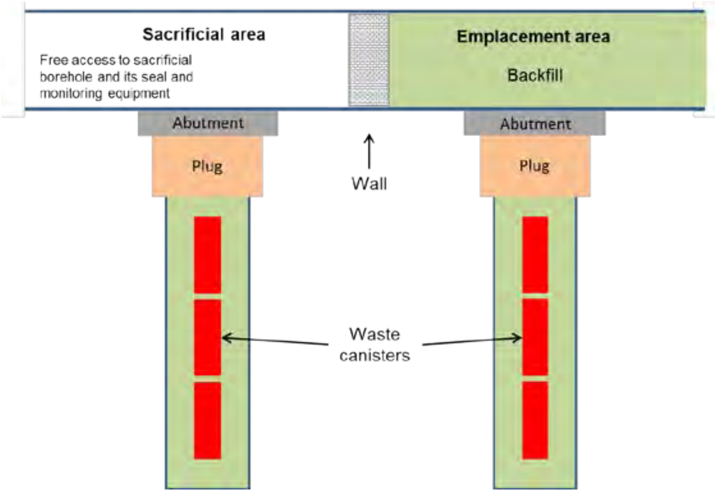


Fig. 0.32: Possible implementation of dummy boreholes for plug monitoring purposes

After the decision has been made to finish the test phase in the three test boreholes, the emplacement of the real waste can be started. With regard to the statements given in the report of the repository commission, considering a "hot" test phase, it is proposed that the remaining part of the first emplacement drift shall be used as a test drift. After the first emplacement boreholes have been filled with real waste and sealed in this part of the drift, monitoring systems shall be installed successively during the backfilling operation to monitor the evolution of the backfill, the conditions at the contact zone between backfill and rock and the host rock behaviour in the near field of the test drift. In addition, the last emplacement borehole will be used as a monitoring borehole and its seal will be monitored similar to the seals in the three test boreholes. After final closure of this test drift, a "waiting period" is foreseen during which a continuous evaluation of the monitoring results shall be performed. As a first approach a period of one year seems reasonable. The monitoring results obtained during this "waiting period" are assumed to be a fundamental input to the decision for a green light for continuous waste emplacement.

In the first monitoring field five boreholes (marked with red dots) have been selected as monitoring boreholes for borehole seal monitoring in five different emplacement drifts (Fig. 0.31). They are mainly located on a linear profile through the monitoring field. Using this configuration it is possible to cover on the one hand the location with the most intensified heat input in the central part of the monitoring field. On the other hand the profile starts from the outer boundary of the emplacement field where the first boreholes have been filled and goes to the other outer boundary where the last boreholes will be filled. Thus, it covers the whole THM evolution in the first emplacement field.

Another option which is currently under discussion is the use of a so-called "sacrificial borehole" (Fig. 0.33). This borehole could be the last one to be filled in the last emplacement drift in the first emplacement field as shown by the green dot in Fig. 0.31. The idea behind this kind of borehole is that the waste canisters in this borehole are intended to be retrieved prior to final closure of the repository and disposed of in another already prepared emplacement borehole in a reserved area (empty field areas shown in Fig. 0.30). This borehole will be heavily instrumented for monitoring not only the seal but the canister environment as well. For monitoring equipment wired systems would be allowed since the



systems will be completely recovered after waste retrieval. A weakening of any barrier function is not to be considered.

Fig. 0.33:
Sketch of the sacrificial borehole area.

The complete recovery of the monitoring equipment which would have been under operation for a few decades (hopefully) would allow investigations about the aging of the system components and thus information about the durability could be obtained. This information will be helpful to estimate the expected lifetime of the sensing systems still in operation at the other monitoring locations.

When the access drift between the first two emplacement fields are not needed any more, migration barriers (see Fig. 0.7) shall be built at its both ends to seal the access to the emplacement field against the rest of the underground facilities as requested by the Safety Requirements (Fig. 0.31). These very first seals are intended to be used as 'monitoring seals'. That means that monitoring systems are intended to be installed to monitor the evolution of these very first seals. The monitoring results can be used to evaluate whether the performance targets defined for these seals can be met or if changes of the barrier design or the monitoring system itself would be necessary. Each emplacement field will be sealed by four migration barriers in the two access drifts. At each of the identified six monitoring fields, two of these barriers are foreseen as monitoring seals.

After all the emplacement fields have been filled with waste and sealed against the remaining underground facilities, an observation phase or a 'pre-closure phase' is following. During the pre-closure phase the shafts and the main drifts, allowing access to the individual emplacement fields and the migration barriers, shall be kept open for a time span to be fixed. The monitoring results obtained during the pre-closure phase are assumed to be a fundamental input to the decision for final closure of the repository.

At the end of the pre-closure phase when the decision for final closure has been made, the main drifts shall be backfilled and the eight main drift seals (cf. Fig. 0.8) at the interface between the infrastructural area and the emplacement areas for spent nuclear fuel and high-active reprocessing waste shall be built. The two of them having the shortest distance to each emplacement area, which are the outermost left and outermost right seal shown in Fig. 0.6, shall act as 'monitoring seals'. Both seals are lying in the most direct connection to the shafts and are therefore seen as essential to be monitored. All lessons learned during several decades of monitoring the migration barriers at the end of the access drifts to the emplacement fields will be available and will found a sound basis for the monitoring system installation at these two seals.

After filling the infrastructural area with gravel which has a high porosity and can act as a temporal gas and water storage, the two shafts will be closed by using two separate sealing modules in each shaft. The preliminary sealing concept is shown in Fig. 0.9. Since the two shafts represent the main access to the earth's surface, all of the four sealing modules shall be monitored.

4 Monitoring parameter identification

One of the important tasks of the MODERN2020 project is to develop a transparent process for identification of parameters to be monitored in a repository for high-level waste with a special focus on the engineered barrier system. At the beginning of the MODERN2020 project a preliminary parameter screening process has been developed (White et al. 2015) which provides a workflow (Fig. 0.34) supplemented by a couple of guiding questions to identify parameters worth monitoring. This workflow has been documented and explained in the deliverable D2.1.

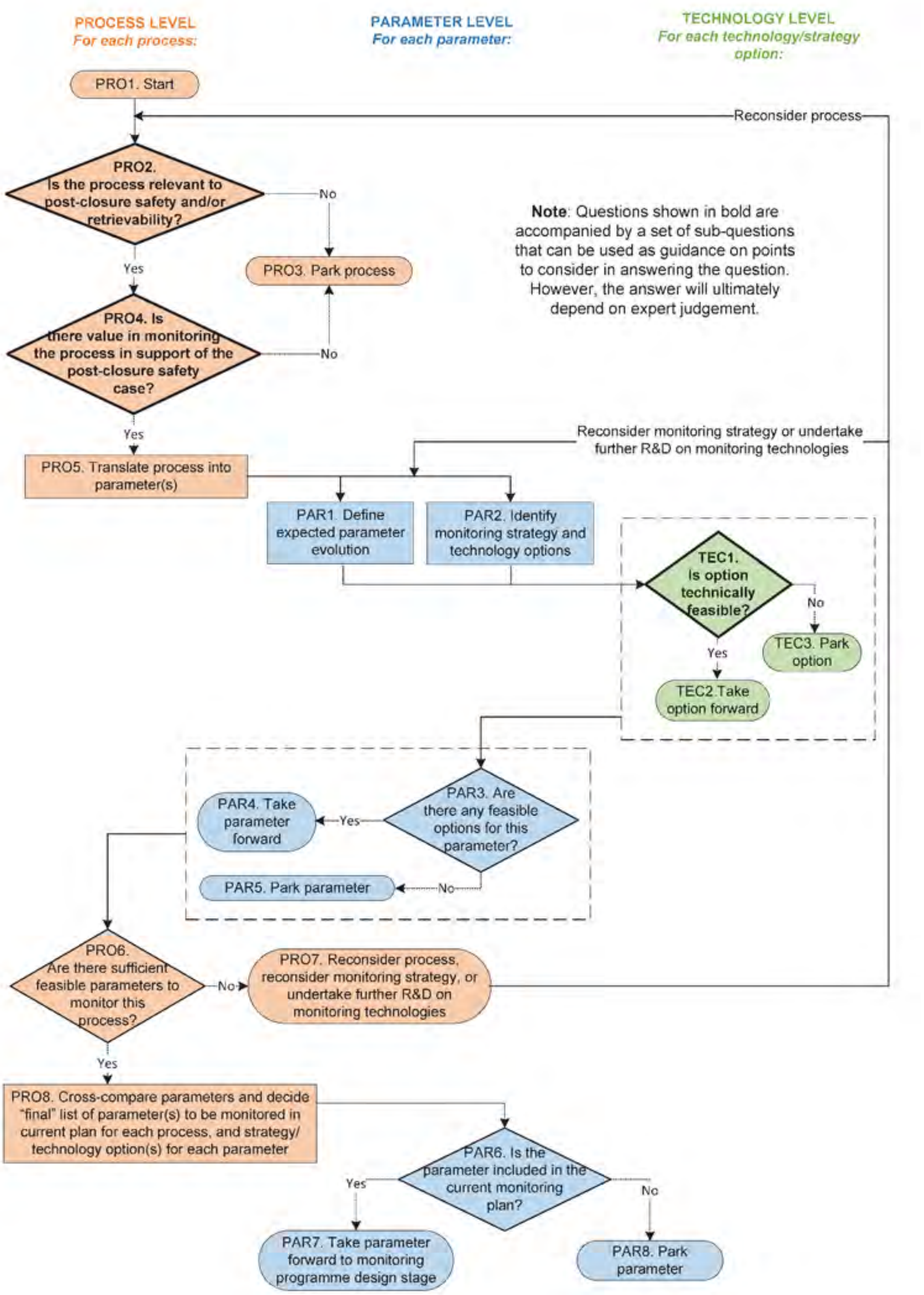


Fig. 0.34: Workflow of the preliminary parameter screening process developed during task 2.1 of the MODERN2020 project.

During further work in the MODERN2020 project this preliminary workflow shall be tested based on different cases on its applicability to different concepts. The report in hand describes the test results obtained from the German ANSICHT test case.

4.1 Selection of processes worth monitoring

The parameter screening workflow is separated into three different levels: the process level 'PRO' (orange), the parameter level 'PAR' (blue) and the technology level 'TEC' (green). It starts on the process level with the box PRO1.

For a selected repository component or engineered barrier (EB) in the ANSICHT test case the specific process list relevant for this component has to be identified first. This is the important point where a link is set between the monitoring concept under development and the site specific FEP catalogue. During the ANSICHT project site specific FEP catalogues have recently been developed (Stark 2014 and Stark 2016). These FEP catalogues represent a comprehensive system description where all repository components as well as all the processes going on in and around the repository are listed and described including an estimation about the probability of occurrence. Based on these FEP catalogues an analysis of the expected and alternative repository evolutions can be performed. This catalogue contains the processes to be considered when looking at a specific engineered barrier.

For testing the screening process in the ANSICHT test case a specific seal has been selected which is the seal on top of each emplacement borehole described in the chapter before. With regard to this seal the FEP catalogue has been screened to determine the FEP acting on this seal. Table 0.3 gives an overview of the compiled FEPs. These selected FEPs have been analysed to set up the specific list of processes which may influence the designed performance targets and thus the safety function of the barrier which is defined as:

Safety function of borehole seal

The borehole seal shall minimize the advective fluid flow into the borehole and out of it.

With this safety function the emplacement borehole seals provide a significant contribution to meet the 'advection criterion' mentioned in the German Safety Requirements which have been quantified for calculational barrier integrity proofs by Jobmann et al. (2015).

Table 0.3: List of selected FEPs to be considered when evaluating the seal performance of the emplacement boreholes (selected from Stark et al. 2014).

FEP no.	FEP name	Remarks
1.2.03.01	Earthquake	Specific event to be considered in the design in any case
1.3.03.01	Transgression or regression	May change vertical loads
2.1.05.01	Barrier material	Describes the material properties of the barrier
2.1.05.06	Borehole seals	Describes the seal and its properties
2.1.05.07	Alteration of plugs	Describes possible changes
2.1.07.02	Fluid pressure	Acts as a mechanical load and forces fluid flow
2.1.07.03	Backfill compaction	Changes mechanical load and backfill properties
2.1.07.05	Early failure of shaft seals	Early fluid inflow to be considered
2.1.07.06	Early failure of drift seals	Early fluid inflow to be considered
2.1.08.01	Amount of Solutions in the cavities	Changes the fluid pressure
2.1.08.05	Swelling and shrinking of clay minerals	Swelling pressure acts as mechanical load
2.1.09.01	Hydro-chemical conditions	May change corrosion activities

2.1.09.06	Corrosion of cement-phases	May change abutment properties
2.1.10.02	Microbial processes	May change properties of sealing element
2.1.11.01	Thermal expansion and contraction	Changes mechanical loads and pore pressure
2.1.11.04	Heat flow	May lead to temperature induced property changes
2.1.12.01	Gas production	Produces pore pressure changes
2.2.01.01	EDZ and unsaturated zone	Describes EDZ properties
2.2.02.01	Host rock	To be considered as mechanical load for the seal
2.2.03.01	Adjacent rock	To be considered as mechanical load for the seal
2.2.06.01	Stress changes	Characterize mechanical loads

With regard to this safety function, performance targets have been designed to meet this safety function. The performance targets are also referred to as 'safety function indicators'. Since the role of the seal is related to advective flow the performance targets are subdivided in hydraulic and mechanical targets. The seal shall have a low water permeability but a sufficient gas permeability to avoid fissure building due to high gas pressure from thermal expansion and corrosion. from preliminary calculations performed during the ANSICHT project it is known that in case all of the seals located on the shortest way from the emplacement boreholes to the boundary of the containment providing rock zone (CRZ) have a permeability after saturation that is less than 10^{-17} m^2, the so-called 'advection criterion' can be met which means that the advective flow in the drift system is slow enough to avoid a radionuclide release via the CRZ boundary (Jobmann et al. 2017b). The performance target is thus defined as:

Performance target: $k \leq 1 \cdot 10^{-17}$ m^2 (after water saturation)

From the mechanical point of view the design of the targets is mainly related to the swelling pressure evolution of the bentonite element and the stress evolution. The swelling pressure shall be limited to not exceed the minimum principle stress in the host rock to avoid rock damage and thus the building of new fluid pathways next to the seal. Experimental results from the in-situ shaft closure test in Salzdetfurth showed that by a designed and achieved swelling pressure of about 1 MPa of a bentonite sealing element a permeability in the range of $1.0 \cdot 10^{-17} – 7.8 \cdot 10^{-18}$ m^2 could be achieved (Engelhardt et al. 2011). Indicative calculations during the ANSICHT project showed that a swelling pressure higher than 1 MPa would probably lead to tensile stresses in the adjacent host rock with the consequence of not meeting the fluid pressure criterion in the host rock. Thus, the following performance target for the swelling pressure p_q was defined:

Performance target: $p_q \approx 1\, MPa$

A limited swelling pressure is also necessary to avoid a significant displacement of the abutment above which would lead to a loosening-up of the bentonite element and thus change its properties. In Wagner (2005) it is shown that if the loosening-up of the bentonite element is less than 3% (volume) the density and thus the achievable swelling pressure and related permeability will not significantly change. If 3% will be exceeded a significant reduction of swelling pressure and permeability is to be expected. The limitation of the loosening-up can thus be taken as an additional performance target supplementing the above mentioned targets.

Performance target: Loosening-up $\leq$ 3% of sealing element length

In the framework of the ANSICHT project the hydraulic impact on the bentonite element has been evaluated by applying the fluid pressure criterion as given in Jobmann et al. (2015). This criterion is related to the minimum principle stress. Numerical calculations for analysing barrier integrity an approach is used that takes into account the coupling of thermal, hydraulic, and mechanical processes (THM). Hydraulic-mechanical coupling is based on the application of effective stresses, an approach that can be ascribed to Terzaghi & Fröhlich (1936). According to this, the total (external) stresses σ^{tot}

are in equilibrium with the effective stresses σ^{eff} that act on the grain structure and are linked to the pore pressure p via the Biot coefficient α:

$$\sigma^{eff} = \sigma^{tot} - \alpha \cdot p \qquad (4.1)$$

Positive stress values are indicated as tensile stresses, negative values as compressive stresses. Generally, the mechanical behaviour (stress-strain behaviour) is expressed by means of the effective stress. Secondary water pathways that can lead to an ingress or release of potentially contaminated aqueous solutions are open macro cracks. Cracks can form if the effective stresses exceed the tensile strength of the host rock. Using the concept of effective stresses, the tensile strength can be reached by mechanical and hydraulic processes or a combination of both.

As the tensile strength of the compacted bentonite material can be zero, the corresponding criterion should be the effective tensile stress itself. In this case, the principal stress of the effective stress tensor that has the highest tensile stress needs to be analysed. Defining the three main stresses:

$$\sigma_I^{eff} \leq \sigma_{II}^{eff} \leq \sigma_{III}^{eff} \qquad (4.2)$$

allows to describe the areas where effective tensile stresses occur by means of the following inequation:

$$\sigma_{III}^{eff} \geq 0 \qquad (4.3)$$

The fluid pressure criterion and thus another performance target can be written as

Performance target: $\sigma_{III}^{eff} = \sigma_{III} - p \geq 0$ (free of tensile stress) (4.4)

The swelling pressure of the bentonite yields a significant contribution to σ_{III}. Additional pressure contributions will arise from own weight, overburden pressure and the flow induced pressure. That means that the heat load of an emplacement borehole and its seal shall be designed in a way that the bentonite element will be free of tensile stresses.

The performance targets identified for the borehole seal are summarized in Table 0.4.

Table 0.4: Performance targets identified for the borehole seal

Performance target No.	Description	Target
PT-1	Permeability of the bentonite element	k ≤ $1 \cdot 10^{-17}$ m^2
PT-2	Swelling pressure of the bentonite element	$p_q \approx 1\ MPa$
PT-3	Loosening-up of the bentonite element	≤ 3% of plug length
PT-4	Bentonite element shall be free of tensile stresses	$\sigma_{III}^{eff} = \sigma_{III} - p \geq 0$

The next step is then to link the specific FEP list given in Table 0.3 to the performance targets for the borehole seal given in Table 0.4 in order to identify the relevant processes able to question the achievement of the performance targets. In total ten relevant processes have been identified that may be considered in view of the performance targets. These relevant processes are compiled in Table 0.5. These ten processes (Table 0.5) are then taken as input to the parameter screening process in parallel. The first box to be worked on is the box PRO2.

Table 0.5: Processes to be monitored with regard to the borehole seal in view of the performance targets

Process No.	Description
I	Fluid inflow from the drift above through abutment and bentonite plug
II	Mechanical load on the abutment from above (backfill mass, rock pressure at later times)
III	Convergence of the emplacement borehole (after emplacement)
IV	Fluid pressure from below due to thermal expansion and gas generation
V	Saturation evolution of the bentonite plug
VI	Swelling pressure evolution of the bentonite plug
VII	Chemical alteration of minerals (swelling pressure reduction)
VIII	(Heat flow) temperature evolution in bentonite plug
IX	Fluid flow through the bentonite plug out of the borehole
X	Displacement of the abutment in direction to the drift above

4.2 Test of the screening workflow

PRO1. START

The report D2.1 says: … *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. …*

Looking at the repository concept of the ANSICHT case, we think that it is not the best way to start with a single process out of a general list of processes which should be monitored in a repository. Starting with a process would mean to check the whole repository and evaluate the safety relevance of this process at all locations. A process can have a very different evolution at different locations in the repository and it is not worth monitoring everywhere. We think that a better way of starting is to look at a specific repository component, which is essential for the safety analysis like for example the individual geotechnical barriers. Focussing on these specific elements, all processes shall be identified which act on a specific barrier and which may have an influence on the designed performance of the barrier. Thus, for the ANSICHT case, PRO1 is not a single process but a small list of processes specifically acting on the barrier under consideration. And this specific list of processes should be screened in parallel, that means at each step of the screening process all of the selected processes should be looked at.

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

The D2.1 report says that *with regard to recent NEA guidance it is important to select a limited number of parameters (and hence processes) 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 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.*

The four supplementary guidance questions given in the D2.1 report have been considered during this test and slightly changed to fit them to the way the screening process is applied in the ANSICHT test case. Changes have been marked by cross-outs and new text is written in red.

PRO2.1 Is the process directly related to one or more safety functions of ~~any~~ the repository element ~~of the repository system~~ under consideration?

PRO2.2 Is the process related to any safety function indicator or performance target of the element under consideration?

PRO2.3 Is the process linked to a parameter modelled in the safety assessment that has a significant impact on system performance (dose/risk)?

PRO2.4 Is the process perhaps in combination with other processes related to system performance that could lead to a decision to (partly) retrieve waste or otherwise reverse the disposal process?

Each of the ten identified relevant processes given in Table 0.5 have been considered at this step. The answers to the slightly modified supplementary guidance questions related to each of the processes are given in Table 0.6 as a question-process-matrix. The answer to the main question PRO2 has not been given directly but with the help of the supplementary guidance questions. We applied the "criterion" that if there is a "yes" to at least one of the supplementary guidance questions then the answer to the main question PRO2 is "yes" otherwise the answer is "no".

Table 0.6: Answers within the question-process-matrix for the step PRO2 (process no. cf. Table 0.5)

Process / Question	I	II	III	IV	V	VI	VII	VIII	IX	X
PRO2.	**yes**	**yes**	**no**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**
Supplementary questions										
PRO2.1	yes	no	no	yes	yes	no	no	no	yes	no
PRO2.2	yes PT-2	yes PT-3	no	yes PT-4	yes PT-1 PT-2	yes PT-2	yes PT-2	yes PT-4	yes PT-1	yes PT-3
PRO2.3	no	no	no	yes	yes	yes	no	no	yes	no
PRO2.4	no	no	no	yes +VI	no	no	no	yes +IV	yes +IV+X	no

Applying the "one-yes" criterion, nine of the ten processes got a yes as an answer to the main question PRO2 whether the process is relevant to post-closure safety and/or retrievability. Only for process number III all answers to the guiding questions are "no". The process is not directly related to the safety function (PRO2.1) since it mainly results in pressure changes which are already more directly tackled by the processes fluid- or pore pressure evolution and swelling pressure evolution. The answer to PRO2.2 is similar, since the performance targets are related to the pressure evolution. The cavity (borehole) convergence is not a parameter or a primary variable which is modelled in performance assessment studies (PRO2.3). Those models simulate stress and pore pressure evolution and the fluid flow and radionuclide migration as primary processes which may lead to dose/risk assessments. The part of the borehole which takes up the waste is stabilized by a metallic liner designed to withstand the rock pressure for several hundred years. Only the part where the plug is located, a direct contact of the bentonite element to the host rock is foreseen (Fig. 0.4). A decision to waste retrieval (PRO2.4) does not depend on the convergence of the lined borehole. Thus, the main question got as well a "no".

PRO3.
Park process

The guidance given in the D2.1 report says that *if it is determined during the work on step PRO2 that one of the processes 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. 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.*

For the ANSICHT test case this means that the process number III 'convergence of emplacement boreholes' is parked. There will be no translation into parameters which are to be monitored and thus not included in the current development of an EBS monitoring concept. But as stated in D2.1, this process remains documented within the system for later review. In the ANSICHT test case this process will be parked until the next update of the safety case and/or the monitoring concept is performed.

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

As stated in the D2.1 report *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.*

Again the supplementary guidance questions have been considered and slightly changed to fit them to the way the screening process is applied in the ANSICHT test case. Changes have been marked by cross-outs and new text is written in red. The main change is in PRO4.4. The question has just being "switched" in a way that the answer "yes" or "no" is switched. In this way it is consistent with the other questions and the "one-yes" criterion can be applied again.

In view of the "one-yes" criterion, the questions PRO4.3 and PRO4.6 have been exchanged with regard to the sequence given in the D2.1 report. The latter has been assigned to be a sub-question of all the other 5 questions. The reason for changing it that way is that if there is not a single "yes" to one of the first five questions, there seems to be no reason for monitoring it. If the only "yes" is given to the question of quantifiability than this would mean to monitor it just because you can do it or you can get results during the monitoring period but without any relevance to safety related aspects. Just because it is possible shall not be a reason to actually do it.

PRO4.1 Could monitoring the process reduce uncertainty in repository performance over-and-above knowledge derived from research, development and demonstration (RD&D)?

PRO4.2 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)?

PRO4.3 Could monitoring the process result in greater system understanding that would be incorporated in a periodic update to the post-closure safety case?

PRO4.4 ~~Could any uncertainty that would be addressed by monitoring the process be more readily addressed by changes to the repository design?~~
Would it be more suitable to address uncertainties by monitoring the process than by changes to the repository design?

PRO4.5 Could monitoring the process support general repository or specific EBS design improvements?

Sub-question for PRO4.1 to PRO4.5

PRO4.6 Could the changes to the repository system resulting from the process be quantifiable during the monitoring period?

Each of the remained processes have been considered at this step. The answers to the slightly modified supplementary guidance questions related to each of the processes are given in Table 0.7 as a question-process-matrix. The answer to the main question PRO4 has not been given directly but again with the help of the supplementary guidance questions applying the "one-yes" criterion for questions PRO4.1 to PRO4.5. If the answer to sub-question PRO4.6 is "no" then the process is parked whatever the answers to the first five questions are.

Table 0.7: Answers within the question-process-matrix for the step PRO4 (process no. cf. Table 0.5).

Process	I	II	III	IV	V	VI	VII	VIII	IX	X

Question			parked							
PRO4.	**yes**	**yes**		**yes**	**yes**	**yes**	**no**	**yes**	**yes**	**yes**
Supplementary questions										
PRO4.1	no	no		yes	yes	yes	no	no	yes	yes
PRO4.2	yes	no		yes	yes	yes	no	yes	yes	yes
PRO4.3	no	no		yes	no	no	no	no	yes	no
PRO4.4	yes	yes		yes	yes	yes	no	yes	yes	yes
PRO4.5	yes	no		yes	yes	yes	no	no	yes	yes
Sub-question PRO4.6	yes	yes		yes	yes	yes	no	yes	yes	yes

The main reason for getting a "no" for process number VII is that the reaction kinetics for mineral changes are very slow. Even if a monitoring period of 100 years is assumed after repository closure no significant changes in the material properties will happen during that period. Thus, the changes are not quantifiable in the monitoring period and the answer to PRO4.6 is "no". Therefore this process is parked.

PRO3.
Park process

For the ANSICHT test case the process number VII 'chemical alteration of minerals' is parked. There will be no translation into parameters which are to be monitored and thus not included in the current development of an EBS monitoring concept. But as stated in D2.1, this process remains documented within the system for later review. In the ANSICHT test case this process will be parked until the next update of the safety case and/or the monitoring concept is performed.

PRO5.
Translate process into parameter(s)

According to the D2.1 report *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).*

After going through the steps PRO2 and PRO4 two processes have been parked that means eight from ten processes are remaining for further consideration.

Process I and IX are characterising the fluid flow through the seal but from different directions. The parameter characterising the fluid flow is the (Darcy) flow velocity characterized by the permeability. Process II describes the mechanical load on the abutment from above which is characterised by the vertical total pressure. The pressure from below mainly due to thermal induced pressure and gas generation, which is process IV, is characterizes by the pore pressure. The next two processes are dealing with the bentonite element describing the saturation (process V) and the swelling of the bentonite (process VI). The corresponding parameters are water saturation and swelling pressure. The heat flow induced by the radioactive waste (process VIII) is characterized by the temperature. The last relevant process describes the movement of the abutment as a result of the pressure from below due to the swelling of the bentonite, the thermal expansion effects and the gas generation. The parameter to monitor this effect is the vertical displacement of the abutment. Table 0.8 summarizes the identified parameters resulting in a total of seven parameters for further consideration.

Table 0.8: Preliminary process-parameter matrix for monitoring borehole seals

Process / Parameter	I	II	IV	V	VI	VIII	IX	X
1	Permeability						Permeability	

2		Vertical pressure						
3			Pore pressure					
4				Water saturation				
5					Swelling pressure			
6						Temperature		
7								Vertical displacement

PAR1.
Define expected parameter evolution

The D2.1 report states that *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.*

As part of the ANSICHT test case the barrier evolution has been simulated. The applied model and the simulation results are described in section 2.2.

PAR2.
Identify monitoring strategy and technology options

D2.1 report: *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.*

The high level monitoring strategy consists of monitoring dummy emplacement boreholes and thus dummy seals, monitoring boreholes, a sacrificial borehole, and monitoring drift and shaft seals. A separate pilot or test facility is not considered. The monitoring strategy has been described in section 3.3.3. With regard to the technology the state of the art report (AITEMIN et al. 2013) compiled during the MoDeRn project has been used to check whether suitable sensing and data transmission systems are available. The preferred options are described in section 5 except for the first parameter "flow velocity" being the parameter characterizing the processes I and IX (Table 0.5). A couple of different technical options are available for in-situ flow measurements. But all of these options are related to borehole measurements. Measuring the Darcy velocity or flow rate through a large bentonite element without having access to the outflow seems not possible. For this reason, a new option was considered to get indirect information about the flow velocity. Applying Darcy's law the specific discharge can be calculated as (Lege et al. 1996)

$$q = k_f \cdot \frac{\Delta p}{l} \qquad (4.5)$$

with k_f = hydraulic conductivity, Δp = pressure gradient, and l = length of the element.

For the abutment part of the plug it can be assumed that the permeability and thus the hydraulic conductivity of this element can be designed with a sufficient accuracy by applying a suitable recipe. Such recipe design is a standard procedure for the production of e. g. roadway concrete that is designed to have a certain hydraulic conductivity to allow for a sufficient rain water drainage. Sufficient knowledge is available for concrete design (e. g. Schneider et al. 2012, McCain & Dewoolkar 2010, Kalinski & Yerra 2005, Batezini & Balbo 2015, Pease 2010). If the hydraulic conductivity is known a priori, the difference in pore pressure needs to be determined to allow for the specific discharge calculation. That means, the pore pressure is the parameter to be monitored at the top and the bottom of the abutment to allow for the velocity calculation for process I and IX. The applicability of this method needs the following requirements to be met.

- applicability of Darcy's law
- isothermal conditions
- the medium is water saturated
- the flow is in the direction of the pore pressure gradient without lateral losses
- steady state pressure conditions

Since the system will need some time to reach steady state conditions there will be a time period after installation of the plug where this method will not provide correct results. This is not really a drawback because one of the performance targets of the bentonite element below the abutment is a low permeability value and thus a low flow velocity on the long term after its saturation. Monitoring the long-term flow velocity would be a significant input for the safety case.

To apply this method for the bentonite element is difficult because the permeability of the bentonite after saturation and swelling cannot be designed as precise as for the concrete abutment. That means the first thing to do is trying to determine the hydraulic conductivity of the element after saturation. To do this, the analogue between the hydraulic flow and the thermal flow can be used. The heat flow density *q* through an element can be calculated using eq. 4.6 which is similar to eq. 4.5.

$$q = \lambda \cdot \frac{\Delta T}{l} \qquad (4.6)$$

with λ = thermal conductivity, ΔT = Temperature gradient, and l = length of the element.

A prevalent method to measure the thermal conductivity of a specimen is the so-called 'divided bar' method (Militzer & Weber 1985). The heat flow through a specimen with known thermal conductivity, the standard specimen A, is compared to the heat flow through a specimen with an unknown thermal conductivity (material B). This situation is illustrated in Fig. 0.35.

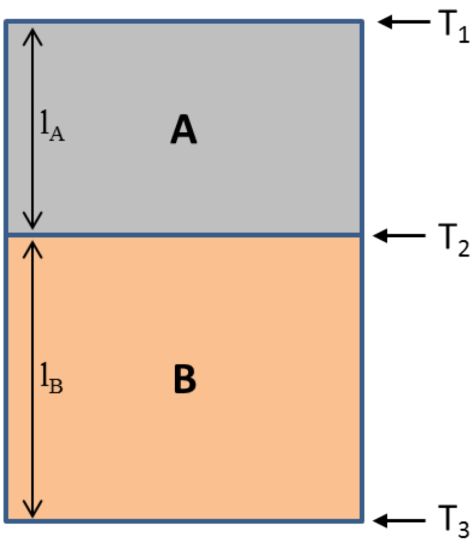


Fig. 0.35:
Principle configuration of a divided bar apparatus to measure the thermal conductivity of a specimen (T3 > T2 > T1 = temperatures)

Under steady state conditions the heat flow density is the same in both materials. That means eq. (4.6) can be written for both materials and treated as equivalent.

$$q_A = \lambda_A \cdot \frac{\Delta T_A}{l_A} = q_B = \lambda_B \cdot \frac{\Delta T_B}{l_B} \quad (4.7)$$

Dissolving the equation for λ_B yields

$$\lambda_B = \lambda_A \cdot \frac{\Delta T_A}{\Delta T_B} \cdot \frac{l_B}{l_A} \quad (4.8)$$

with $\Delta T_A = T_2 - T_1$ and $\Delta T_B = T_3 - T_2$

In analogy to this, the hydraulic conductivity can as well be estimated using this divided bar (db) method by applying equation 4.5 and using the pore pressure differences.

$$k_{fB} = k_{fA} \cdot \frac{\Delta p_A}{\Delta p_B} \cdot \frac{l_B}{l_A} \quad (4.9)$$

with $\Delta p_A = p_2 - p_1$ and $\Delta p_B = p_3 - p_2$

It has to be clearly noted that this is not a precise method for determining the hydraulic conductivity of an element, but it can give a good estimation whether the designed long-term hydraulic conductivity can be achieved by just monitoring the pore pressure gradients. It has also to be noted that there will be a temperature gradient along the bentonite element which is calculated to be in the range of about 20°C after saturation. Using a mean value of this range the uncertainty regarding a correct calculation of the fluid density and dynamic viscosity is small and tolerable.

TEC1.
Is option technically feasible?

D2.1 report: *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 (subdivided by the author) to assist with this and provide a framework for recording the results.*

Part 1 ("technical" questions)

TEC1.1 Can the proposed technology meet sensitivity, accuracy and frequency requirements for monitoring the parameter over the monitoring period?

TEC1.2 Can the proposed technology meet reliability and durability requirements for monitoring the parameter over the monitoring period?

TEC1.3 Can the proposed technology function effectively under repository conditions for the monitoring period?

TEC1.4 Can the proposed technology be applied without significantly affecting the passive safety of the repository system?

Part 2 ("impact" questions)

TEC1.5 Are the radiological doses to workers that could result from the installation, data acquisition or maintenance of the technology acceptable?

TEC1.6 Are the non-radiological risks to workers that could result from the installation, data acquisition or maintenance of the technology acceptable?

TEC1.7 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?

TEC1.8 Is the likely impact of the development, manufacture or deployment of the technology on the environment acceptable?

Going through the guidance questions for TEC1, we found it useful to subdivide the eight question in two groups of four questions. The first questions TEC1.1 to TEC1.4 are real "technical" questions and have therefore been titled accordingly. The second group are titled "impact" questions, since they are mainly dealing with impacts on workers' health, repository operation procedures and environmental issues. Besides subdividing the questions with regard to their content, there seems also to be a difference in who should answer these questions. The pure "technical" questions are clearly to be answered by the implementer in the first place while the "impact" questions might as well be looked at by the regulator and/or stakeholders especially regarding the last question TEC1.8. We think it would be useful to subdivide TEC1 in the main workflow as well. An option would be to change the dashed line box containing TEC1, TEC2, and TEC3 and make it similar to the combination of PRO2, PRO3 and PRO4. The question to be asked under TEC2 could be: *Are the impacts of implementation acceptable?* In case of 'yes' go to PAR3, in case of 'no' go to TEC3.

Looking at the first part, we found that the questions TEC1.2 and TEC1.3 are very difficult to answer and couldn't get a clear 'yes' or 'no'. While TEC1.1 can be answered by looking at current system descriptions and data sheets, for TEC1.2 and TEC1.3 the person who has to answer them has to look into the future for e. g. a few decades. Therefore, we suggest to "soften" the two questions by asking e. g.: *Based on current state of the art technology, can it be assumed that the proposed technology …* The answers to the questions are considering this proposed softening and are compiled in Table 0.9.

Table 0.9: Answers to sub-questions for TEC1 mainly based on MoDeRn State of the Art Report (AITEMIN et al. 2013)

	Flow velocity	**Vertical pressure**	**Pore pressure**	**Water saturation**	**Swelling pressure**	**Temperature**	**Vertical displacement**
Technology option	indirect db option	e. g. vibrating wire or FO sensors	e. g. vibrating wire or FO sensors	e. g. ADR method	e. g. vibrating wire or FO sensors	e. g. RTD or FO based systems	e. g. vibrating wire systems
Questions Part 1							
TEC1.1	yes	yes	yes	yes	yes	yes	yes
TEC1.2	yes	yes	yes	yes	yes	yes	yes
TEC1.3	yes	yes	yes	yes	yes	yes	yes
TEC1.4	yes	yes	yes	yes	yes	yes	yes
Questions Part 2							
TEC1.5	yes	yes	yes	yes	yes	yes	yes
TEC1.6	yes	yes	yes	yes	yes	yes	yes
TEC1.7	yes	yes	yes	yes	yes	yes	yes
TEC1.8	yes	yes	yes	yes	yes	yes	yes

The criterion we applied for taking the option forward is: if a parameter gets a single 'no' to one of the questions the option will be parked. It appears that all questions got a 'yes' which means all options are taken forward.

TEC2.
Take option forward

Report D2.1 says: *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.*

We think that TEC2 should be changed as mentioned above and a direct link should be set to PAR3.

PAR3.
Are there any feasible options for this parameter?

Report D2.1 says: *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.*

For each of the remaining parameters at least one technical option could be identified (Table 0.10). That means, monitoring the parameter is feasible.

Table 0.10: Answers to question PAR3 for the remaining parameters

Question	Flow velocity	Vertical pressure	Pore pressure	Water saturation	Swelling pressure	Temperature	Vertical displacement
PAR3	yes	yes	yes	yes	yes	yes	yes
Technology option	indirect db option	e. g. vibrating wire or FO sensors	e. g. vibrating wire or FO sensors	e. g. ADR method	e. g. vibrating wire or FO sensors	e. g. RTD or FO based systems	e. g. vibrating wire systems

PAR4.
Take parameter forward

Report D2.1: *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.*

All parameters and technical options given in Table 0.10 are taken forward.

PAR5.
Park parameter

Report D2.1: *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.*

With regard to Table 0.10 no parameters have been parked.

After finishing PAR5, we think there is some overlap in the steps from TEC1 to PAR5. The distinction between TEC1 and PAR3 is not really clear. One of the goals is to get a screening process that is transparent to external viewers (e. g. stakeholders). In case of experts having at least difficulties to understand the difference, maybe we should consider a clarification in this regard to be as clear as possible. We proposed changes as shown in the revised workflow in section 7.

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

D5.1 report: *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.*

With regard to Table 0.8 there are at least one parameter per process. This is assumed to be sufficient.

PRO7.
Reconsider process, monitoring strategy, or conduct further R&D on monitoring technologies
D5.1 report: *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.*
- *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.

With regard to the identified parameters, no reconsiderations seem to be necessary. But …

We think the PRO7 box contains too much options compared to all the other boxes. In addition, this box contains issues regarding processes, parameters, and technology and can thus not be assigned to one of the three levels. The re-evaluation of the process in case no feasible parameters are available seems similar to the "no" answer to the questions PRO2 and PRO4 which is PRO3. Thus, we suggest to split the PRO7 box and add a box "Park process" here instead of "reconsider process". In this sense we do not agree to the first bullet point given above. The screening process starts with safety relevant processes. Then, after the screening, it turns out that there is no parameter able to be monitored to get information about the evolution of the process. And so, it is said that the process is not relevant anymore because we cannot observe it via parameters. We think, this kind of logic is unsuitable. By saying "park process" we would not question the relevance of the process but we would keep it in the system and clearly indicate that there is a problem monitoring it.

After rephrasing the remaining box can be assigned to the parameter level as shown in the revised workflow in section 7.

PRO8.
Cross-compare parameters
D5.1 report: *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.*

By reaching this step for the first time and thus for the first process, we think, this box should be re-located. The point is, that after just looking at the first process, there is no possibility to do a cross-comparison of parameters, because other processes have not been looked at so far and no other parameters are available. The cross-comparison can and should be done after all selected processes have been analysed and translated into parameters. That means, after finishing the screening process for all processes.

PAR6.
Is the parameter included in the current monitoring plan?
D2.1 report: *This final question takes the parameter screening methodology to a logical conclusion, considering each parameter in turn.*

We think that this question seems needless. To our understanding the development of a monitoring plan starts after the parameter screening when the final parameter list is available. By approaching this question for the first time we misunderstood it by thinking this questions refers to a "current", that means already existing, monitoring plan developed prior to the screening process; which wouldn't' make sense without having parameters.

We suggest to exchange it by another question which we think should be included:
"Are there any further objections or reasons for not monitoring a specific parameter (e.g. the effort is to high)?" We think the question of effort has not been tackled so far and would also allow for bringing in the question of costs, if desired.

The parameters given in table 4.9 are taken as the final parameter list and are used to develop the monitoring plan for the specific barrier.

5 Monitoring system description

With regard to the monitoring parameters identified for the emplacement borehole seals in the last section, this section describes the planned or potential monitoring system. In the first place this monitoring system is foreseen for the dummy phase where the seals above the electrical heaters are implemented. Lessons learned during this dummy phase may lead to an updated version of this concept. As long as this is not the case this preliminary monitoring concept is assumed to be used for all of the identified monitoring boreholes.

Each seal of an vertical emplacement borehole consist of a bentonite sealing element and a concrete abutment laying above to keep the bentonite element in place. In both components monitoring systems shall be installed on a layered basis. That means there is no intention to install sensors homogeneously distributed in the sealing element. Such a distribution may help building preferential pathways through the bentonite element by going from one sensor to the next. At least it is difficult to prove that this will not happen. For this reason, sensing and transmission systems shall be installed at several horizontal levels, the so-called "monitoring levels". Such a level based system has also been considered during a case study of the MoDeRn project (Jobmann 2013).

5.1 Abutment monitoring

The following figures illustrate the four horizontal monitoring levels located in the abutment. An overview is given in Fig. 0.36. Two monitoring levels are located at the top and the bottom of the abutment and another two levels are in 30 cm distance to the top and the bottom. The reason for locating the levels 30 cm inside the abutment is to assure a homogenized pore pressor situation within the component without any surface influences. The top level which is monitoring level 1 (ML-1) consists of pressure and displacement sensors (Fig. 0.37). The vertical displacement sensors are indicated by black rectangles in the horizontal cross-section and by the angularly black line in the vertical cross-section.

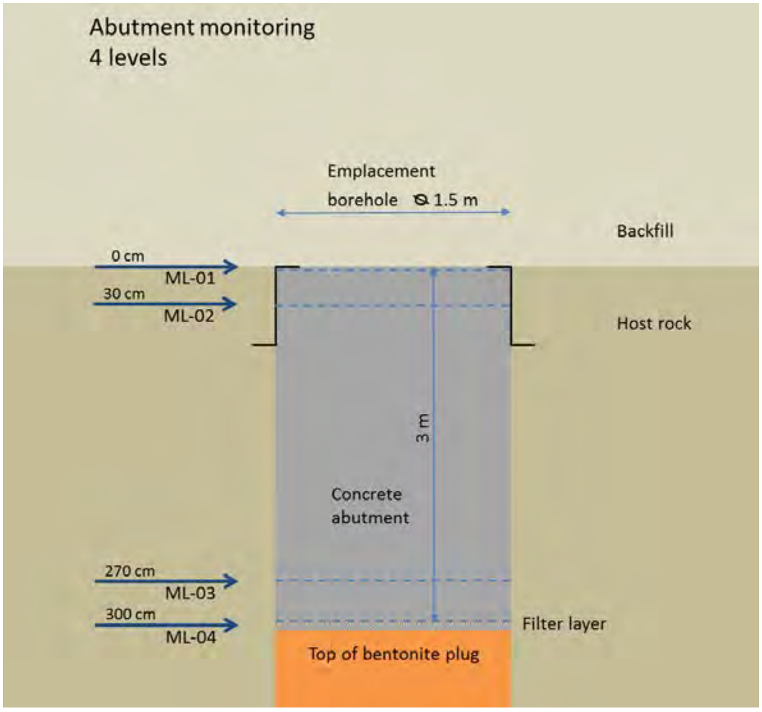


Fig. 0.36:
Location of the horizontal monitoring levels ML-1 to ML-4 in the abutment.

These sensors shall record a potential uplift of the abutment which allows an evaluation whether the abutment will be able to keep the bentonite sufficiently in place during its swelling process as defined by the performance targets. The pressure sensors are indicated by the black circles in the horizontal cross-section. These sensors shall record the vertical pressure at the top of the abutment. The backfill above the abutment supports the abutment in its task due to the backfill's own weight which will continuously grow during the backfill saturation. After some time the drift convergence will as well support the task of the abutment by compacting the backfill. Both, the own weight of the backfill and the later rock convergence and backfill compaction will increase the vertical pressure which shall be recorded.

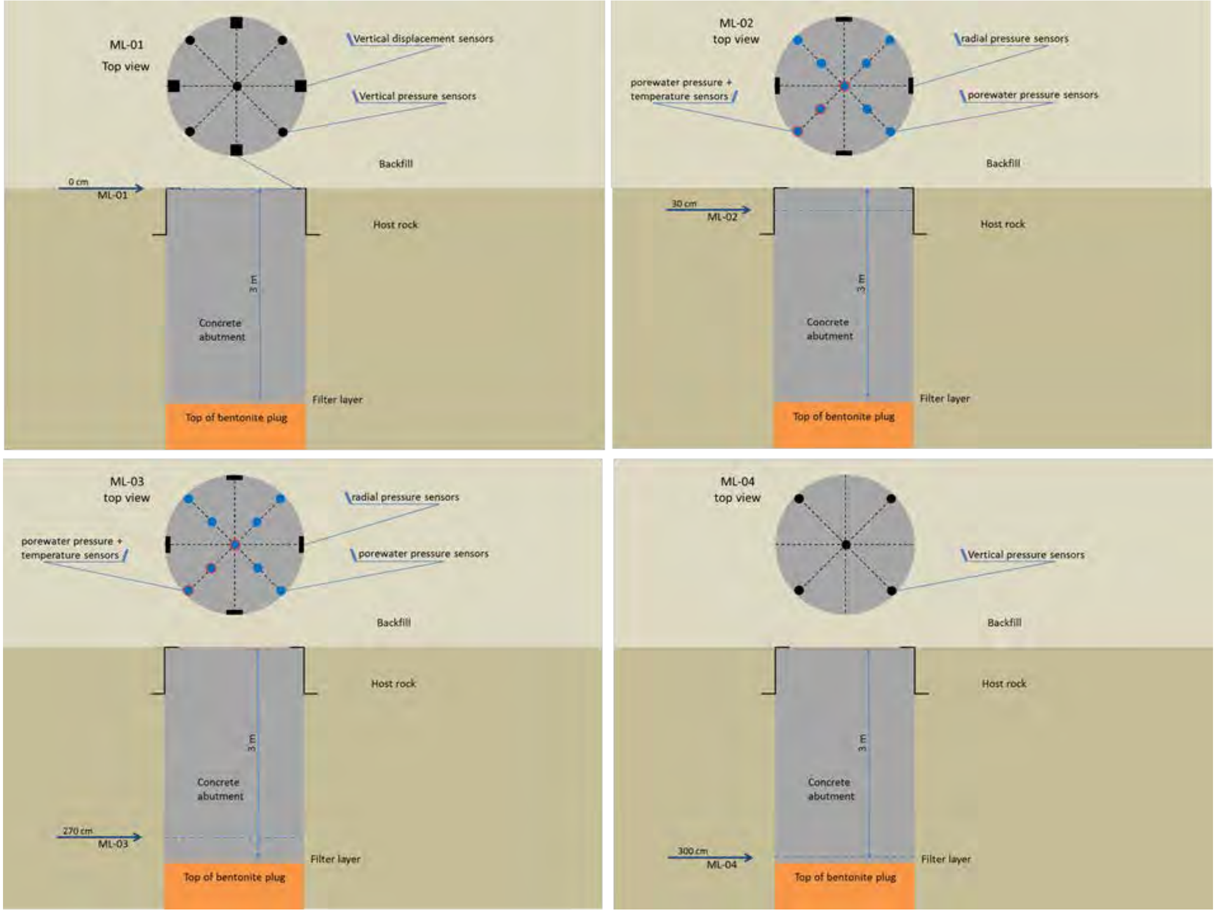


Fig. 0.37: Design of the monitoring levels ML-1 to ML-4 within the abutment.

On the monitoring level ML-2 and ML-3 the parameters pore pressure, the radial pressure component and the temperature are to be measured. The pore pressure shall be measured on two linear profiles oriented perpendicular to each other as shown in Fig. 0.37. This configuration allows to record the pore pressure evolution in the centre of the abutment as well as at four locations at the interface to the host rock. Since the pore pressure is monitored at both monitoring levels an indication of the fluid flow direction can be obtained. On one of the linear profiles going through the abutment in both monitoring levels the temperature shall be recorded at least at three sensor locations from the borehole wall to the centre of the abutment. The temperature information allows for a correct calculation of the fluid viscosity and its density. The radial pressure shall be recorded at four locations at the interface between the abutment and the borehole wall. In this configuration each of the two pairs of sensors shall be located across from each other and thus covering the whole circle of the borehole. The main reason for monitoring the radial pressure is to compare it with the radial pressure monitored in the bentonite element below that helps to identify the pressure component resulting from the swelling of the bentonite.

On monitoring level 4 (ML-4) vertical pressure sensors shall be installed similar to monitoring level 1 (ML-1). The idea is to monitor the pressure coming from the bentonite element below. The pressure evolution will mainly be a result of the bentonite swelling, the thermal expansion of the material and the fluid pressure. The pressure difference between ML-1 and ML-4 together with the measured vertical displacements will allow for a consistent interpretation of the abutment uplift and thus whether the uplift criterion can be met.

5.2 Bentonite element monitoring

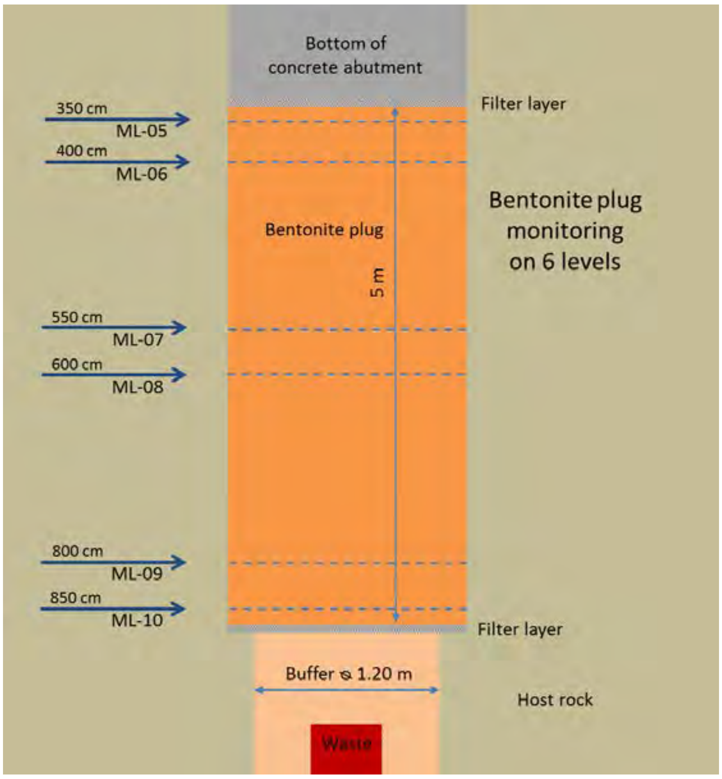


Fig. 0.38 gives an overview of the monitoring levels foreseen for the bentonite sealing element below the abutment. Six monitoring levels are planned, two in the middle of the sealing element (ML-7 and ML-8), two at the top (ML-5 and ML-6) and two at the bottom (ML-9 and ML-10) of the element. At both sides the outermost monitoring levels are a few centimetres within the sealing element to avoid surface effects at the sensors.

Fig. 0.38
Location of the horizontal monitoring levels ML-5 to ML-10 in the bentonite sealing element.

The distance between each of the two levels is about 0.5 m. The reason for not distributing all the monitoring levels equally is that is intended to have two larger areas of bentonite without any equipment inside. The configuration of using two quite near monitoring levels at three different areas of the element is assumed to be helpful for evaluating the difference of water movement coming from the top due to drift inflow and from the bottom of the element due to thermally driven flow.

Fig. 0.39 shows a horizontal cross-sectional view of monitoring level ML-5. Similar to the monitoring level in the abutment above, the pore pressure shall be measured on two linear profiles oriented perpendicular to each other. This allows to record the pore pressure evolution in the centre of the bentonite element as well as at four locations at the interface to the host rock. On one of the linear profiles going through the sealing element the temperature shall be recorded at least at three sensor locations from the borehole wall to the centre of the bentonite element. The temperature information allows for a correct calculation of the fluid viscosity and its density in this level. Additionally, there are four sensor foreseen for recording the humidity or water content. The radial pressure shall be recorded at four locations at the interface between the bentonite element and the borehole wall. Each of the two pairs of sensors shall be located across from each other and thus covering the whole circle of the borehole. The main reason for monitoring the radial pressure is to identify the pressure component resulting from the swelling of the bentonite. For this purpose it is very helpful to compare the pressures with the radial pressure monitored in the abutment above at similar locations since there is no swelling to be expected like in the bentonite.

The design of the following monitoring levels ML-6 to ML-10 is similar to the one of ML-5. Slight changes are foreseen for the monitoring levels ML-8 and ML-10. On these levels more temperature sensors are foreseen to check for the homogeneous horizontal temperature distribution in the bentonite element. Taking together the pore pressure evolution at all sensors this configuration allows for analysing the progress of saturation and gives indication about the direction of fluid inflow. The pore pressure differences along the vertical axis of the bentonite element after full saturation provide not only information about the fluid flow direction but also indications about the permeability (performance target) that can be achieved in the bentonite element on the long term (cf. section 4).

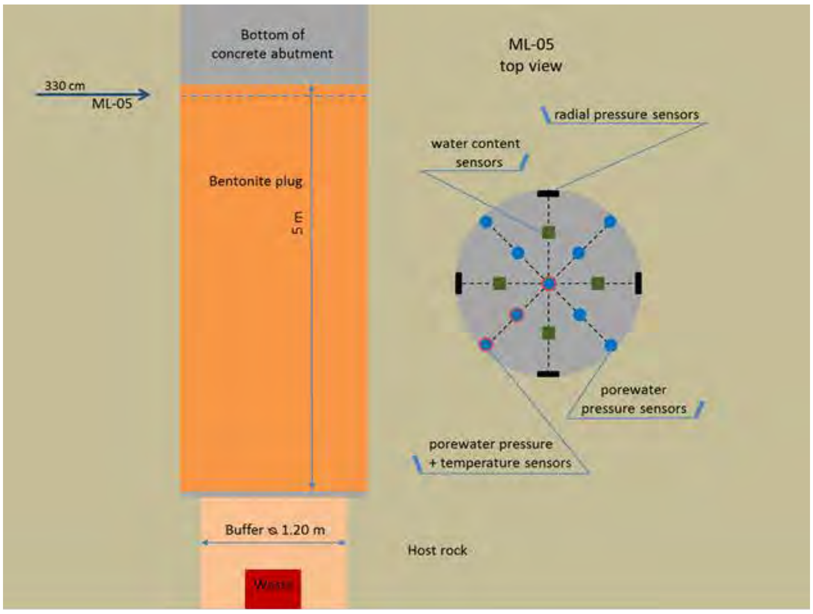


Fig. 0.39:

Location of monitoring level ML-5 and the horizontal cross-sectional view showing the locations of the different sensors.

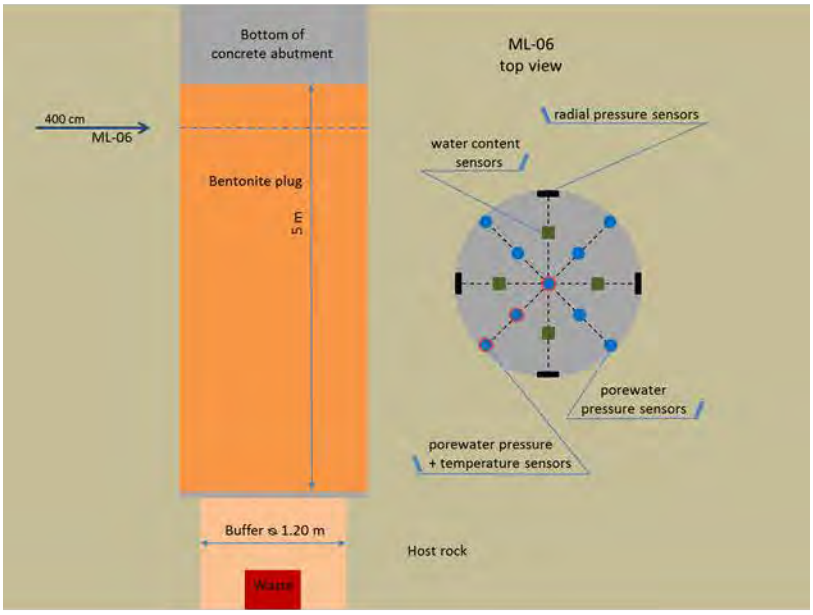


Fig. 0.40:

Location of monitoring level ML-6 and the horizontal cross-sectional view showing the locations of the different sensors.

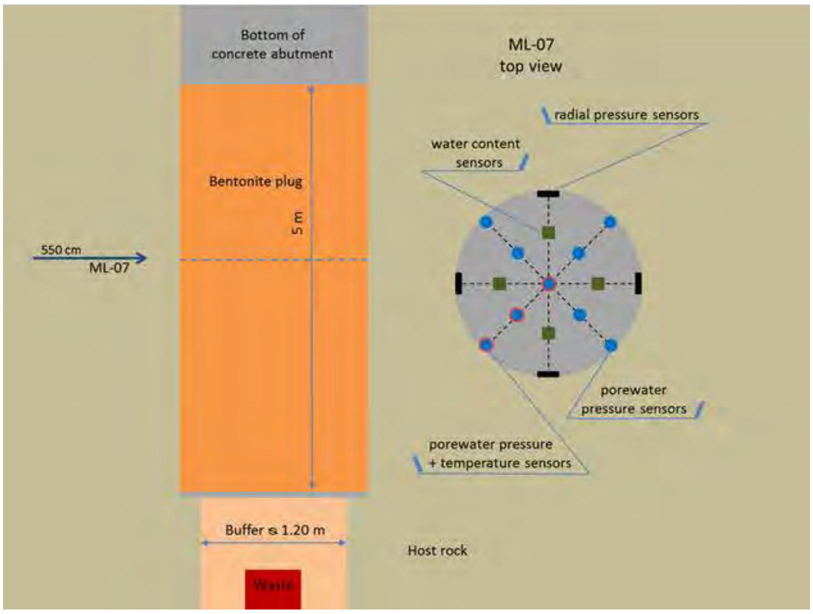


Fig. 0.41:

Location of monitoring level ML-7 and the horizontal cross-sectional view showing the locations of the different sensors.

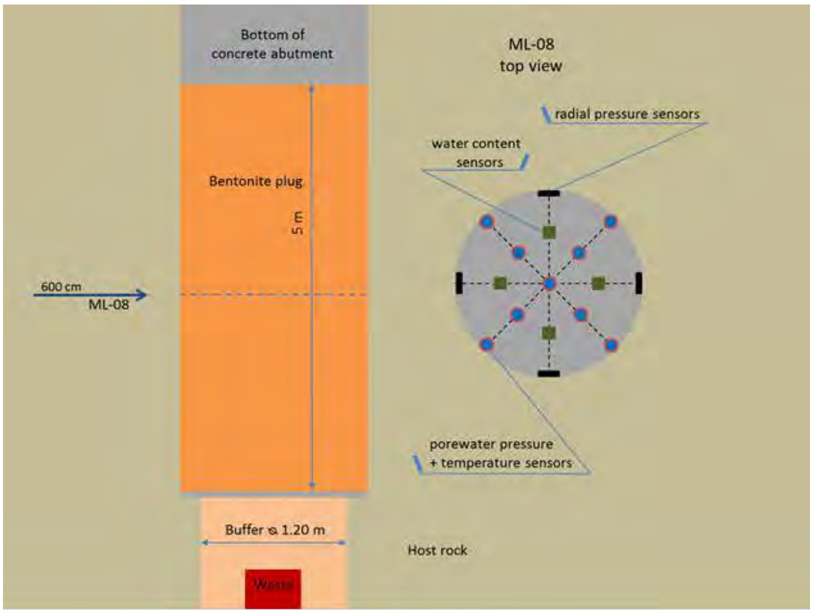


Fig. 0.42:

Location of monitoring level ML-8 and the horizontal cross-sectional view showing the locations of the different sensors.

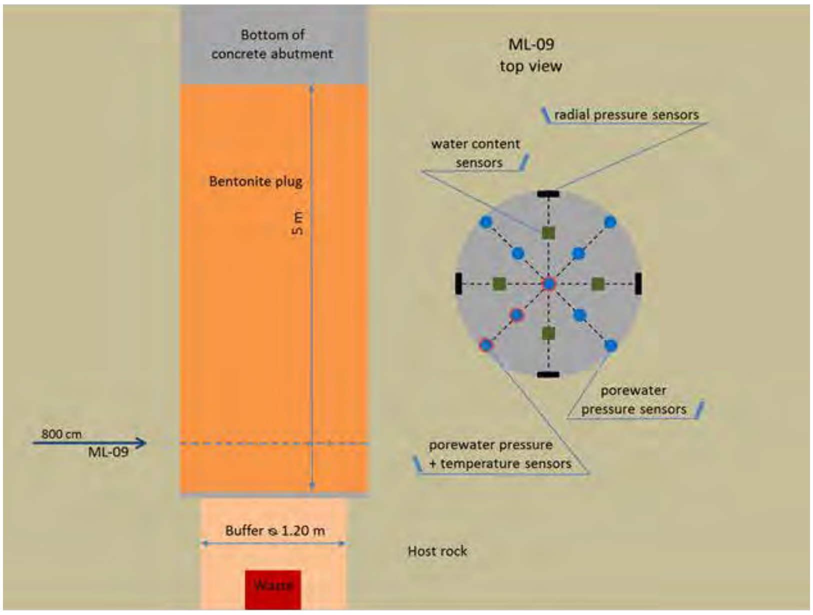


Fig. 0.43:

Location of monitoring level ML-9 and the horizontal cross-sectional view showing the locations of the different sensors.

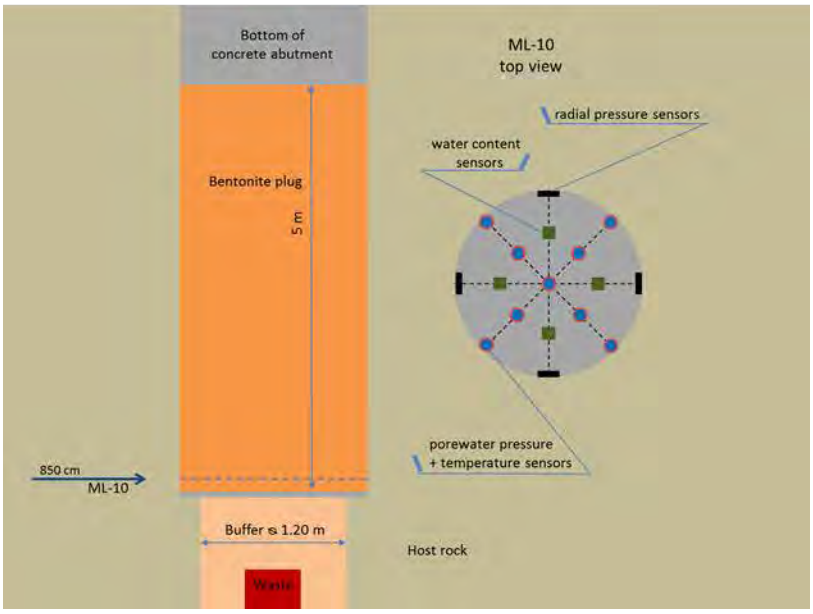


Fig. 0.44:

Location of monitoring level ML-10 and the horizontal cross-sectional view showing the locations of the different sensors.

5.3 Specific system requirements

Specific sensors to be implemented at the individual monitoring levels have not yet been selected. The German Safety Requirements stipulate that all technical equipment systems utilized be state of the art in science and technology. Since there are several year to come prior to the installation of sensors, this selection has been postponed. Therefore, instead of describing sensors currently available, the requirements of the sensing systems in terms of measurement range, accuracy, resolution and temperature range (Table 0.11), as well as proposed minimum measurement frequencies (Table 0.12) for all sensors in the system are described. Basis for this description are the simulation of the system behaviour during the first 150 years.

Table 0.11: Requirements on sensing systems

Parameter	Range	Accuracy	Resolution	Temperature range
Temperature	20 – 100°C	0.1 K	0.01 K	20 to 90°C
Vertical pressure	0.1 – 10 MPa	0.1 MPa	0.01 MPa	20 to 90°C
Radial pressure	0.1 – 10 MPa	0.1 MPa	0.01 MPa	20 to 90°C
Pore pressure	0.1 – 10 MPa	0.1 MPa	0.01 MPa	20 to 90°C
Displacement	-10 to +30 cm	0.1 cm	0.01 cm	20 to 90°C
Water content	0 – 100% (full saturation)	± 5%	± 1%	20 to 90°C

Table 0.12: Proposed minimum measurement frequencies (h=hours, d=days, m=months)

Parameter	Day 1 to 30 (Readings / time unit)	Day 31 to 365 (Readings / time unit)	Year 2 to 10 (Readings / time unit)	Year 11 to 100 (Readings / time unit)
Temperature	1 / h	1 /d	4 / m	1 / m
Vertical pressure	1 / h	1 /d	4 / m	1 / m
Radial pressure	1 / h	1 /d	4 / m	1 / m
Pore pressure	1 / h	1 /d	4 / m	1 / m
Displacement	1 / h	1 /d	4 / m	1 / m
Water content	1 / h	1 /d	4 / m	1 / m

The choice of the sensing systems is assumed to consider some **general principles** proposed by DBE TECHNOLOGY. These general principles are compiled in Table 0.13. The consequences resulting from these general principles are given in the table as well.

Table 0.13: General principles proposed by DBETEC with regard to the use of sensing technologies

	Principle	Consequence
1	No cables shall go through a sealing element along the axis of solute movement	Wireless systems are indispensable
2	Cabling between sensors within a sealing element shall be minimized as far as possible	Prefer autonomous sensors especially with regard to power supply and data transmission
3	Sensors shall not be distributed homogeneously in a sealing element	Use of monitoring levels
4	The amount of sensors within a sealing element shall be minimized as far as possible	Use multiple parameter sensors to the extent possible

With regard to the first general principle there is a need for implementing systems for wireless data transmission. Based on the experience gained from the MoDeRn project, wireless systems to be used in sealing elements making use of high frequency electromagnetic technology (Bárcena et al. 2013, NDA et al. 2013b). Using these high frequency system, a limited transmission distance has to be considered. Thus, a system is proposed making use of relay stations for bridging longer distances.

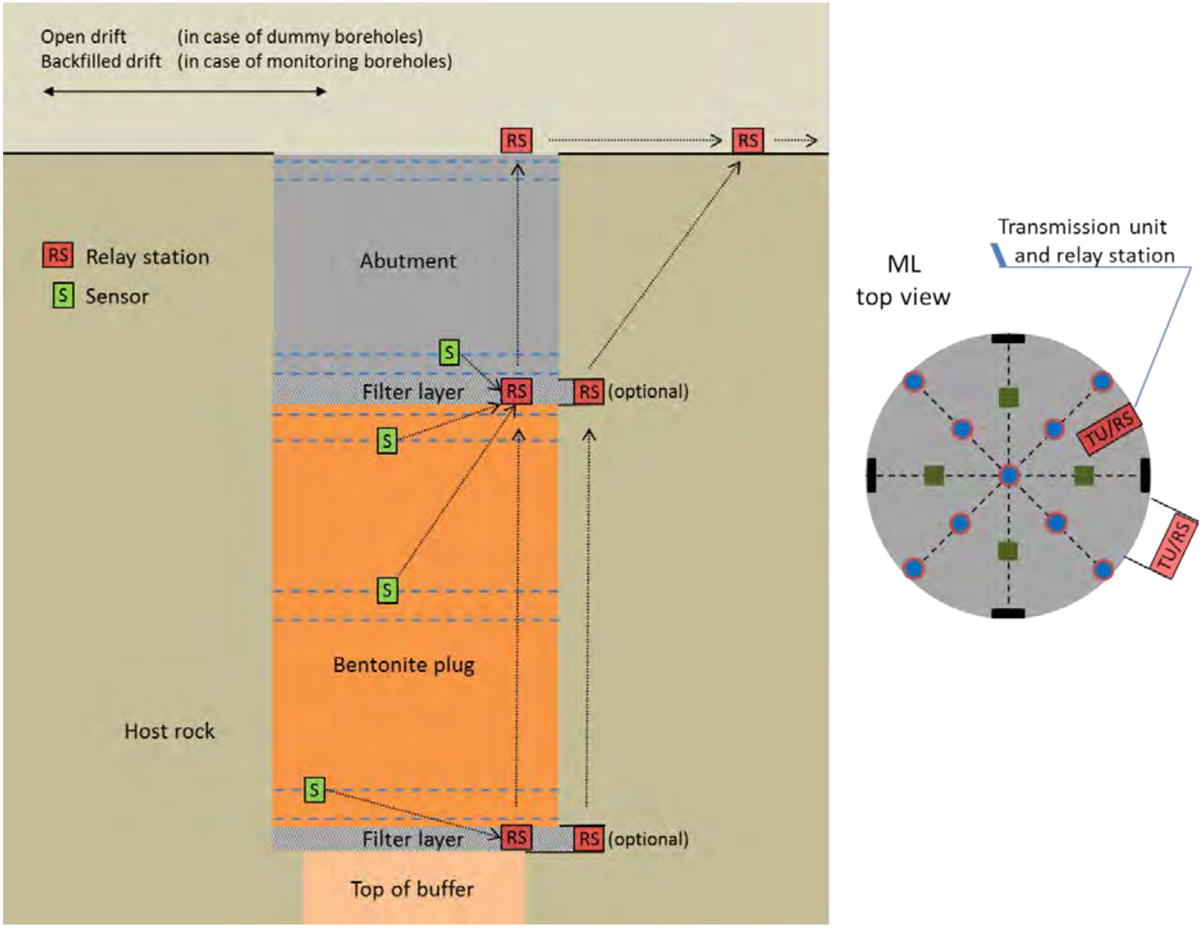


Fig. 0.45: Proposed locations for wireless transmission units

Such a system proposal is shown in Fig. 0.45. During the MoDeRn project multiple parameter sensors have been developed including a small data transmission unit. These sensor are able to send their recordings to a nearby receiver (NDA et al. 2013b). Making use of such kind of autonomous sensors, relay stations could be implemented in the sealing system being part of a so-called 'data hopping system'. In this manner, recordings of the individual sensors can be transmitted via several relay stations to a central receiving unit for further interpretation.

Within the borehole plug, suitable location would be in the filter sections at the bottom and at the top of the sealing element. At these locations they will not disturb the sealing element. Based on the experimental experience gained during MoDeRn, the signal damping within the sealing element might be strong. A signal transmission through the intact host rock is assumed to be less problematic. The intact rock has a much lower porosity and a stable soil skeleton, both of which leads to a better signal transmission. Therefore, the option is proposed to install the relay stations in a special niche in the host rock at the level of the filter layers (Fig. 0.45). This option might become the preferred option since the conditions will be more or less the same in the nearby host rock during the monitoring period while the conditions within the sealing element will continuously change during the saturation phase which will last a couple of years. The dumping effect will thus continuously change due to the different amount of water present in the sealing element. In-situ test will have to be performed to identify the most appropriate distances within the host rock (or/and within the sealing construction).

6 Conclusions and recommendations

The parameter screening process shown in Fig. 0.34 generally provides a good way of achieving a list of parameters worth monitoring in a repository. The sub-division into process level, parameter level, and technology level is a good idea and was found to be helpful although there seem to be some overlaps not only visually but also regarding the content of questions which makes it a bit confusion, at least in our opinion. We made a proposal to overcome these difficulties.

With regard to the ANSICHT case, we think that it is not the best way to start with a single process, going on in or around the repository, and go through the screening process down to a parameter. Starting with a process would mean to check the entire repository and evaluate the safety relevance of this process at all locations. A process can have a very different evolution at different locations in the repository and it is not worth monitoring everywhere. We think that a better way of starting is to look at a specific repository component, which is essential for the safety analysis like for example the individual geotechnical barriers (EB). Focussing on these specific elements, as a first step all processes are to be identified which act on a specific barrier and which may have an influence on the designed performance of the barrier. Thus, for the ANSICHT case, PRO1 is not a single process but a small list of processes specifically acting on the barrier under consideration. And this specific list of processes should be screened in parallel to identify the parameters to be included in the monitoring concept. That means, at each screening step, all selected processes should be considered.

Starting the screening process that way, we found that the first half of the screening process illustrated in Fig. 0.34 worked well. With regard to the different "starting approach" and evaluation criteria, we proposed a few changes in the wording of the supplementary guidance questions assigned to the main questions PRO2 and PRO4 (cf. section 4.2) which in general we found to be quite helpful. They also form a sound basis for being transparent and comprehensive in giving reasons for selecting or not selecting parameters.

In the second half of the screening process we think there are a few overlaps and redundancies. Especially, the distinction between TEC1 and PAR3 is not really clear. One of the goals is to achieve a screening process that is transparent to external viewers (e. g. stakeholders). In case of experts having at least difficulties to understand the difference, maybe we should consider a clarification in this regard to be as clear as possible. Going through the supplementary guidance questions assigned to TEC1, we think, a sub-division would make sense. The first four questions are pure technical questions and the other four are tackling impacts on the repository system. In our opinion, this sub-division should not be restricted to the guidance questions but also to the main question in the workflow. Thus, we propose a new box below TEC1 in the workflow named TEC2 containing the question "Are the impacts of implementation acceptable?". Looking at the first part of the corresponding guidance questions, we found that the questions TEC1.2 and TEC1.3 are very difficult to answer and couldn't get a clear 'yes' or 'no'. While TEC1.1 can be answered by looking at current system descriptions and data sheets, for TEC1.2 and TEC1.3 the person who has to answer them has to look into the future for e. g. a few decades. Therefore, we suggest to "soften" the two questions as given in section 4.2.

For the rest of the screening work flow, we think a re-arrangement of boxes, additional links, and the new PAR4 box might be helpful. Especially, the sub-division of the original PRO7 box into the proposed new PRO7 and PAR5 boxes helps to clearly differentiate between the three levels. Additionally, we think that visually a more restrictive division between the three levels 'process level', 'parameter level', and 'technology level' would make the illustration more clear. Thus, we propose a revised workflow to address these re-arrangements. The proposed version is shown in Fig. 0.46.

In particular, we do not agree to the first bullet point given in the D5.1 report describing PRO7. The screening process starts with safety relevant processes. Then, after the screening, it turns out that there is no parameter able to be monitored to get information about the evolution of the process. And so, it is said that the process may not be relevant anymore and should thus be reconsidered because we cannot observe it via parameters. We think, this kind of logic is unsuitable. By saying "park process" we would not question the relevance of the process but we would keep it in the system and clearly indicate that there is a problem monitoring it.

The proposed revised parameter screening workflow starts on the process level (orange) and ends on the parameter level (blue) going through the eye of a needle which is the available technology (green).

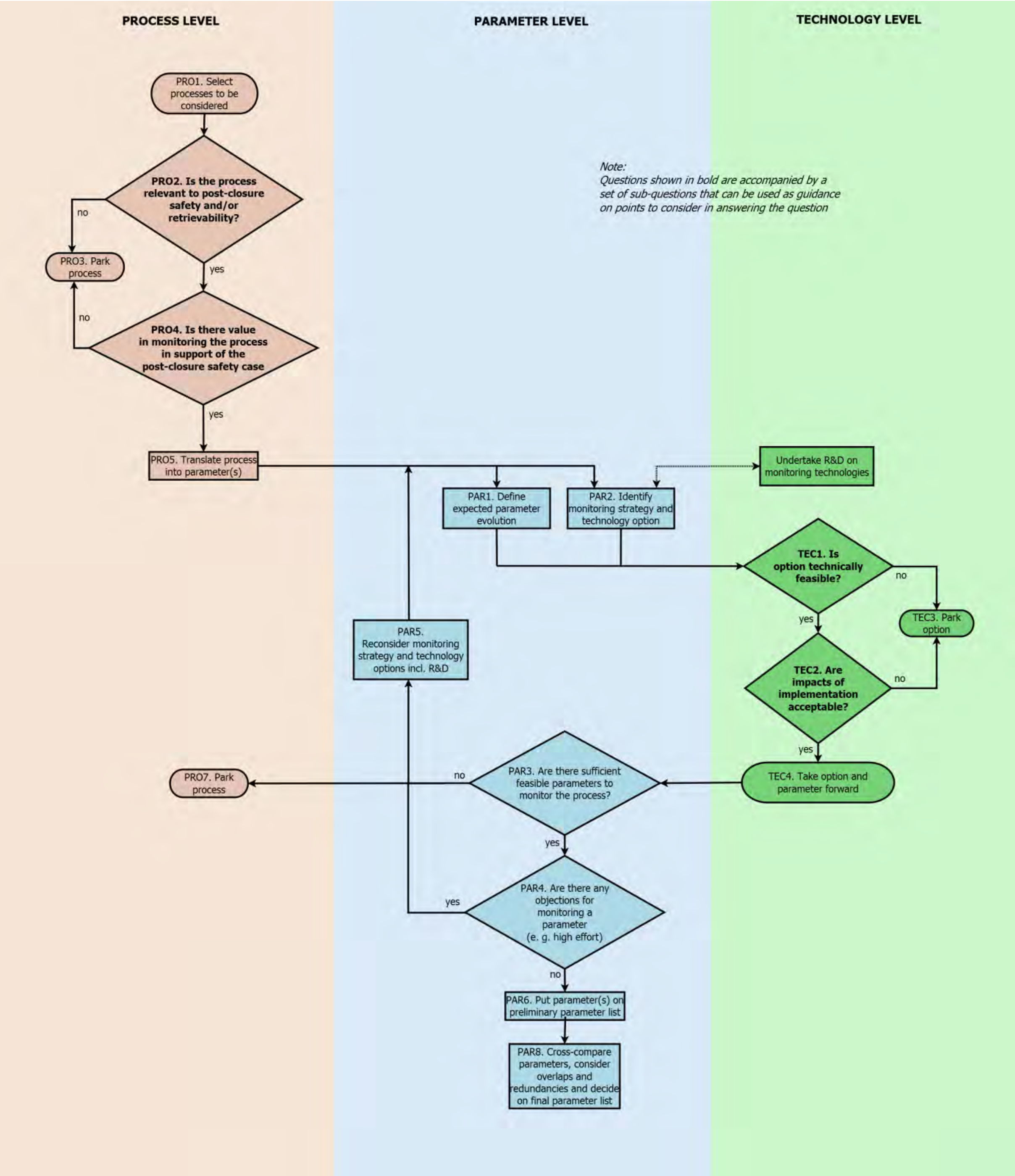


Fig. 0.46: Proposed revision of the MODERN2020 Screening Workflow based on the ANSICHT test case

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Appendix 1 – Issues to address by Test cases

Issues		Comments
1_System description		
d)	What is the adopted approach for the system description: safety case, safety functions, FEP´s, proxies ?	
e)	Describe the EBS and host-rock processes	The purpose is to give an overview and a context , for deep details it is better to provide a reference.
f)	Explain the set of parameters that are involved in the EBS/host-rock processes	This should cover a complete set which corresponds to what could be measured (=preliminary parameter list), being the population from which a sample of relevant parameters is drawn which shall be monitored.
2_Parameters		
k)	Explain the implementation of the methodology/workflow for the parameter screening process, i e how to arrive at the parameters to actually monitor.	This is an adaptation to nation- and site specific of the generic screening methodology given by Task 2.1.
l)	Explain what parameters are actually going to be monitored (i. e. screened parameter list) and why.	The chosen parameters should be relevant and measureable and their monitoring not impact detrimentally on the safety of the system.
m)	Describe the expected system behaviour/evolution of processes and measured EBS monitoring parameters. (holistic)	With system behaviour is meant the spatial-temporal development of an aggregate of monitored parameters of the coupled rock-EBS system.
n)	What are the performance measures for the expected behaviour?	With performance measure is meant a qualitative method or quantitative measure or a combination of both to compare monitoring results with an a-priori modelled behaviour. E.g. temperature evolution - comparison/correlation between the temperature time series for given points in space and or snap shots of many points in space at different time.
o)	Explain the methodology of going from measured parameters to actual behaviour to comparison with expected system behaviour.	The intention is to have a transparent description of the stepwise process and underlying consideration/motivations of going from single measured parameters to interpreted system behaviour based on an aggregate of monitored parameters and to compare this with expectations based on the a-priori modelled results.
p)	Describe a range of possible actions in response to measured "deviations"	Here it is necessary to explain the “baseline” i.e. expected behaviour and relate monitored parameters to it, then a discussion of feasible/possible bounds which are deemed “acceptable”. Outside of this bound are what may be envisaged as “deviations” which could be addressed by certain actions as a direct response.
q)	Explain the methodology and application of Q/C and Q/A procedures for the implementation and operation of the EBS monitoring	If quality control measures relevant for the implementation of the EBS monitoring system then these should be described and explained
r)	What are the uncertainties in the implementation and operation of the EBS monitoring and how are they handled: parameters, redundancy, system behaviour, (decision making),….?	These relate e.g. to reliability of monitored data over long periods of time, what are they and how are they mitigated? Is parameter redundancy one way? Other uncertainties are interaction of regulators and citizen stakeholder with monitoring results – what is their interpretation and desire for action - how is this addressed?
s)	Suggestions for improvement/revisions to the parameter screening process and the Screening template in Appendix B.	The undertaken parameter screening process provides valuable experience which shall be utilised for improvement.
t)	Explain how you assess whether the monitoring system might impact on the long-term safety of the EBS. What are your considerations and deliberations?	This issue is implicit through the Screening methodology but shall be explicitly addressed.

3_Added value		
d)	What are the motivations for undertaking EBS monitoring?	
e)	Explain how EBS monitoring may support confidence building and decision making process	
f)	Explain how EBS monitoring may contribute towards the interaction with citizen stakeholders in support of confidence building	
4_Decision support		
d)	Explain which decisions may be supported by monitoring results, if any.	
e)	Explain how monitoring data may support the understanding of the expected behaviour with respect to repository operations and long-term safety (post closure).	
f)	Describe the management functions (generic) required for the decisions making process and the involved deciders.	

Appendix 2 –

Appendix E: Nagra/Opalinus Clay

Executive summary

Introduction

The present study is intended as a contribution to Modern2020 Work Package 2, which concerns the linking of monitoring objectives to the safety case and decision-making strategies, and, in particular, Task 2.2 of this work package, which concerns screening test cases.

Motivated by Modern2020, as well as its own specific programme needs, Nagra has developed its own preliminary methodology for the identification of candidate monitoring parameters related to long-term safety, including an assessment of how and where these parameters could be monitored. The methodology is summarised in Fig. 1.

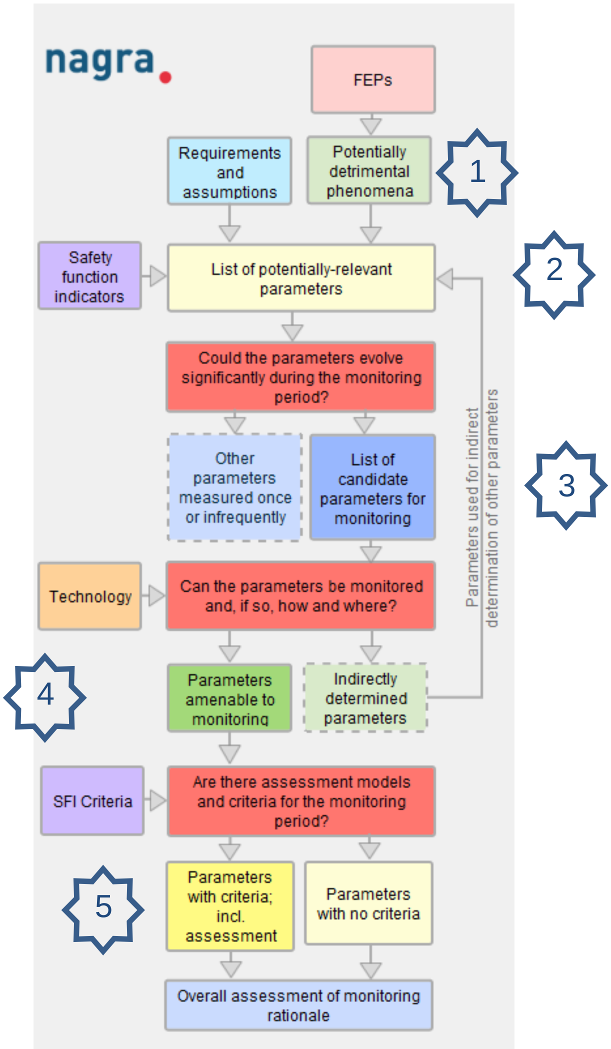

Fig. 1: Summary of Nagra's preliminary methodology for the identification of candidate monitoring parameters related to long-term safety. Key steps highlighted using numbered stars are described in more detail in the following sections.

The methodology has been implemented as a database tool (Fig. 1 is a screenshot from the front page of this tool) and applied using information from Nagra's high-level waste programme. The information comes in part from Nagra's Project Opalinus Clay (Nagra 2002a,b,c), which presented a comprehensive description of the post-closure radiological safety assessment of a repository for spent fuel (SF), vitrified high-level waste (HLW) from the reprocessing of spent fuel and long-lived intermediate-level waste (ILW), sited in the Opalinus Clay formation in northern Switzerland. Additional information, however, comes from more recent material published in support of the ongoing site selection process.

The present document describes the individual steps in this methodology and compares them where appropriate with the steps of the Modern2020 Screening Methodology, as present in "Work Package 2, Task 2.2 – Screening test cases; Guiding instructions V 1.2" issued 2016-10-11. First, however, the concept of monitored long-term geological disposal is described, which provides a basis for geological disposal concepts considered in Switzerland.

Monitored long-term geological disposal in Switzerland

Swiss Nuclear Energy Law explicitly requires that the disposal of radioactive waste takes place in one or more geological repositories, and that repositories are monitored for some time before final closure (KEG 2003). The disposal strategy that Nagra has refined over the years is based on the concept of monitored long-term geological disposal, which involves an extended period of monitoring, during which retrieval of the waste is relatively easy, and the emplacement of a representative fraction of the waste in a pilot facility which:

- serves as a demonstration facility for emplacement technology;
- provides information on the behaviour of the barrier system and to check predictive models;
- allows early detection of any unexpected and undesirable system evolution; and
- provides input for decisions regarding the commencement of operations and eventually the closure of the entire facility.

In addition to monitoring of the pilot facility, the disposal rooms of the main facility and the access tunnels can be monitored if needed, at least until they are backfilled and sealed, and possibly in a more limited manner thereafter. Furthermore, a test facility - or facility for underground geological investigations - will provide additional information in support of decision making, and some of this information can be classified as "monitoring", i.e. continuous, in-situ measurement of parameter.

It should also be noted that, in Nagra's safety concept, the Opalinus Clay host rock, is a key "pillar of safety". It has a low hydraulic conductivity, a fine, homogeneous pore structure and a self-sealing capacity, thus providing a strong barrier to radionuclide transport and a suitable environment for the engineered barrier system. Emphasis in the safety case, and in the monitoring programme, is thus on phenomena that could potentially damage or by-pass the host rock as a safety barrier, rather than on extensive and detailed monitoring of the engineered barrier system.

Identification of potentially detrimental safety-relevant phenomena

The first step in the preliminary methodology for the identification of candidate monitoring parameters (Step 1 in Fig. 1) is to identify potentially detrimental safety-relevant phenomena, taken to be those that are could, in the post-closure period, potentially compromise:

- adherence to the requirements on system components, or
- the validity of the reference model assumptions for safety assessment

and whose impact, though not necessarily the peak impact, could be detectable during the monitoring time fame, taken to be in the order of one hundred years.

The starting point to identify such phenomena the Project Opalinus Clay FEP list (Nagra 2002c), from which those FEPs known with confidence to have a zero or negligible chance of occurrence, a minimal detrimental impact on the disposal system or to occur over too long a timescale to be of interest in the context of monitoring are first excluded. The various requirements on system components and reference model assumptions for safety assessment are then considered in turn, and an assessment is made as to whether there are any phenomena (FEPs), including but not necessarily limited to those in the FEP list, with the potential to compromise adherence to a requirement or to invalidate an assumption.

The final result of the trial application of this step based on Nagra's disposal concept is a list of 58 potentially detrimental safety-relevant phenomena. The step can be mapped essentially to steps PRO2 to PRO 4 of the Modern2020 Screening Methodology.

Parameters relevant to long-term safety

A parameter is judged to be potentially relevant to long-term safety if it:

- quantifies, influences (in terms of timing, rate, spatial extent etc.) or indicates the occurrence of a potentially detrimental safety-relevant phenomenon,
- defines a requirement on the system or system components (e.g. requirements are set on parameters such as buffer temperature, hydraulic conductivity etc.),
- defines reference safety assessment model assumptions (e.g. the assumption is made that the transport-relevant properties of the buffer and hence the parameters that quantify these properties are constant is space and time), or
- is a safety function indicator.

Thus, to identify potentially-relevant parameters (Step 2 in Fig. 1), the detrimental safety-relevant phenomena identified in the previous step are considered in turn in terms of parameters that could quantify, influence or indicate their occurrence. Requirements and safety assessment model assumptions are similarly considered in turn. The resulting list of parameters is augmented (if these are not already present in the list) by parameters that are so-called safety function indicators[8].

The result of the trial application of this step is a list of 62 potentially-relevant parameters. In the Modern2020 Screening Methodology, the translation of safety-relevant phenomena (processes) into parameters occurs in a single step, considering only the phenomena themselves (step PRO5 of the Modern2020 Screening Methodology). The Nagra approach, on the other hand, considers also the parameters that define requirements and assumptions, as well as safety function indicators, as potentially targets for monitoring, irrespective of whether any phenomena are identified that could compromise these requirements, or call these assumptions into question, have been identified.

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[8] These are parameters that measure the consequences of specific potentially detrimental phenomena on post-closure safety functions. They are derived along with associated criteria that, if met, mean that it can be assumed the safety functions will be provided as intended.

Parameters that are (in principle) candidates for monitoring

In order to be a parameter that is in principle a candidate for monitoring from a long-term safety perspective, a parameter must not only be potentially relevant to long-term safety but must also have the potential to evolve significantly during the monitoring period. Identifying such parameters is Step 3 in the methodology shown in Fig. 1. Other long-term safety relevant parameters are expected not to vary significantly are typically measured once or infrequently, rather than being continuously monitored. Some may be measured *in situ*, whereas, for others, it may be sufficient to use measurements from another underground rock laboratory (URL) or surface laboratory.

The result of the trial application of this step is a set of 52 candidate parameters for monitoring of the 62 parameters that are identified as safety relevant. The step has no obvious counterpart in the Modern2020 Screening Methodology. It should be noted that just because a parameter is judged to be a candidate for monitoring, this does not mean it can be monitored in practice, which is the subject of the next step.

Parameters amenable to monitoring in practice

Having identified potentially-relevant parameters, the next step in the methodology adopted in the present test case (Step 4 in Fig. 1) is to determine if they can be monitored[9] in practice and, if so, where and at what stage in repository development the measurements or minoring should take place. The technology available for measuring or monitoring each parameter is also considered at this stage.

While the technology exists to monitor some parameters directly, others have to be inferred indirectly from other parameters. For example, the evolving hydraulic conductivity of the SF/HLW buffer can be inferred indirectly from e.g. the buffer swelling pressure and saturation. The result of the trial application of this step is a set of 40 parameters that are actually amenable to monitoring of the 52 parameters that are identified as potential candidates. The step can be mapped essentially to steps PAR 1 to PAR 5 and TEC 1 to TEC 3 of the Modern2020 Screening Methodology. The only difference between the present methodology and the Modern2020 Screening Methodology is that the present methodology explicitly acknowledges that some parameters can be evaluated indirectly by monitoring other parameters, if direct technology for monitoring not available.

For those parameters that can be monitored, the options available for doing so are constrained by the Swiss approach of monitored long-term geological disposal. These options consist of monitoring:

- in the repository test facility (facility for underground geological investigations),
- in the pilot facility, either prior or after backfilling and sealing,
- in the access tunnels, ramp and shafts, either prior or after backfilling and sealing,
- in the operations tunnels, either prior or after backfilling and sealing,
- in boreholes drilled from the surface or from the test facility into the host rock,
- at the surface itself, or
- in the repository emplacement rooms (but only prior to backfilling).

Backfilling and sealing of these repository elements occurs sequentially, as illustrated in Fig. 2, which shows the options available for measurement or monitoring as a series of timelines, with associated implementation stages and decision points. A key consideration is avoiding any

[9] Here, measurement refers to the determination of a parameter at a single, discrete time point and monitoring to measurements made continuously or at multiple, consecutive time points.

detrimental impact on long-term safety due to monitoring equipment and associated cables, boreholes, etc. Hence, the test facility or pilot facility are monitored in preference to the emplacement rooms, unless there are good reasons otherwise.

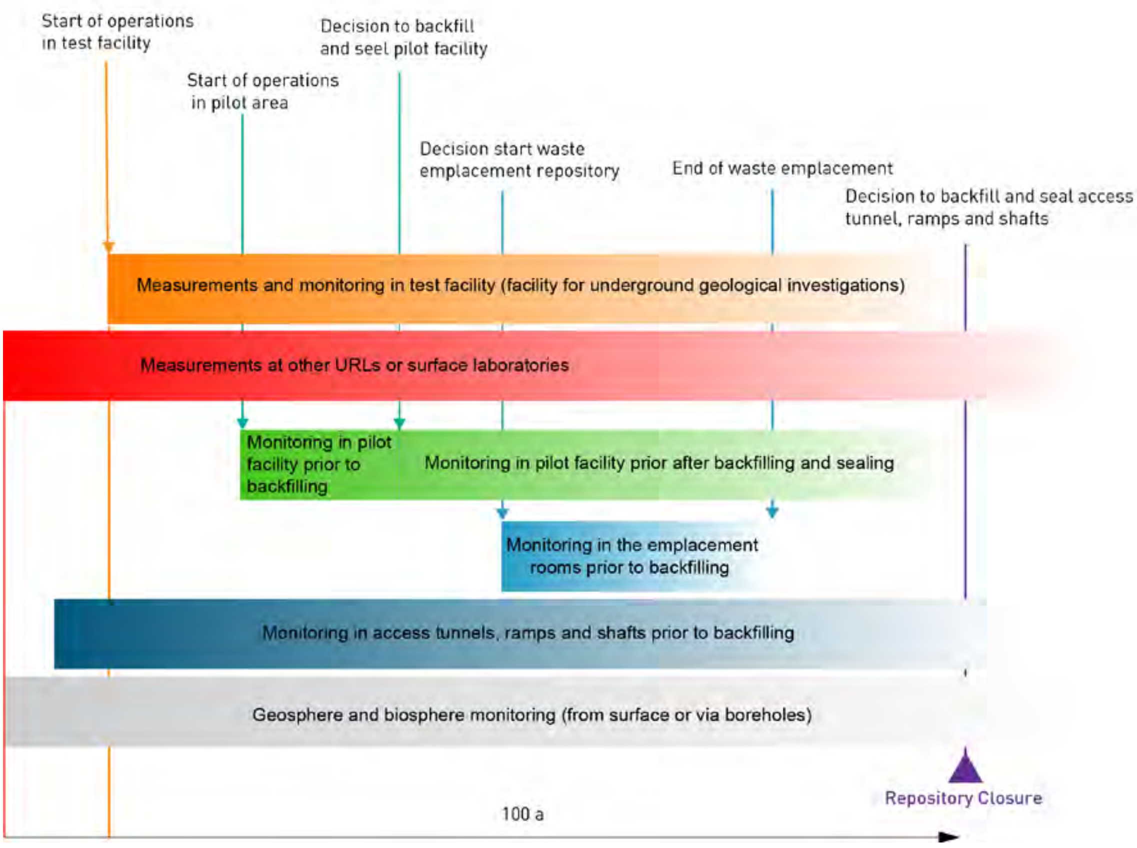

Fig. 2: Schematic illustration of options available for measurement or monitoring along a series of timelines, with associated implementation stages and decision points.

Models and criteria

The monitoring of a parameter is clearly of most interest if the outcome of monitoring can be compared with predictions made in advance of the monitoring programme, and with criteria that, if violated, would trigger an action of some kind. The identification of models and criteria is the next step in the methodology adopted in the present test case (Step 5 in Fig. 1).

Criteria include, for example, those that are used in framing the various requirements on specific system components. In general, if these criteria are violated, then a system requirement is not met and an assessment needs to be made of any actions that should be taken as a consequence. As illustrated in Fig. 3, a parameter is deemed most directly useful to monitor if, on the basis of modelling, there is some uncertainty as to whether or not a criterion will be satisfied within the monitoring time frame (especially if the consequence if the criterion is violated are significant). On the other hand, there may be high confidence that a criterion will be satisfied within the monitoring time frame, but less confidence thereafter. Here, there may also be some usefulness in carrying out monitoring, since the ability of models to accurately predict the evolution of a parameter within the monitoring time frame may give increased confidence in its predictive capabilities at later times. Finally, there may be high confidence, on the basis of well tested models, that a criterion will always be satisfied. Here, the usefulness of monitoring may be limited to convincing any individuals, presumably outside Nagra, who remain sceptical about Nagra's models.

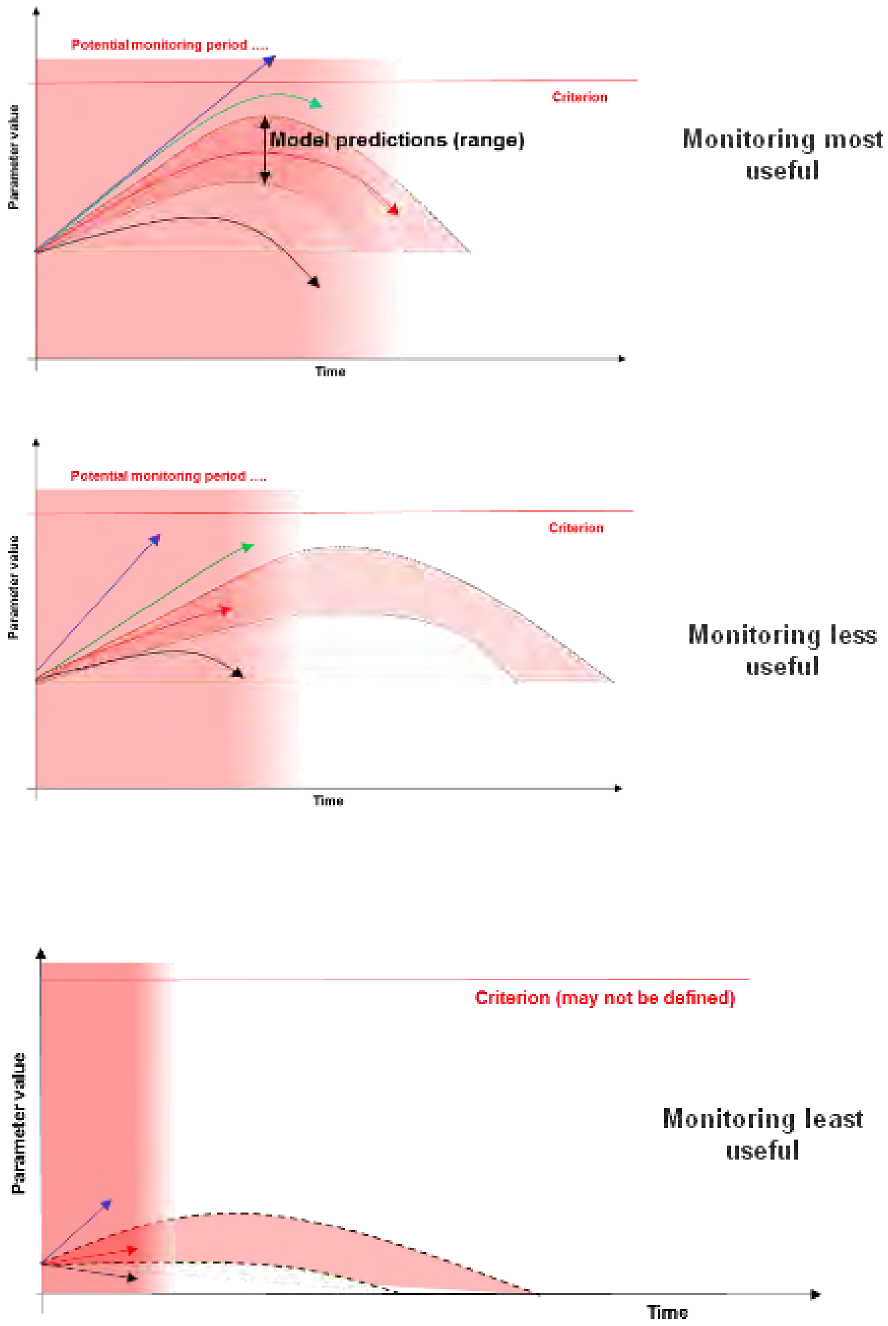

Fig. 3: Schematic illustration of the approach adopted to categorise parameters in terms of monitoring usefulness.

The comparison of model predictions with parameter criteria is not explicitly represented in the Modern2020 methodology.

Monitoring in the confidence building and decision-making process

A key role of monitoring is to support decision making and to build confidence in models that support performance and safety assessment. In Nagra's programme, although monitoring of conditions in the host rock will take place in the test facility prior to, as well as during, repository construction, the primary focus of monitoring activities will be on the pilot facility (and to some extent the main facility and access structures) during the monitoring phase. The key timing decision that monitoring during this phase will support is the decision to backfill the main access tunnels and close the repository. There are, however, other timing decisions that could also be affected by monitoring outcomes. An example is the decision on when to backfill the ventilation of access, operations, and ventilation tunnels. There are essentially two bounding options in this regard:

- backfill these tunnels as soon as emplacement operations are over (in accordance with the scheme presented above);
- delay backfilling until the decision has been taken to close the whole facility.

Monitoring, and specifically the monitoring of creep in the walls of access, operations, and ventilation tunnels, could support a decision on which of these bounding options (or some option in between) to adopt. In particular, if creep is found to be low, it could be advantageous to delay backfilling - delayed backfilling gives more flexibility by providing continuing easy access to the emplacement tunnels[10].

In any programme, unexpected monitoring outcomes, including non-conformance with model predictions, will require an appropriate response, which may involve decisions, for example, to engage in further research, to modify engineered design or even to retrieve waste packages. A tentative generic response plan is shown in Fig. 4.

If a monitored parameter falls outside the range expected, e.g. on the basis of system modelling, then the first step is clearly to check for any possible malfunctioning of the monitoring equipment. If no problem with the equipment is found, then measures will be taken to elucidate the reason for non-conformance with model predictions. Possible measures include:

- Undertaking further basic research on processes potentially influencing the parameter.
- Undertaking more detailed, system modelling that could reduce uncertainties in the model predictions.
- Collect further data.

These measures are not mutually exclusive, e.g. more detailed modelling may require both further basic research and additional data.

[10] This is consistent with the observational method in geotechnical engineering, whereby, during the tunnel construction of a tunnel or other structure, a continuous, managed and integrated process of design, construction control, monitoring and review is adopted, enabling appropriate, previously-defined modifications to be incorporated during (or after) construction (https://en.wikipedia.org/wiki/Observational_method_(geotechnics)).

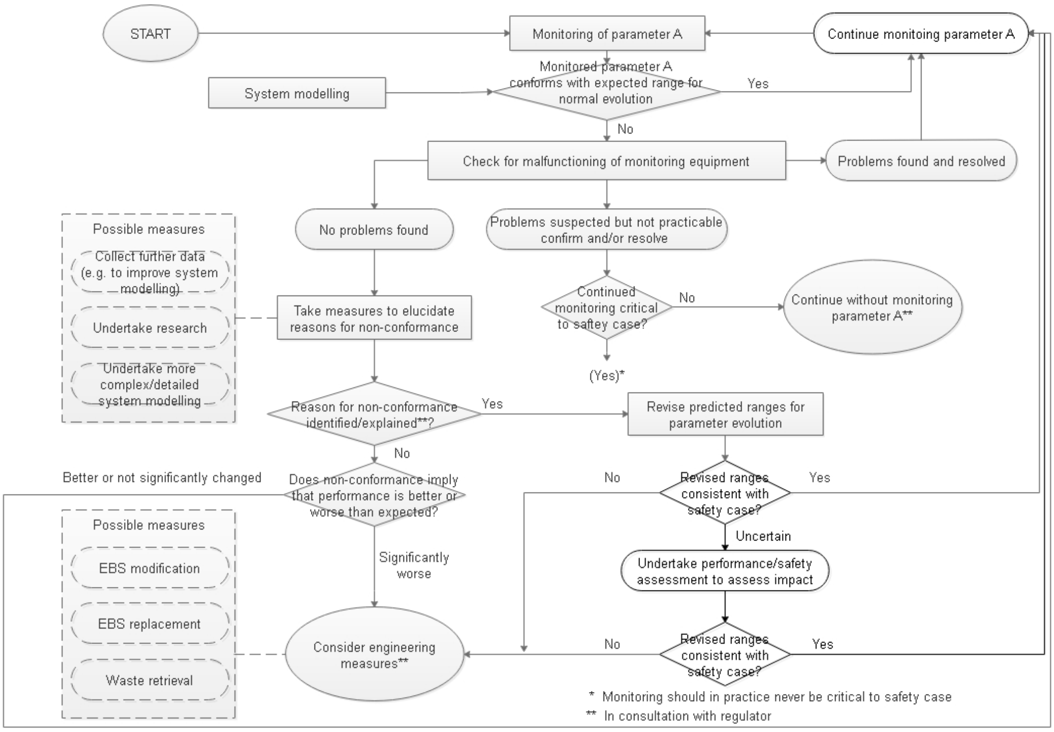

Fig. 4: Tentative, generic response plan in the event of non-conformance of monitored parameters with model predictions.

If the reasons for non-conformance turn out to be deficiencies in the model (including underlying assumptions and data), these model deficiencies will be rectified as far as possible and revised predictions made. If the monitored parameter is consistent with the revised predictions, and the revised predictions themselves do not compromise the safety case, then the monitoring of the parameter will simply continue. If it is uncertain whether or not the revised predictions compromise the safety case, then a performance (or safety) assessment may need to be made to elucidate this point. Finally, if the revised predictions do compromise the safety case, then engineering measures may need to be taken, including:

- EBS modification,
- EBS replacement, or even
- waste retrieval.

If no significant deficiencies in the model are identified and the reasons for non-conformance with model predictions continue to be unexplained, it needs to be assessed whether non-conformance implies performance of the system is better or worse than expected. If the answer is that the performance is better than expected, then it may be decided to take no further measures other than to continue monitoring the parameter (although a lack of understanding of the reasons for non-conformance is always undesirable, and efforts will certainly continue to rectify the situation). If, on the other hand, the performance is worse than expected to a degree that could compromise the safety case, them the engineering measures listed above may need to be considered.

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Appendix F: OPERA Test Case (NRG)

Contents

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 on geological disposal. The main focus of the project is monitoring of the repository near-field during the operational period to support decision making and to build further confidence in the post-closure safety case.

This report addresses the following objectives of Modern2020 WP2, Task 2.2:

- Test the methodologies to identify engineered barrier system- (EBS) and host-rock-related monitoring parameters for the national programme in the Netherlands as developed in Task 2.1 of the Modern2020 project;
- Develop further understanding of EBS and host rock evolutions in the Dutch OPERA concept for the geological disposal of radioactive waste to inform the development and implementation of dedicated monitoring programmes.

The present contribution reflects on the status of the Dutch national programme for the geological disposal of radioactive waste contributing to this task and discusses the future prospect of developing a monitoring programme.

Approach

Considering that the geological disposal programme in the Netherlands is presently in a conceptual stage, NRG has adopted the following approach for the work performed in Modern2020 WP2, Task 2.2:

- The Dutch OPERA concept for radioactive waste disposal and the related OPERA safety functions have been described with special reference to the EBS and host rock;
- Description of features, events, and processes (FEPs) potentially affecting the EBS and host-rock functionalities; processes have been identified which are judged relevant in affecting the various components of the Dutch disposal concept;
- The expected evolution of the most relevant processes occurring in the disposal system during the monitoring period has been described and time scales have been assigned to the representative processes;
- Parameters representative for EBS and host-rock processes have been identified which provide a preliminary list of processes relevant for the safety of the disposal system, that serve as input for the screening to be performed in this report;
- The preliminary list of processes has been used to test and evaluate the Modern2020 screening methodology; proposals for modifications of the Modern2020 workflow have been elucidated;

Added value

Considering the geological disposal programme in the Netherlands, the following topics are relevantly upgraded as result of the work performed for Modern2020 WP2, Task 2.2:

- The first compilation of main processes and related parameter and evolutions, based on the OPERA concept's safety functions, scenarios and FEPs has been established in a single document;
- Processes have been identified which are judged most relevant in affecting the various components of the Dutch disposal concept, more specifically the engineered barrier system and the Boom Clay host rock;
- Parameters have been identified which provide indications of processes relevant for the safety of the disposal system, and which may be monitored in practice by using the screening methodology developed in Task 2.1 of Modern2020;

- The expected evolution of the most relevant processes occurring in the disposal system during the monitoring period has been described;
- The Modern2020 screening methodology for establishing monitoring parameter lists for the Dutch disposal concept has been evaluated, and proposals for modifications have been elucidated;
- Uncertainties and lacunas concerning process understanding of the Dutch concept for geological disposal have been identified.

Main findings and conclusions

A thorough inventory has been compiled of processes and parameters potentially affecting the various barriers of the OPERA disposal system:

- Waste form;
- Waste container;
- Backfill;
- Disposal cell plug;
- Gallery lining;
- Near-field of the host rock;
- Far-field of the host rock;
- Shaft seal.

The amount of information on the various barriers differs, with some barriers currently only in a very generic stage of development, e.g. the disposal cell plug, or even not yet considered in the OPERA disposal concept, e.g. the shaft seal. All above-mentioned engineered barriers are described and the main processes impacting their performance were identified. However, due to the limited scope of this study, the actual Modern2020 screening methodology was performed for one example barrier only: the OPERA Supercontainer.

Each of the steps of the Modern2020 screening methodology has been assessed for the OPERA Supercontainer, with the level of detail dependent on the amount of information available.

Based on the (limited) information available concerning alternative evolution scenarios (AES) of the disposal system, a qualitative assessment of the evolution of monitorable parameters as indicators of the selected AES's has been described when possible.

No quantitative design criteria for each of the barriers of the OPERA disposal concept have yet been established. As a consequence, the testing of the Modern2020 screening methodology could only be performed with sufficient adequacy up to step PAR2.

Assessment of the steps subsequent to TEC1/2/3 is presently considered too premature within the Dutch context. On the other hand, in case a technology option is considered presently not feasible but sufficiently relevant to develop further, there would be sufficient time left prior to final disposal to develop the particular option or to consider another option, i.e. making TEC1/2/3 less relevant in the current stage.

The assessment of each step identified a potential lack of clarity in the descriptions of the various steps of the screening methodology as well as the additional questions that have been formulated for most of the steps. Modifications of steps of the Modern2020 flowchart were suggested, and an overview of the modified workflow is given Figure 1-25). The most distinct modifications compared to the base flowchart (Figure 1.3) concern the removal of TEC2/TEC3, the removal of the seemingly obsolete step PAR4, and the identification of the iteration loops originating from PRO7.

The present exercise may serve as a basis to further evolve the OPERA disposal concept and to develop a monitoring plan in the Netherlands.

1 Introduction

1.1 Background

The EU H2020 project Modern2020 deals with the Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal and is jointly funded by the Euratom research and training programme 2014-2018 and European nuclear waste management organisations (WMOs). The Project is running from 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 monitoring programme, taking into account requirements of specific national programmes on geological disposal. 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 of 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 implementing monitoring programmes, and related technologies and systems 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.
- 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, including an international conference, a training school, and the Modern2020 Synthesis Report.

This report is NRG's contribution to Work Package 2 of the Modern2020 Project. WP2 aims to evaluate monitoring strategies, consider decisions requiring support from monitoring data, and develop methodologies for screening monitoring parameter lists. These approaches are considered and tested in Task 2.2, evaluating safety cases for the Dutch repository concept 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, Task 2.2:

- Test the methodologies identified in Task 2.1 of the Modern2020 project to identify EBS and host-rock monitoring parameters for the national programmes considered in WP2;
- Develop further understanding of EBS and host rock evolution in specific concepts for the geological disposal of radioactive waste to inform the development and implementation of dedicated monitoring programmes;
- Assess the feasibility of the Modern2020 Screening Methodology, and provide suggestions for improving the Methodology.

The present Modern2020 Task 2.2 Deliverable reflects on the ability of the Dutch programme to define an actual monitoring programme, and discusses its benefits at various stages of implementation.

Considering the current stage of the geological disposal programme in the Netherlands, more specific objectives addressed in this report are the following:

- Identify processes which are judged relevant in affecting the various components of the Dutch disposal concept, more specifically the engineered barrier system and the Boom Clay host rock;
- Identify parameters which provide indications of processes relevant or the safety of the disposal system, and which may be monitored in practice by using the screening methodology developed in Task 2.1 of Modern2020;
- Evaluate the Modern2020 screening methodology for establishing monitoring parameter lists for the Dutch disposal concept;
- Increase understanding in the role of monitoring within the post-closure safety case of the Dutch disposal concept for the geological disposal of radioactive waste.

An additional important outcome of this task is the identification of uncertainties and knowledge gaps concerning process understanding of the Dutch concept for geological disposal. Of particular interest are the lessons learned about inventory and assessing the processes relevant to the safety of a disposal concept. These can be used to iteratively refine the current conceptual design in a structured manner to arrive at a more detailed design, including well-defined design requirements of a particular sub-system. An example of such a process is depicted in Figure 1.1, in which, for the plug/seal system, the design basis workflow developed in the EU-FP7 project DOPAS is shown. The end stage of this process are preliminary design requirements of a sub-system which, in principle, need to be verified, e.g. by means of monitoring processes relevant to the performance of the sub-system.

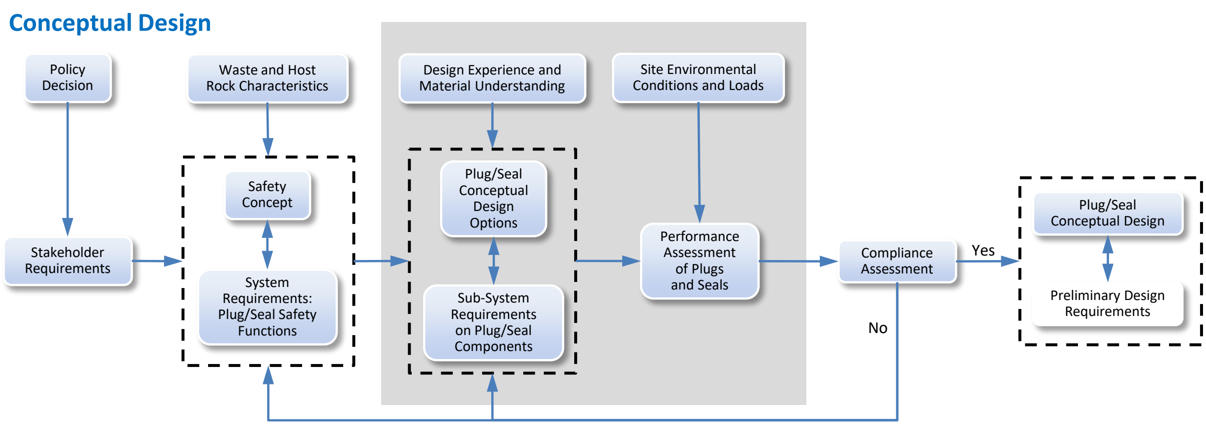


Figure 1.1: The DOPAS Design Basis Workflow (adapted from (White, 2016)).

1.3 Scope of this Report

The results presented in this report are restricted to the present state of the Dutch national programme for geological disposal, for which no monitoring program has yet been developed and little experimental work done in support of barrier performance. Because no consolidated overview of processes and parameters of the various barriers of the Dutch disposal concept existed prior to the Modern2020 project, a status quo of the current understanding of this matter had to be developed first.

The evaluation in this report contains a structured approach to link safety functions, and safety relevant processes to parameters that can serve as indicators for these processes, and subsequently could be monitored in a geological disposal facility. Consequently, relatively much effort has been put in compiling and presenting a comprehensive overview of the processes and parameters of interest.

Although the actual Modern2020 screening methodology was performed only for one example barrier, the OPERA Supercontainer, for the elaboration of the preliminary process list, all main engineered and geological barriers of the Dutch disposal concept are described and the main processes impacting their performance are identified.

1.4 Approach

The analysis described in this report is the first assessment of the potential monitoring aspects applicable to a Dutch repository concept. The analysis is applied to the present site-independent OPERA reference concept for the final disposal of radioactive waste in Boom Clay host rock (Verhoef, 2014a).

Prior to the process and parameter screening according to the Modern2020 Screening Methodology (see Figure 1.3 on the next page), first a preliminary list of parameters had to be established comparable to what has been done by several partners during the MoDeRn project (Jobmann, 2013). A two stage process is followed:

- in the **first stage**, a preliminary parameter list is derived (Chapters 2 to 5)
- in the **second stage**, the Modern2020 workflow is followed aiming at developing a monitoring plan (Chapter 6)

Figure 1.2 below summarized the work performed in the **first stage**:

- For the purpose of identifying candidate processes and parameters for monitoring the OPERA facility, the main contextual aspects arising from the Dutch RWM strategy are summarized, and a general outline of the current OPERA disposal concept is given, including the safety functions of the various components of the disposal system (Chapter 2).
- Subsequently, the scenarios considered in the present screening are elaborated and described, and for each scenario the safety functions are linked to FEPs, based on the current OPERA FEP database (Chapter 3).
- In a next step, by a full screening of the FEP-list, a generic list of processes has been generated, and the related safety functions and scenarios have been identified (Chapter 4).
- In the final step (Chapter 5), a preliminary list of processes and parameters was generated, following a structured, barrier-wise approach: for each barrier considered, general properties and features are summarized and the related safety functions and other functions are described. Based on the screening of the FEP-list in the previous chapters, the related main processes have been identified and described. Taking into account the expected evolution of the individual processes in time, a selection of parameters has been identified which are considered monitorable on a practical time scale. This results then in the preliminary list of processes and parameters that forms the input of the Modern2020 Screening in the second stage.

In the **second stage**, Chapter 6, a screening of the preliminary list is performed, following the Modern2002 workflow in Figure 1.3.

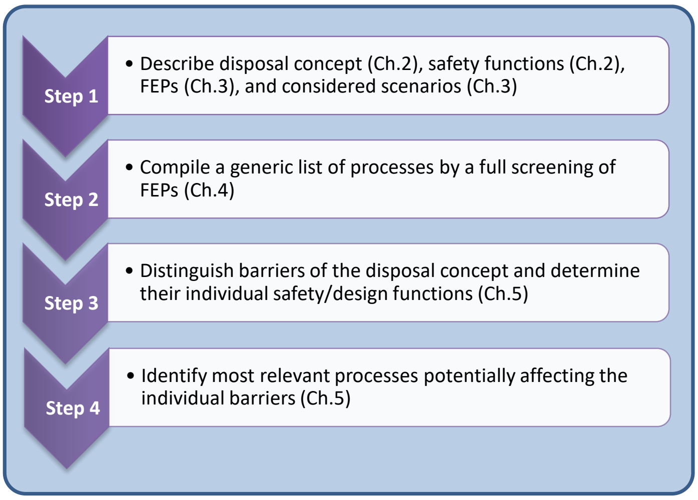


Figure 1.2: Procedure for establishing a preliminary list of parameters for the OPERA disposal concept.

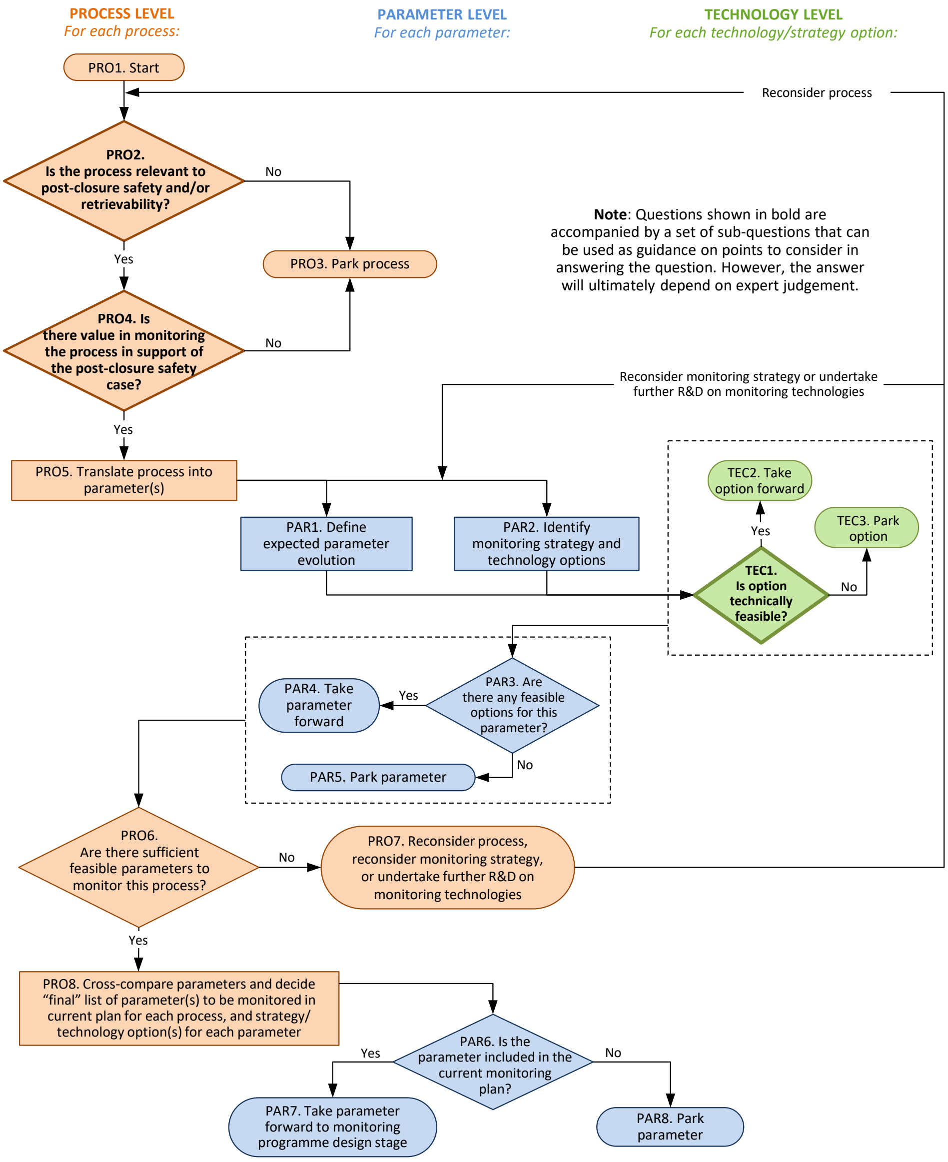


Figure 1.3: The Modern2020 Screening Methodology.

It should be noted that the structured approach followed in the first stage has overlap with the screening performed in the second stage, i.e. it provides already answers to the question PRO1 - PRO5 and PAR1. Due to the limited scope of this task, screening in the second stage is focussed to one example case, i.e. the OPERA Supercontainer. However, the derivation of the process list in the first stage is performed for all relevant barrier components, i.e. Chapter 5 provides sufficient basis to perform a screening for other barrier components as well in a later stage.

1.5 Report Structure

The remainder of this report is set out as follows:

- Chapter 2 outlines the Dutch OPERA disposal concept for the geological disposal of radioactive waste and contextual aspects.
- Chapter 3 describes future evolutions of the OPERA disposal system, viz. scenarios that have been identified as part of the OPERA program. The described scenarios comprise both the normal evolution scenario and a selection of alternative scenarios.
- Chapter 4 lists events and processes which intend to serve as a basis for further screening and evaluation. The list is based on the OPERA FEP Database which has been developed as part of the OPERA programme.
- Chapter 5 provides a more detailed, descriptive overview of processes and parameters that have been identified as relevant for the performance of the various components of the engineered barrier system and the Boom Clay host rock.
- Chapter 6 treats the testing of the Modern2020 screening methodology, and, based on the screening exercise, several modifications to the Modern2020 flowchart are proposed.
- In Chapter 7 conclusions are drawn with respect the applicability of the screening methodology developed in WP2 of the Modern2020 project.

2 Dutch OPERA Disposal Concept

2.1 Introduction

Already in the 1980's the Netherlands decided for a policy of long-term interim surface storage of radioactive waste (VROM, 1984), with start of actual geological disposal currently not foreseen before the next century.

The nuclear programme of the Netherlands is comparably small, with currently one NPP, resulting in relatively small amounts of radioactive waste intended for disposal. The extended period of surface interim storage of radioactive waste provides an opportunity to perform research and development on the potential and possibilities of geological disposal, either in a national repository or as part of a multi-national facility. Research on the various aspects is necessary to reduce existing uncertainties, to maintain the necessary knowledge and competence in the Netherlands, and to be prepared for entering a site selection process in case of a change of urgency of geological disposal policy in the Netherlands.

Despite that the policy of long-term interim storage favours a certain "wait-and-see" attitude, during the last 40 years many efforts have been devoted in the Netherlands to investigating geologic disposal of radioactive waste, for example in the framework of the ICK[11] (ICK, 1979), OPLA[12] (OPLA, 1989), OPLA-1A (RGD, 1993) and CORA[13] (CORA, 2001) programmes. Additional work has been done in several EU Framework projects like EVEREST, BAMBUS, PAMINA, THERESA, and TIMODAZ. The main focus of earlier programmes was on disposal in rock salt and included both performance assessments and detailed analyses on generic repository designs. The research interest in Boom Clay is more recent, reaching to the end of last century. Only recently (Hart, 2015a; Hart, 2015b) the results of all past programmes on rock salt have been integrated according to the recently developed and generally accepted methodology of the safety case by NEA (NEA, 2008) and IAEA (IAEA, 2012).

In June 2011 the five-year research programme for the geological disposal of radioactive waste, OPERA, started (Verhoef, 2011a). The objective of the OPERA research programme is to provide a first, preliminary safety case for a disposal concept in Boom Clay. The OPERA program is structured in 7 Work Packages comprising 43 Tasks, each addressing an aspect relevant for building a Safety Case for deep geological disposal in the Netherlands (Verhoef, 2011a). One of the purposes of the OPERA safety case is to structure the research activities in the near future. The OPERA safety case is conditional since only the long-term safety of a generic repository will be assessed.

Although the OPERA research programme is primarily focused on the disposal concept in Boom Clay, part of the management strategy in the Netherlands is also to develop and maintain the knowledge on the disposal of radioactive waste in rock salt (see (Hart, 2015a), (Hart, 2015b)). However, insufficient elements are readily available for rock salt that allows to perform the intended screening within the Modern2020 project. A limited screening of a German disposal concept in rock salt was performed in the MoDeRn project (Jobmann, 2013). The present document addresses only the OPERA concept in Boom Clay (Verhoef, 2014a).

2.2 Basis of the Dutch waste management strategy

The 1984 Governmental policy plan (VROM, 1984) together with the policy statement on retrievability (VROM, 1993), form the basis for the Dutch strategy principles, which can be summarised in the following five points (Haverkate, 2002: p.19):

1. Radiation protection;

[11] Interdepartementale Commissie Kernenergie (Interdepartmental Nuclear Energy Commission)
[12] Commissie Opberging op Land (Commission on Onshore Disposal)
[13] Commissie Opberging Radioactief Afval (Commission on Disposal of Radioactive Waste)

2. Isolation, control, and surveillance;
3. Central organisation for managing radioactive wastes;
4. Onshore long-term retrievable disposal;
5. Ongoing research in finding acceptable waste management solutions.

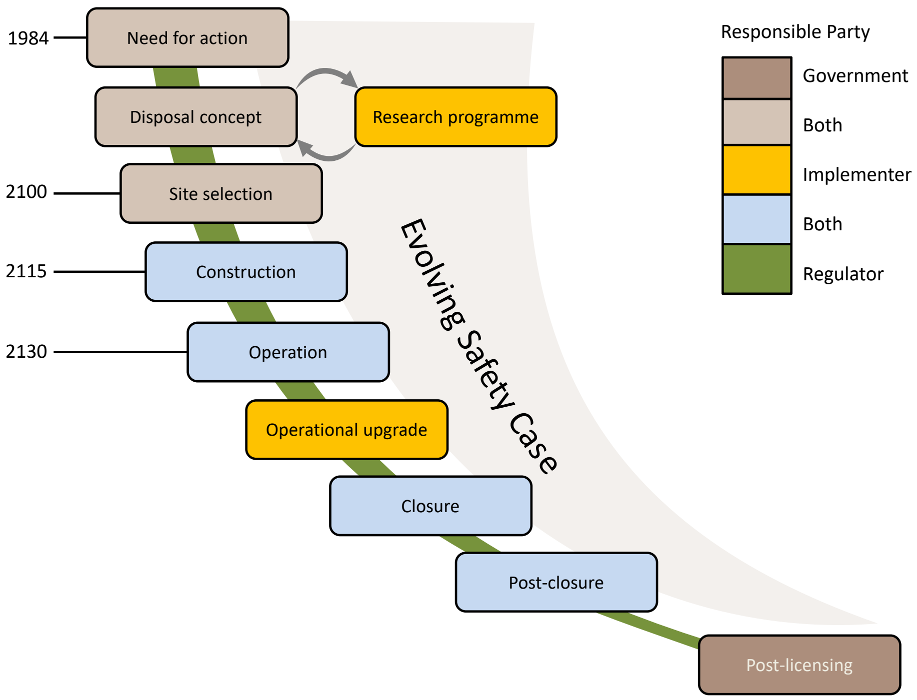
These items have been translated into a safety strategy, which has been summarised in the OPERA Research Plan (Verhoef, 2011a), the OPERA Meerjarenplan (Verhoef, 2011b), and in the recently published Safety Strategy document (Verhoef, 2014c), and elucidated in the following sections.

2.2.1 Present views on the Dutch waste management strategy

In the Netherlands, the development of a geological disposal facility for radioactive waste is foreseen to commence after the year 2100. One of the benefits of extended surface storage is the ongoing radioactive decay and reduction of heat output from heat-generating High Level Waste (HLW)[14]. As a consequence, potential thermal effects on the EBS and surrounding host rock are reduced which is a favourable aspect for developing and maintaining the post-closure Safety Case.

In addition to the requirement of retrievability, the Netherlands adapted general ideas on reversibility and staged closure, where at various stages in the implementation and lifecycle of the geological disposal facility, decisions are needed to proceed through the lifecycle and move towards the next stage. These decisions are to be supported by a Safety Case (IAEA, 2012: p.10). **Figure 1-4** shows the elements in the decision-making processes on geological disposal and the planned timing for the Netherlands that follows from the current Dutch policy (Verhoef, 2011b: Figure 2).

From present day until the foreseen site selection in 2100, preliminary Safety Cases relying on generic assumptions about the properties of the host rock will be iterated, based on the outcomes of subsequent research programmes. Around the turn of next century, sufficient confidence should be acquired to support the decision for site selection.



[14] Deviating from the usual international definitions, in the Netherlands high-active ILW is denoted as 'non-heat generating HLW'. Consequently, heat-generating HLW is denoted as such explicitly.

Figure 1-4 Elements in the decision-making processes on geological disposal including the timeline for the Netherlands.

2.2.2 Boundary conditions and strategic choices

The current Dutch policy encompasses a long-term surface storage and subsequently the disposal of all radioactive waste above the exemption level, including spent fuel from research reactors, vitrified HLW, ILW/LLW, including depleted uranium (TENORM waste).

The boundary conditions to provide a general orientation for long-term research programmes are derived from the relevant international and national regulatory framework (IAEA, EU (Euratom), ICRP) and national policy. The boundary conditions for geological disposal of radioactive waste in the Netherlands have been outlined in (Verhoef, 2014c: Chapter 2). A summary of these boundary conditions is given below.

- *The ICM criteria (isolate, control and monitor) form the basis of the radioactive waste management policy.*
- *Radioactive waste is stored above ground for a period of at least 100 years.*
- *A single organisation (i.e. COVRA) has been established for management of all steps of the radioactive waste management process.*
- *In addition to a national geological disposal facility (GDF), the option of a multinational GDF is not excluded.*
- *All radioactive waste is intended to be disposed of in a single, deep GDF operating in 2130.*
- *The GDF has to be designed, operated and closed such that the process is reversible and the waste is retrievable.*
- *Both rock salt and clay formations are being considered as potential host rocks for geological disposal in the Netherlands.*
- *Specific regulatory criteria for the siting or the performance of a geological disposal facility have not yet been defined.*
- *The public has to be given the necessary opportunities to participate effectively in the decision-making process regarding radioactive waste.*

Based on these boundary conditions strategic measures have been engaged, as outlined in the following text box. The strategic choices formulated in (Verhoef, 2014c) are focused on Boom Clay as a host rock, but they are also applicable to rock salt as a host rock.

- *The GDF will be constructed at sufficient depth to take into account the impact of surface phenomena.*
- *The GDF will be constructed within a Tertiary Clay formation or Zechstein rock salt formation.*
- *The materials and implementation procedures should not unduly perturb the safety functions of the host formation, or of any other component.*
- *In the case of heat-generating waste, the engineered barriers will be designed to provide complete containment of the wastes at least through the thermal phase.*
- *Waste types will be divided into groups to be emplaced in separate sections of the geological disposal facility.*
- *The various disposal galleries and sections, and the geological disposal facility as a whole, will be closed (access routes backfilled and sealed) following a progressive, step-wise procedure.*
- *Geological disposal planning will assume that surveillance and monitoring will continue for as long as deemed necessary.*
- *There are preferences for using shielded waste packages that minimise operations and consequent operational radiation doses in the underground.*
- *There are preferences for materials and implementation procedures for which broad experience and knowledge already exists.*

The topic of monitoring in deep geological disposal is presently being addressed in the Netherlands in a very generic way, and no guidance or specific requirements are provided.

2.2.3 Siting strategy

Considering the present stage in the decision-making process in the Netherlands, no siting of a radioactive waste repository is foreseen in the near future. Research and waste management efforts will therefore be limited to the aspect of building up public and technical confidence in the technical feasibility and radiological safety of radioactive waste disposal (Verhoef, 2011a: p. 7). In due time, searching for an appropriate location will be performed in consultation with stakeholders from various scientific, political, and societal groups.

2.2.4 Retrievability

An important motivation of monitoring R&D in the Netherlands is the Dutch requirement of retrievability after closure of the repository. Consequently, monitoring of processes relevant for the post-closure safety may serve as input for a possible decision of waste retrieval.

The Dutch government issued a policy directive in 1993 stating that underground disposal of highly toxic waste (including radioactive waste) was permissible in the Netherlands, provided that it remains retrievable over the long term (VROM, 1993).

Whereas no explicit legislation or (practical) guidelines for waste retrieval have been developed in the Netherlands, the general concept of retrievability is discussed internationally and worked out in recent years to greater detail by developing principles like ‘retrievability’, ‘reversibility’, geological disposal as a ‘staged process’ and the possible utilization of pilot facilities.

As part of the OPERA program, a topic report addresses the aspects of retrievability, reversibility, staged closure and the possible role of monitoring (Schröder, 2015). One of the conclusions of that report was that the principle of reversibility provides helpful options to develop the implementation process in the coming years in a straight-forward way, resolving the issue of responsibility of the present generation while still leaving options open for future generations. However, it can also add an element of arbitrariness and, in case of the Dutch policy of long-term interim storage, encourage a tendency to ‘wait and see’. The best way to deal with the latter topic is the definition of a clear roadmap with well-defined milestones in 5- to 10-years intervals.

In September 2015 the Dutch Ministry of Infrastructure and Environment released the draft national programme for the management of radioactive waste and spent fuel (MIE, 2015). Appendix E of that report explains the role of monitoring: monitoring provides information for decision making and building confidence for the public and authorities, and monitoring is considered to be necessary in the phase of retrievability. In that context, monitoring is not an objective on its own, but should support decision-making on retrievability.

2.3 Multiple barrier system

The ICM criteria (cf. Section 2.2.2) stipulate that geological disposal has to isolate the radioactive waste from the biosphere until the radioactivity of the waste has decayed to natural levels. The required long-term isolation can be achieved by a system of multiple barriers (Verhoef, 2011a: Section 4.1). These barriers can be natural (geological) and man-made (engineered) and can be subdivided into the following subsystems (Verhoef, 2011a: p.8; see also Figure 1-5):

- The near-field – including:
  - wastes packages (waste matrix, container, overpack if used)
  - additional engineered barriers (buffer materials if used, gallery lining, seals, cap or cover)

- and the host rock zone disturbed during the excavations (excavation disturbed zone, EDZ);

- The far-field - the undisturbed host rock and surrounding geological formations (or overburden);
- The biosphere - the various elements (atmosphere, soil, sediments, and surface waters) and the living organisms (including humans) that interact with them.

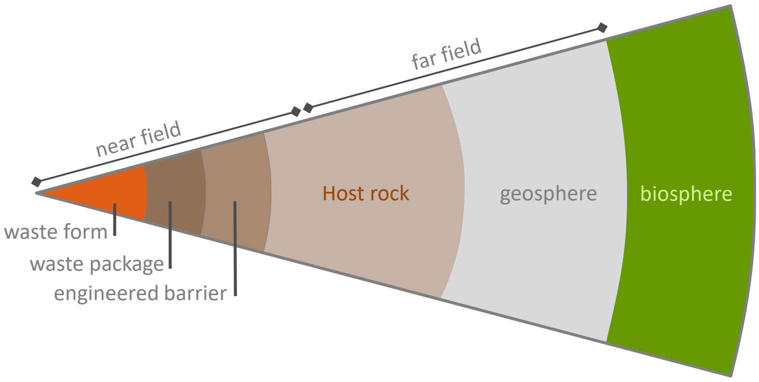


Figure 1-5 Compartments of a design of a repository concept.

Within the OPERA program, Work Packages and Tasks have been attributed to acquire and develop knowledge on safety-related aspects and processes that potentially may contribute to or challenge the subsequent barriers of the disposal concept in Boom Clay. An important tool in that respect is the consideration of safety functions provided by the main components of the system and its geological coverage.

2.4 Safety functions

In the OPERA concept of the geological disposal for radioactive waste in Boom Clay host rock the safety functions as defined by ONDRAF/NIRAS (Smith, 2009: Section 3.4.1) have been adopted. Safety functions are defined as the functions that a disposal system should fulfil to achieve its fundamental objective of providing long-term safety through a concentration and confinement strategy, while limiting the burden placed on future generations (Smith, 2009: p.12). Figure 1-6 gives a graphical presentation of the safety functions attributed to the OPERA disposal system in Boom Clay for HLW

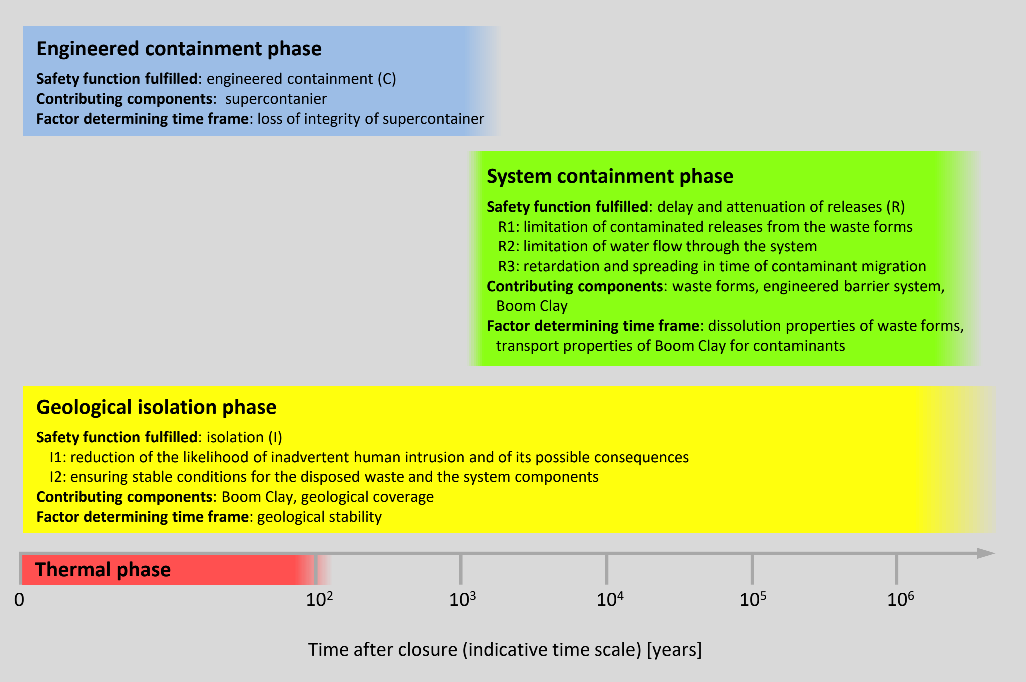


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Figure 1-6 Safety functions provided by the main components of the disposal system in Boom Clay and its geological coverage. The timescale applies to HLW.

The following descriptions of the safety functions apply (Smith, 2009: Annex 1; ONDRAF/NIRAS, 2013: p.32):

Engineered containment (C)
The function of engineered containment is described as the function that consists of preventing for as long as required the dispersion of contaminants from the waste forms by using one or several appropriate impermeable engineered barriers (relevant for heat-generating waste). The indicative time shown in Figure 1-6 applies to HLW[15].

Delay and attenuation of the releases (R)
The function that consists of retaining the contaminants within the disposal system[16] for as long as required; the following sub-functions are distinguished:

- The safety function 'Limitation of contaminant releases from the waste forms' (R1), by restricting the release and spreading of radionuclides and other contaminants from the waste forms.
- The safety function 'Limitation of the water flow through the system' (R2), by preventing or limiting the water flow through the system and hence the quantity of contaminants migrating.
- The safety function 'Retardation and spreading in time of contaminants migration' (R3), by delaying and spreading in time the migration of contaminants released from the waste packages.

Isolation (I)
The function that consists of isolating the wastes durably from man and the environment, by preventing direct access to the waste and by protecting the repository from the potential detrimental processes occurring in its environment. Two sub-functions are defined:

[15] For other waste fractions this function is not required due to the absence of the thermal phase.
[16] A repository together with the host formation in which it is built (Smith, 2009: Annex 1).

- The safety function 'Reduction of the likelihood of inadvertent human intrusion and of its possible consequences' (I1) is related to the Boom Clay and the geological coverage: The I1-function consists of limiting the likelihood of inadvertent human intrusion and, in case such intrusion does occur, of limiting its possible consequences in terms of radiological and chemical impact on humans and the environment.
- The safety function 'Ensuring stable conditions for the disposed waste and the system components' (I2) is related to the Boom Clay and the geological coverage: The I2-function consists of protecting the waste and the engineered barrier system from changes and perturbations occurring in the environment of the facility, such as climatic variations, erosion, uplifting, seismic events or relatively rapid changes in chemical and physical conditions.

An overview of the objectives of the safety functions and the barriers and compartments of the OPERA disposal system are shown in Table 1-1 (based on Verhoef, 2011a: Table 1).

Table 1-1 Overview of safety functions, objectives, components and barriers

Safety function	Objectives	Component/barrier
(C) Engineered containment	Prevent the release of contaminants from the waste disposal packages	Waste package
(R1) Limitation of contaminant releases	Delay and spread the RN release from the waste forms	Waste form
(R2) Limitation of water flow	Prevent and/or limit advective transport of groundwater	Engineered barrier system Host rock (Boom Clay)
(R3) Retardation of contaminant migration	Delay RN transport and dilute RN concentrations	Host rock (Boom Clay)
(I1) Reduction of the likelihood of inadvertent human intrusion	Limit the likelihood and impact of human intrusion	Host rock (Boom Clay) Geological coverage
(I2) Ensuring stable conditions	Limit the likelihood and impact of erosion exposing the wastes	Host rock (Boom Clay) Geological coverage (long term)

The safety functions play a crucial role in the FEP screening procedure (see Section 3.2). In the OPERA safety assessment the safety functions have been taken into account for verifying their role in the various scenarios proposed for the safety assessment (see Chapter 3).

2.5 Waste characteristics

Characteristics of the radioactive wastes to be finally disposed of are provided in (Verhoef, 2014a) and Verhoef, 2015). In (Verhoef, 2015) a distinction is made between the various OPERA waste types or "waste families". Waste families are groups of radioactive waste from the same origin, of similar nature, and having identical or closely related conditioning characteristics while belonging to the same category of the current waste classification (Verhoef, 2015: Section 1.2).

Table 1-2 gives an overview of the disposal sections of the OPERA disposal concept (cf. Figure 1-8), the waste allocated there, and the accompanying container and conditioning applied (Schröder, 2017c: Table 3-1).

Table 1-2: Waste composition of the disposal sections

Disposal section	OPERA waste type ("Waste Family")	Waste conditioning	Waste container	Number of waste packages
Vitrified HLW	Vitrified waste (CSD-V)	Vitrified	OPERA Supercontainer	478

Spent Fuel	Spent research reactor fuel[1]	HEU	None	OPERA Supercontainer	15
		LEU	None	OPERA Supercontainer	60
Non heat generating HLW	Compacted hulls and ends (CSD-C)		Compacted	OPERA Supercontainer	600
	Legacy waste, fissile		Concrete	OPERA Supercontainer	100
LILW[2]	Depleted uranium		Concrete	Konrad galvanized steel Type-II container	9060
	Compacted waste		Concrete	200 litre galvanized steel container	140’000
	Processed liquid molybdenum waste		Concrete	1000 litre magnetite container	6000
			Concrete	1000 litre quartz container	2000
	Processed liquid waste with spent ion exchangers		Concrete	1000 litre concrete containers with magnetite aggregate	4000

[1] HEU: high-enriched uranium; LEU: low-enriched uranium
[2] In the OPERA safety assessment, depleted uranium is treated as a separate disposal section

2.6 OPERA reference concept

For the OPERA Safety Case on Boom Clay, the ‘OPERA reference concept’ is the system concept under consideration (Verhoef, 2014a). The OPERA reference concept is a location-independent concept. With respect to the design stages distinguished in the EU-FP7 project DOPAS (White, 2016), the OPERA reference concept must be classified as *Conceptual Design* in first instance:

- It provides a description of the general layout of a repository structure, various repository components and their arrangement, and the principal type of material used for each component;
- In the OPERA programme, the range of expected environmental conditions are elaborated, (e.g. Vis, 2014; Koenen, 2014);
- The safety functions of the components and the overall structure are described qualitatively.

However, the OPERA reference concept has also some features of a *Basic Design*:

- Some components in the conceptual design are described in more detail, with approximate quantitative specification of geometry and material parameters given either in the reference concept or elaborated later in more detail (Verhoef, 2014b; Verhoef, 2015; Yuan, 2016a);
- The properties of the environmental conditions are considered in detail for the barriers that are expected to contribute relevantly to safety (e.g., Schröder, 2017a; Schröder, 2017b; Schröder, 2017c). These are not based on characterisation of a site, but on expected properties on a variety of locations that meet initial requirements;

On the other hand, little elaboration of the assumptions underpinning the design of EBS components has been conducted, and the expected performance of EBS components is not described quantitatively.

In general, based on the judgement that the natural barrier is the most important contributor to the long-term safety for most scenarios, EBS components have been defined and analysed in less detail than the natural barrier. Besides, due to the long-term interim storage of HLW the extent and impact of the thermal phase is limited. The constructional requirements related to thermal processes are therefore less stringent.

With respect to the disposal of heat producing waste, the OPERA reference concept adapts the current Belgian ‘Supercontainer’ concept, but with different dimensions (smaller containers, shorter disposal galleries) that reflect the existing national differences in waste characteristics and amounts, and addresses the requirement of retrievability. Furthermore, the OPERA concept addresses the requirement of retrievability of the waste, a major cornerstone of the Dutch policy on radioactive waste disposal.

Figure 1-7 depicts an outline of the surface and underground facilities of the OPERA disposal concept in Boom Clay (Verhoef, 2014a: p.11). The OPERA disposal facility consists of both surface and underground facilities.

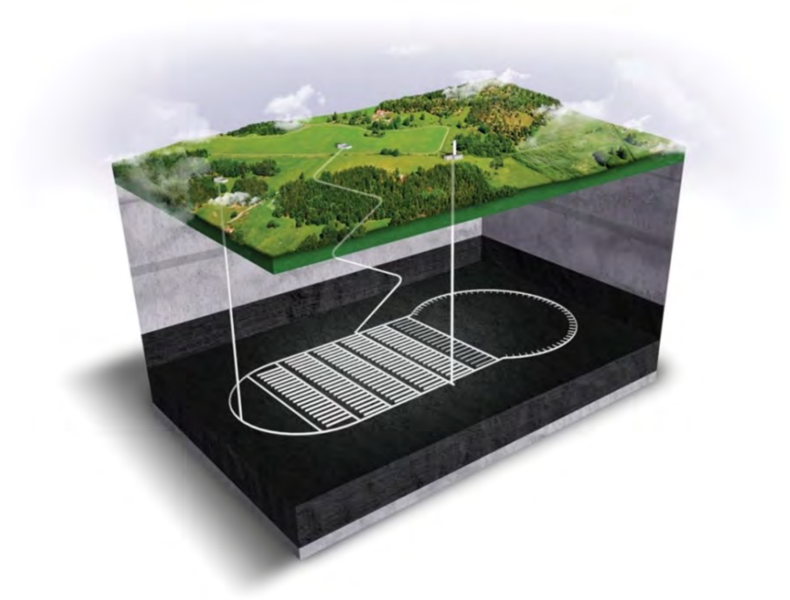


Figure 1-7 Artist impression of a geological repository for the disposal of radioactive waste in Boom Clay.

The underground facilities contain separate disposal sections for the various types of wastes, a pilot facility and a workshop, all connected by the main gallery (see Figure 1-8; Verhoef, 2014a: p.12) . The main gallery is an orbicular structure, which connects with the ground level via two access shafts and/or (optional) an inclined ramp.

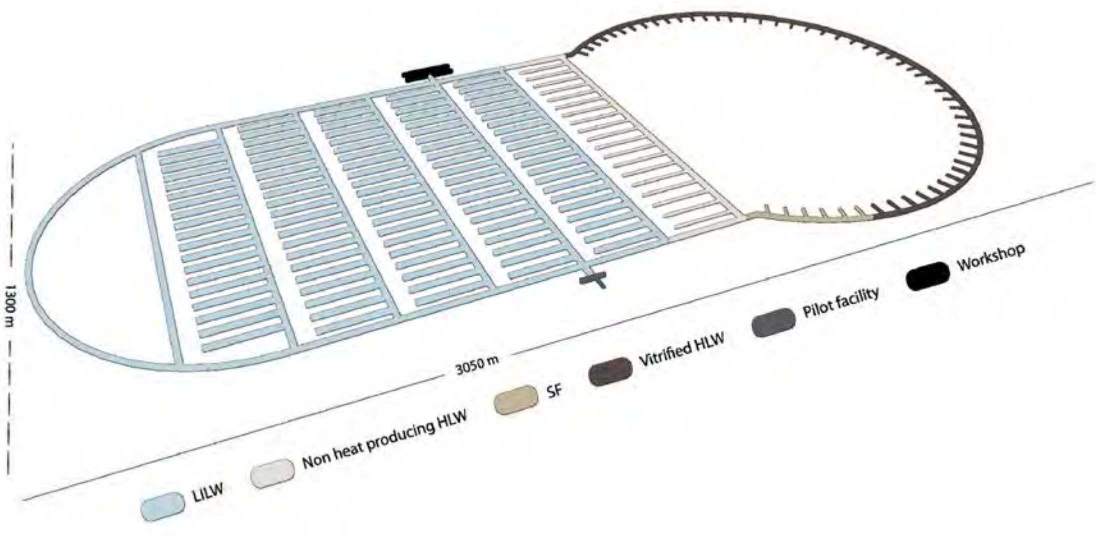


Figure 1-8 Artist impression of the disposal sections of the underground facility.

The facility contains four waste disposal sections for (1) vitrified HLW, (2) spent fuel from research reactors, (3) non-heat generating HLW and (4) ILW/LLW and depleted uranium. Each section is optimised with regard to dimensions and modes of transport of the waste containers through the galleries. The six secondary galleries are branches of the main gallery and lead to the waste disposal drifts in the various waste sections.

The **disposal tunnels** in the separate waste disposal sections are horizontal boreholes that are directly connected to the main gallery in case of vitrified HLW and spent fuel (Figure 1-9) or can be accessed through the secondary galleries (other waste types). The disposal tunnels are supported by concrete wedge-shaped blocks. After the emplacement of the waste packages, the disposal drifts are backfilled with grout and hydraulically sealed off using a plug.

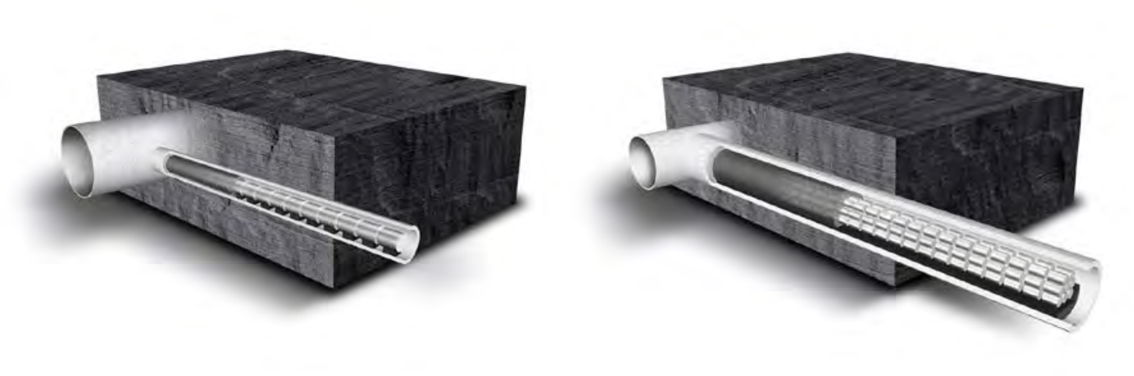


Figure 1-9 General layout of the HLW (left) and LILW (right) waste sections.

To allow for an efficient storage and disposal, standardised waste packages are used. The LILW is conditioned with concrete for the long-term interim storage which is assumed to be suitable for direct geological disposal, without further packaging or conditioning. The depleted uranium is disposed of in KONRAD type II containers. HLW containers will be overpacked in Supercontainers (Figure 1-10; Verhoef, 2014a: p.15) before their emplacement in the repository. In OPERA a Supercontainer with uniform outer dimensions is used for the heat-generating HLW, for spent fuel from research reactors as well as for the non-heat generating HLW. Figure 1-10 shows an artist impression of the OPERA Supercontainer for heat-generating HLW.

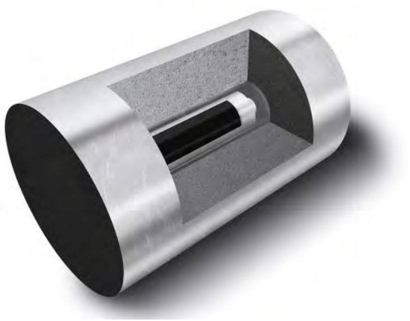


Figure 1-10 Artistic impression of the OPERA container.

The various other components of the EBS of the OPERA disposal concept and their safety functions are discussed in more detail in Chapter 5 of this document. Additionally, the safety functions, relevant processes and representative parameters for the individual EBS components are evaluated there.

3 Scenario development in OPERA

3.1 Introduction

One of the objectives of monitoring of (components of) a facility for the geological disposal of radioactive waste is to be able to detect anomalies from the expected (“normal”) evolution of the disposal system. It is important to consider the performance of the disposal system under both expected and deviating future conditions. For evaluating various future evolutions, many factors need to be taken into account, e.g. events or processes that could affect the performance of the disposal facility as well as future human actions, climate and other environmental changes. Development of scenarios, viz. descriptions of possible evolutions of the disposal system, constitutes the fundamental basis for the quantitative assessment of the safety of a repository.

Scenario outlines for a disposal in clay have already been developed since the earliest safety assessments for geological disposal. For example, in the EC PAGIS study of 1988 (Marivoet, 1988) Normal Evolution Scenarios and two Altered Evolution Scenarios (climatic changes and faulting) were identified for two reference sites: in Boom Clay and in Callovo-Oxfordian clay. Since then the list of scenarios has been growing in the various national and international programmes.

At the start of OPERA the following list of scenarios was already available from various studies, e.g. the Belgian SAFIR-2 study (ONDRAF/NIRAS, 2001: Section 11.5.2.2.2):

- Normal Evolution Scenario (includes the expected future climatic changes)
- Abandonment Scenario
- Poor Sealing Scenario
- Anthropogenic greenhouse scenario
- Fault Scenario
- Intensified glaciation scenario
- Human Intrusion and Human Action Scenarios

The OPERA method of scenario development is based on the PROSA-method (Prij, 1993), that has been extended during the CORA research programme (Grupa, 2000: Ch.2), and includes recent developments from the project PAMINA in light of the discussion regarding the role of safety functions (Beuth, 2009; Bailey, 2011: p.98-113). The PROSA-method is iterative and makes use of a preliminary set of scenario outlines prepared in an early stage of OPERA.

An important aspect of the development of scenarios is to ensure that all features, events, and processes (FEPs) of the disposal system that are relevant safety of the disposal facility are being addressed. This topic is discussed shortly in the following section.

3.2 Features, Events, and Processes

In OPERA a FEP screening process has been undertaken in order to identify potential alternative scenarios additional to the ones mentioned in the previous section. This screening method is typically a ‘top-down’ method for developing scenarios, as described in SSG-23 (IAEA, 2012: p.54). The method is based on analyses of how the safety functions of the disposal system may be affected by possible events and processes. This FEP screening process has also been used to identify FEPs that potentially may lead to additional assessment cases.

The FEP screening process performed as part of this study uses the OPERA FEP database developed in the OPERA project OSCAR (Schelland, 2014). The OPERA FEP Database was applied to identify scenarios and assessment cases that have been adopted for the OPERA safety assessment. The procedure was to identify those FEPs that may have an adverse effect on one or more of the safety functions that have been allocated to the OPERA disposal concept in Boom Clay (Grupa, 2016). In total, 366 FEPs have been identified and listed. Their relevance for OPERA has been described in (Schelland, 2014). The following five classes of FEPs have been distinguished:

- *External factors*, e.g. geological and climatic events and processes, and future human actions (excavations, drilling, mining, …);
- *Waste Package Factors*, e.g. waste forms and properties, thermal and chemical processes occurring in the waste;
- *Repository related factors*, an inventory of radiological, chemical, hydraulic, thermal, and physical/mechanical processes relevant for the evolution of the engineered barriers of the facility;
- *Geosphere related factors*, e.g. geochemical evolution of the geosphere[17], thermal and hydraulic processes, transport of contaminants;
- *Biosphere related factors*, e.g. processes influencing the future radiological impact on humans and the environment.

Many of the 366 FEPs are, to some extent, included in the OPERA integrated safety assessment model either in the form of models or as (sets of) parameters.

In the present report the FEP database has been used to check for completeness of the processes and events which may be relevant for the functioning of (a component of) the OPERA disposal system (see Ch.5).

3.3 Scenarios considered in Modern2020

The relevant scenarios identified for further analysis as part of the OPERA safety assessment are summarised in Table 1-3 (Grupa, 2016). Note that due to the limitation of the OPERA safety case on the long-term safety, scenarios related to e.g. operational safety are not considered in OPERA.

Table 1-3 indicates scenarios addressed in the Modern2020 screening process. Based on the considerations provided in Table 1-3, a limited number of alternative evolution scenarios were selected to be accounted for in more detail as part of Modern2020. The selected scenarios are described in more detail in Sections 3.3.1 to 3.3.6. The descriptions include a list of related FEPs as identified in (Grupa, 2016).

[17] In OPERA, the geosphere (or: "far field") comprises the host rock that is not damaged during excavating of volumes as well as the geological media surrounding the host rock (Verhoef, 2014a: p.3).

Table 1-3: Scenarios and cases identified in OPERA and taken forward in the Modern2020 screening process

Scenarios and cases		Considered in Modern2020 screening
	Normal Evolution Scenario	
N1	Central assessment case	Yes
N2	Radioactive gas transport case	Yes - covered by EGC1
N3	Gas pressure build-up case (normal range)	Yes - covered by EGC1
N4	Early canister failure case (normal range)	Yes - covered by EEC1
N5	Deep well assessment case	No – biosphere related scenario
	Abandonment Scenario	
AA1	Abandonment of the facility	Yes
	Poor sealing scenario	
AS1	Poor sealing	Yes
	Anthropogenic Greenhouse Scenario	
AGr1	Flooding of the site – resulting from anthropogenic greenhouse effects	No – considered as long-term scenario
	Fault scenario	
FS1	Undetected fault scenario	No - too little information available
	Intensified glaciation scenario	
AGl1	Deep permafrost case	No – long-term event
AGl2	Deep subglacial erosion case	No – long-term event
AGl3	Glacial loading case	No – long-term event
	Human Intrusion Scenarios	
AH1	Penetration by drilling or mining	No – biosphere related scenario
AH2	Deep well scenario - extreme case	No – biosphere and overburden event
	What-If cases	
EEC1	Excessive Early Container Failure	Yes
EGC1	Excessive Gas generation	Yes
EFD1	Fast and radical dissolution of the waste	Yes – covered by AA1
ECC1	Criticality event	Yes
EHP1	Excessive heat production	Yes – covered by ECC1
SGH1	Hydraulic effects of climate change	No – long-term event
SGC1	Compaction of the Boom Clay and resulting flow	No – long-term event
SHE1	Deep excavation and groundwater flow	No – too little information available
SBM1	Microbiological effects on the EBS and host rock	Yes – covered by EGC1
SAT1	Additional transport modes	No – too little information available

3.3.1 Normal Evolution Scenario (NES)

The Normal Evolution Scenario (NES) represents the most likely evolution of the disposal system. The NES assumes normally progressing and undisturbed construction, operation, and closure of the facility. In the long term, natural processes affect the expected evolution of the facility's engineered barriers. Due to the water content of the clay rock the facility's engineered barriers will slowly degrade as a result of corrosion and leaching processes. Soluble radionuclides will ultimately be released from the repository, and will migrate by diffusion through water present in the pore network in the Boom Clay. Diffusion is the dominant process driving nuclide migration through the host rock. Advective transport is minor, because of the low permeability in the host rock.

For the OPERA disposal design these processes are considered inevitable, and therefore are part of the Normal Evolution Scenario.

The Normal Evolution Scenario can be described broadly by the following sequential steps (see also **Figure 1-11**):

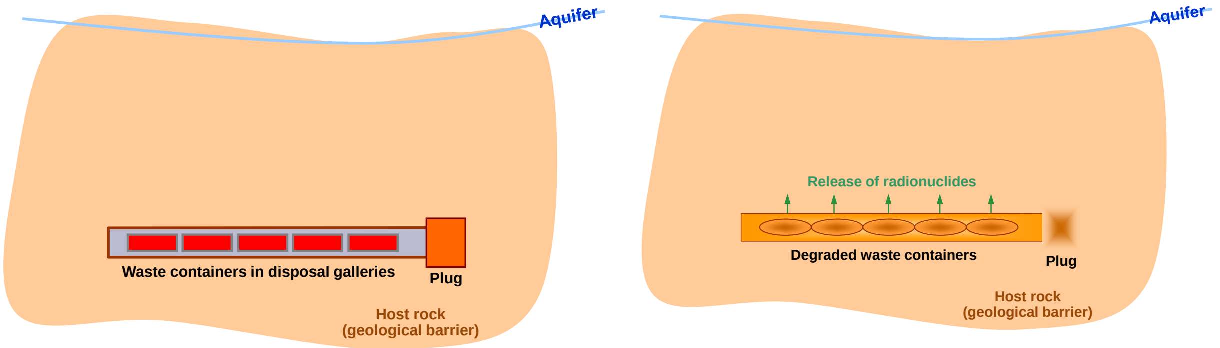
1) The repository is being constructed: shafts and galleries are excavated and consequently the surrounding rock is disturbed to some extent, the so-called "Excavation Disturbed Zone" (EDZ). The waste packages are emplaced in the disposal galleries and open spaces are backfilled with concrete. The gallery lining and the installed sealing plugs are assumed to be intact upon their emplacement, and the inside of the disposal galleries is initially dry.

2) The gallery internals will become saturated relatively fast, i.e. presumably within several decades, with pore water from the surrounding Boom Clay. Eventually, all sections of the disposal facility will be saturated with pore water.

   For ILW and LLW, the waste containers will start to corrode and leach (slowly) relatively soon after closure. For the HLW, the steel canisters and concrete overpacks of the Supercontainers prevent corrosion of the inner waste container which will fail only after some thousands to several tens of thousands years as a result of corrosion processes, whereafter soluble species (some containing radionuclides) will start to leach from those containers, too.

3) Radionuclides released from the waste will migrate into the Boom Clay host rock. Depending on the radionuclide and Boom Clay properties migration rates can vary: weakly retarded or non-retarded mobile species (particularly some fission products) will migrate well into the host rock, whereas retarded, almost immobile nuclides such as the actinides, will remain more in the vicinity of the repository.

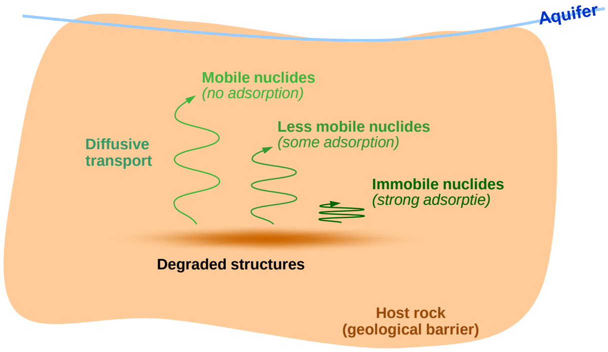
4) After tens of thousands of years the more mobile nuclides will leave the host rock and enter the aquifer system. Subsequently, migration to the biosphere may take an additional ten thousands of years or longer as a result of advective flow processes in the aquifer system. After some hundreds of thousands of years, radionuclides will reach the biosphere, potentially resulting in radiological exposures of future humans or other biota[18].



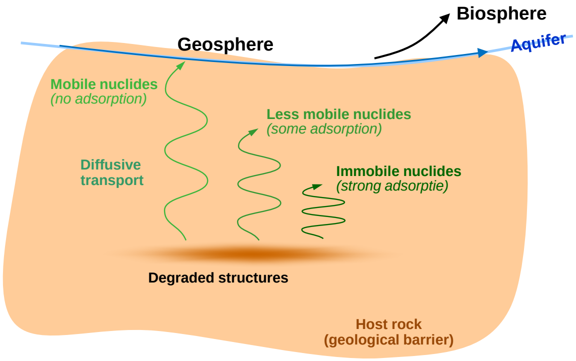
1) Initial condition

2) After some thousands years

[18] For a well-designed and normal functioning disposal system, previous studies suggest that the exposure is much less than the exposure to the natural background radiation.



3) After some ten thousand years



4) After hundreds of thousands of years

Figure 1-11 Schematic illustration of the evolution of the disposal system in Normal Evolution Scenario.

3.3.2 Abandonment of the facility (AES case AA1)

An abandonment of the repository without proper closure implies that the construction of the EBS, including the plugs and seals, will not be completed. The Safety Case stipulates that the repository is safe during all steps of the disposal process, viz. the operational phase, the closure phase, and the post-closure phase. This means that even in case of abandonment of the repository without proper closure, sufficient safety must be provided by other components of the disposal system. This is in line with the multiple barrier principle (Section 2.3).

Given that a repository will be in operation for several decades (Verhoef, 2014a: Figure 3-1), examples of events of concern that may lead to abandonment of the facility are:

- Economic distortion
- War, national disaster
- Mining accident

This event was considered in a few desk studies (e.g. Grupa, 2000; Grupa, 2009) where it has been assumed that abandonment would lead to the following chain of events:

1) Flooding of unsealed galleries
2) Dissolution of soluble parts of the waste in the water, much earlier compared to the Normal Evolution Scenario
3) Advective flow and diffusion through the remains of the underground infrastructure (galleries, shafts)
4) Transport of early-released radioactive material into the aquifer and biosphere
5) Exposure of humans to radioactive material

In the abandonment scenario in (Grupa, 2000: Section S.4.2) it was assumed that:

- waste canisters will be emplaced in the horizontal disposal boreholes;
- the horizontal disposal boreholes have been sealed with a plug;
- the shafts and access galleries have not yet been backfilled and sealed;
- the access galleries are filled with water as a result of flooding;
- the main shaft that is connected to shallow groundwater layers is also filled with water.

In a subsequent sensitivity analysis, performed as part of the EU FP6 project PAMINA, it was additionally assumed that the high level waste canister was contained by 70 cm of cement, representing the concrete buffer of the Supercontainer, the backfill and the lining, and that the disposal cell will be sealed with a (bentonite) plug of 3 m (Schröder, 2009: p.43).

Potential features and processes that may be relevant in this scenario have been analysed in OPERA (Grupa, 2016), utilizing the OPERA FEP database, and are listed in Table 1-4 (modified from Grupa, 2016: Table 4-2).

Table 1-4 Identified FEPs* for *Abandonment* Scenario (AA1)

FEP Name (Nr)	Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Limitation of containment releases (R1)	Limitation of water flow (R2)	Retardation and spreading (R3)	Reduction of human intrusion (I1)	Ensuring stable conditions (I2)
Safety functions affected by FEP						
Accidents and unplanned events (1.1.08)	X	X	X	X		
Flooding (1.2.12.01)			X	X		
Global climate change (1.3.01)			X	X		
Sea level change (1.3.03)						X
Human influences on climate (1.4.01)			X	X		
Collapse of openings (3.2.03.03)			X			

* "X" implies that a safety function is affected by the indicated FEP

The consequences of the scenario AA1 include:

- An early release of contaminants from the waste containers due to the presence of water;
- Enhanced water-mediated transport in the shafts and galleries;
- Enhanced water-mediated transport in the aquifer system.

The Abandonment scenario affects the following safety functions (cf. Table 1-4):

- Engineered containment (C). Obviously, assuming an improper sealing of the various open volumes in the repository, the engineered containment will be affected as water may reach the waste containers very early and much more abundantly.
- Delay and attenuation of the releases (R1, R2, R3). As seals are assumed to be affected in this scenario, all three safety (sub)functions are degraded. For example, as likely the water circulation through the engineered structures is intensified, the performance characteristics of the safety function R2 (Limitation of water flow through the disposal system) related to the water circulation are degraded compared to the Normal Evolution Scenario.
- Isolation (I2). Stable conditions for repository will not be guaranteed in the long term assuming degraded seal and shaft properties.

3.3.3 Poor Sealing scenario (AES case AS1)

The Poor Sealing Scenario (ONDRAF/NIRAS, 2001: Section 11.5.4.5 *Poor sealing of the repository*) is based on the assumption that the shafts, access galleries and disposal galleries are poorly sealed, e.g. due to construction errors, poor construction materials or errors in the design and testing of the facility and/or the seals. In contrast to the Abandonment scenario, the sealing is assumed to be present. Poor sealing of the shafts may result in the formation of a hydrological connection between an aquifer overlying the host rock and the (remains of the) access and disposal galleries. Depending on the hydraulic situation, the pore water pressure in the Boom Clay can be higher than the water pressure in the (remains of the) galleries. In that case, pore water can be squeezed into the (remains of the) galleries, inducing a water flow through the (remains of the) galleries and shaft(s) to the overlying aquifer.

For the OPERA safety assessment it is assumed that, compared to the Normal Evolution Scenario, an advective water flow, resulting from the difference in pore water pressure in the Boom Clay and the water pressure in the (remains of the) galleries, bypasses the Boom Clay host rock and may bypass the deep aquifers, potentially resulting in a faster and less diluting nuclide migration process to the biosphere. The flow pathway could be an inflow through one shaft and an outflow through another shaft. More likely is an inflow through the poorly sealed shafts and an outflow through the Boom Clay - or the reverse flow. For the latter pathway, the water flow rate and the migration rate are limited by the limited amount of water that can flow through the Boom Clay layer taking into account the low permeability of the Boom Clay layer.

The FEPs that are related to a possible Poor Sealing Scenario (see **Table 1-5 -** Grupa, 2016: Table 4-3) are either of geological or technical origin. The more obvious FEPs, related to construction and design features, are included in the FEP-list. Since at present there is no detailed repository construction plan, only the generic FEP design and construction are specified.

Table 1-5 Identified FEP* for *Poor Sealing* Scenario (AS1)

FEP Name (Nr)	Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Limitation of containment releases (R1)	Limitation of water flow (R2)	Retardation and spreading (R3)	Reduction of human intrusion (I1)	Ensuring stable conditions (I2)
Safety functions affected by FEP						
Construction (1.1.05)			X			
Closure (1.1.07)			X	X		
Excavation damaged and disturbed zones (3.1.06)			X			X
Piping/hydraulic erosion (3.2.02.02)	X		X	X		X
Material volume changes - repository (3.2.02.02)			X			X
Collapse of openings (3.2.03.03)			X			X
Corrosion – repository (3.2.04.04)	X		X			X
Transport pathways – repository (3.3.01)			X			

* "X" implies that a safety function is affected by the indicated FEP

Potential features and processes that may be relevant in this scenario include:

- An early release of contaminants from the waste containers due to the enhanced presence of water;
- Enhanced water-mediated transport in the shafts and galleries
- Enhanced water-mediated transport in the aquifer system
- Hydraulic processes in the geosphere

The Poor Sealing scenario affects the following safety functions:

- Engineered containment (C). Obviously, assuming a poor sealing of the various open volumes in the repository, the engineered containment is affected.
- Delay and attenuation of the releases (R2, R3). As all seals are assumed to be affected in this scenario, all three safety (sub)functions are degraded compared to the Normal Evolution Scenario.
- Isolation (I2). Stable conditions for repository will not be guaranteed in the long term assuming degraded seal and shaft properties.

3.3.4 Excessive early containment failure scenario (AES case EEC1)

In case of an *excessive* early containment/canister failure scenario it is assumed that a very early loss of the functionalities of the engineered containment will occur on a series of containers and for the entire inventory. This extreme «What-If» case is in line with the assumptions made by ANDRA about their "Package Failure" scenarios (ANDRA, 2005b: p.513), and covers all forms of uncertainty concerning the corrosion conditions for the waste packages and engineered barriers.

In this case, it is assumed that all of the waste containers' overpacks fail early and allow pore water coming into contact with the waste form relatively early after their emplacement. Although unlikely, this situation might be the result of, for example, a poor understanding of processes affecting the container lifetime for the whole repository. Early canister failure can lead to enhanced corrosion rates and gas generation rates, potentially resulting in increased stresses in the surrounding host rock. As a result, water transport through the host rock might also increase.

The identified FEPs and their potential impact on the safety functions are shown in Table 1-6 (Grupa, 2016: Table 4-8).

Table 1-6 Identified FEPs* for What-If case *Excessive early containment failure* (EEC1)

FEP Name (Nr)	Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Limitation of containment releases (R1)	Limitation of water flow (R2)	Retardation and spreading (R3)	Reduction of human intrusion (I1)	Ensuring stable conditions (I2)
Safety functions affected by FEP						
Operation (1.1.06)	X	X				
Stress-corrosion cracking (2.3.03.04)	X	X				
Corrosion - waste package (2.3.04.04)	X					
Corrosion - repository (3.2.04.04)	X		X			X

* "X" implies that a safety function is affected by the indicated FEP

The premature failure of the containers affects the following safety functions:

- Engineered containment (C). The period of engineered containment is assumed to be shortened substantially. Except for an early release of radionuclides, this may also affect corrosion rates of the engineered barriers, inducing an enhanced gas formation rate.
- Limitation of contaminant releases from the waste forms (R1). Water reaching the waste during the transient may jeopardize release kinetics. The effects of temperature are judged as limited since the temperature increase of the engineered barriers and the surrounding host rock are relatively mild due to the extended surface storage period.
- Limitation of the water flow through the disposal system (R2). Early failure of engineered barriers (including the waste packages) results in an enhanced water transport (desaturation/resaturation) in the disposal system, although this effect is judged of relatively less importance due to the low hydraulic conductivity of the Boom Clay.
- Isolation (I2). Stable conditions for repository will not be guaranteed in the long term assuming degraded seal and shaft properties.

As the Boom Clay remains unaffected the safety function "Retardation and spreading in time of contaminant migration (R3)" is judged to remain intact.

3.3.5 Excessive gas generation scenario (AES case EGC1)

The normal and expected gas generation in the facility is part of the normal evolution and has to be dealt with in the normal evolution scenario. Some additional and potentially adverse effects of gas generation will be treated in Normal Evolution Scenario N3, the *Gas pressure build-up case (normal range)*.

During the FEP screening questions arose what consequences would follow from an *excessive* gas generation and the resulting effects. Excessive gas generation could potentially result from an early and relatively large ingress of (pore) water, or unforeseen chemical and/or biological interactions between disposed waste compounds and/or between these compounds and the ambient materials (Boom Clay, pore water). The potentially affected safety functions are indicated in Table 1-7 (Grupa, 2016: Table 4-9).

At present, it is unclear whether these excessive effects could significantly disturb the normal evolution of the repository, since the Boom Clay seems capable of assimilating the gas without losing its safety functions. Therefore it has been proposed to study the effects of excessive gas generation in a What-If case.

Table 1-7 Identified FEPs* for What-If case *Excessive gas generation* (EGC1)

FEP Name (Nr)	Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Limitation of containment releases (R1)	Limitation of water flow (R2)	Retardation and spreading (R3)	Reduction of human intrusion (I1)	Ensuring stable conditions (I2)
Safety functions affected by FEP						
Gas effects - waste package (2.3.02.03)	X		X			
Impact of biological processes on other processes - waste package (2.3.05.03)	X					
Metal corrosion - waste package (2.3.07.01)	X		X			
Organic degradation - waste package (2.3.07.01)	X	X	X			
Gas-induced failure (2.3.07.07)	X		X			
Impact of gas generation on other processes - waste package (2.3.07.08)	X		X			
Gas-induced dilation - repository (3.3.07.08)	X		X			
Gas-mediated transport- repository (3.3.03)	X		X	X		
Gas dissolution – geosphere (4.2.07.04)				X		
Gas-mediated transport – geosphere (4.3.03)				X		

* “X” implies that a safety function is affected by the indicated FEP

The excessive gas generation may affect the following safety functions:

- Engineered containment (C). The period of engineered containment is assumed to be shortened substantially in case excessive gas generation results from excessive corrosion of the waste packages and/or engineered barriers.
- Limitation of contaminant releases from the waste forms (R1). Water reaching the waste during the transient may jeopardize release kinetics. The effects of temperature are judged as limited since the temperature increase of the engineered barriers and the surrounding host rock are relatively mild due to the extended surface storage period.
- Limitation of the water flow through the disposal system (R2). Early failure of engineered barriers (including the waste packages) results in an enhanced water transport (desaturation/resaturation) in the disposal system, although this effect is judged of relatively less importance due to the low hydraulic conductivity of the Boom Clay.

- Retardation of contaminant migration (R3). It is still an open question whether the migration of any released (volatile) radionuclides will be relevantly enhanced by an excessive gas generation.

3.3.6 Criticality event (AES case ECC1)

Nuclear criticality may occur if a sufficient amount of fissile material is concentrated to a level where spontaneous fission can be induced. The presence of any water may increase the potential for nuclear criticality as it can act as a moderator. In general, criticality of fissile material will lead to a very large and sudden heat production and pressure waves. High temperatures and temperature gradients can lead to enhanced thermal stresses and chemical alteration of materials.

A criticality *accident* in a deep geological repository leading to a nuclear explosion is assumed to be impossible since that would require maintained critical conditions which can only be achieved in a special designed device.

Criticality *incidents* are best described by one or a sequence of intermittent, limited uncontrolled chain reactions, also called “localized criticality.” Localized criticality results in a series of bursts of heat and radiation.

In conditioned LILW any present fissile materials are dispersed over a large volume, and nuclear criticality is impossible. Vitrified high level wastes may contain only minute amounts of fissile materials since the majority of these compounds have been recycled and separated from the fission products that are contained in the HLW. In spent fuel, in particular in highly enriched uranium (HEU), localized criticality has to be avoided by design (Dodd, 2000: p. 84).

The FEPs related to localized criticality and their potential impact on the safety functions are indicated in Table 1-8.

Table 1-8 Identified FEPs* for assessment case *Criticality event* (ECC1)

FEP Name (Nr)	Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Limitation of containment releases (R1)	Limitation of water flow (R2)	Retardation and spreading (R3)	Reduction of human intrusion (I1)	Ensuring stable conditions (I2)
Safety functions affected by FEP						
Radiogenic heat production and transfer (2.3.01.01)	X	X	X			
Criticality (3.2.06.05)	X	X	X			

* “X” implies that a safety function is affected by the indicated FEP

A localized criticality event could potentially affect the following safety functions:

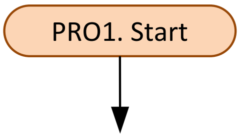
- Engineered containment (C). The engineered containment might fail in case of a localized criticality event as a result of e.g. excessive heat production and sudden related thermo-mechanical effects.
- Limitation of contaminant releases from the waste forms (R1). Early rupture of waste packages and engineered barriers may result from the abovementioned sudden thermo-mechanical effects.
- Limitation of water flow through the system (R2). A disruption of the integrity of the waste packages, engineered barriers and perhaps also the near field affects this safety function.

4 Preliminary list of processes

4.1 General considerations

Basis of the compilation of a preliminary list of processes is the OPERA FEP Database (Schelland, 2014) and related scenario descriptions (Grupa, 2016) as shortly summarized in the previous section. For the parameter screening as part of Modern2020, a more comprehensive list of processes is needed than the overview provided in the previous Chapter 3, where the main FEPs affecting safety functions of the OPERA disposal system were listed. In order to generate a preliminary list of processes, in this chapter an overview of all processes and events in the OPERA FEP Database was compiled and will be discussed below.

Consequently, this chapter refers to the step PRO.1 of the Modern2020 screening methodology:



In a first quick screening of the FEP list it was recognized that not all FEPs in the OPERA Database relate to events and processes, and a few were found to be too ambiguous to take forward. Accordingly, several FEPs are identified that are not taken into account in compiling the subsequent lists:

- FEPs indicating features of the disposal system, e.g. “Quality assurance and control” (FEP 1.1.01), “Waste state” (2.1.01), “Design” (3.1.01), “Stratigraphy” (4.1.01), etc.;
- FEPs related to a disposal system in rock salt;

4.2 Factor analysis

This section lists the remaining events and processes which will to serve as a basis for further screening. In addition to the compilation of features and events, the tables below also indicate:

(1) the role of the FEP in the OPERA disposal concept,
(2) the potentially affected safety function, and
(3) the scenario in which the FEP is judged to play an important role.

The OPERA FEP-list is organized in five “Factors” that are discussed section-wise:

- External factors
- Waste package factors
- Repository factors
- Geosphere factors
- Biosphere factors

The following guidelines are followed with respect to the classification and further processing:

- FEPs relevant for completing the descriptions of the OPERA scenarios but which do not relate to a safety function hazard are indicated as “system description”;
- In some cases, the considered FEP does play a role in an AES, and at the same time is part of the description of the system in other cases. Those FEPs have been assigned two FEP roles accordingly;
- FEPs judged to be irrelevant for the OPERA disposal concept, or in case no process could be identified in which the FEP would significantly affect any of the safety functions, were indicated as “irrelevant”;
- In case it was found that a FEP may affect, either directly or indirectly, one or more safety functions of the OPERA disposal system, the FEP role was set to 'SF hazard’ - Safety Function hazard.

The explanations of the abbreviations relating to the safety functions and the scenarios are provided in Section 2.4 and Table 1-3 respectively.

4.2.1 External factors

"External factors" are the FEPs with causes or origins outside the assessed disposal system, viz. the repository, the surrounding geosphere and overlying biosphere. External factors are generally not influenced (or are only weakly influenced) by processes within the disposal system and are natural or human-induced factors of a regional and/or global nature. Decisions related to repository design, operation and closure are included in this group because these are outside the temporal boundary of the disposal system for the purpose of the post-closure safety assessment. External Factors are often represented as boundary conditions or initiating events and processes in developing scenarios and associated models of the disposal system.

Table 1-9 Listing of events and processes – External factors

FEP Nr	*FEP Name*	*FEP role*	*Affected Safety Function*	*Related OPERA scenario*
Geological factors				
1.2.01.01	Regional uplift	irrelevant		
1.2.01.02	Regional subsidence	system description		all
1.2.01.03	Movement along faults	SF hazard	R1, R2, R3	FS1
1.2.01.04	Glaciotectonic movement	SF hazard	R2, R3	FS1
1.2.01.05	Diapiric movement	irrelevant		
1.2.02	Orogeny (mountain building)	irrelevant		
1.2.03.01	Deformation by intraplate fault movement	SF hazard	R1, R2, R3	FS1
1.2.03.02	Deformation by glacial loading	SF hazard	R2, R3	AGl3
1.2.03.03	Deformation by permafrost formation	irrelevant		
1.2.03.04	Deformation by compaction	irrelevant		
1.2.04.01	Intraplate seismic movement	SF hazard	R2	FS1
1.2.04.02	Glaciotectonic seismicity	SF hazard		
1.2.05	Volcanic and magmatic activity	irrelevant		
1.2.06	Metamorphism (change of minerals/texture)	irrelevant		
1.2.07	Hydrothermal activity	irrelevant		
1.2.08.01	Regional erosion	irrelevant		
1.2.08.02	Regional sedimentation	irrelevant		
1.2.08.03	Glaciation induced erosion and sedimentation	irrelevant		
1.2.09	Diagenesis (change of sediments)	SF hazard	R3	Not indicated
1.2.10	Pedogenesis (soil formation)	system description		all
1.2.12.01	Flooding	SF hazard	R2, R3, I2	AGr1, AA1
1.2.12.02	Change in groundwater level	system description		all
1.2.12.03	Fresh/salt water intrusion	system description		all
Climatic factors				
1.3.01	Global climate change	SF hazard	R2, R3, I2	AGr1, AA1
1.3.02	Regional and local climate change	system description		all
1.3.03	Sea level change	SF hazard	I2	AGr1, AA1
1.3.04	Periglacial effects	SF hazard	R3	AGl1
1.3.05	Local glacial and ice-sheet effects	SF hazard	R2, R3, I2	AGl2, AGl3
1.3.06	Warm climate effects (tropical and desert)	system description		all
1.3.07	Hydrological response to climate change	system description		all
1.3.08	Ecological response to climate changes	system description		all
1.3.09	Human response to climate changes	system description		all
1.3.10	Geomorphological response to climate changes	system description		all

4.2.2 Waste package factors

Waste package factors related to waste packages, i.e. waste forms and any associated packaging, and the associated release and migration of contaminants.

Table 1-10 Listing of events and processes – waste package factors

FEP Nr	*FEP Name*	*FEP role*	*Affected Safety Function*	*Related OPERA scenario*
Thermal processes				
2.3.01.01	Radiogenic heat production and transfer	system description		
2.3.01.02	Chemical heat production and transfer	irrelevant		
2.3.01.03	Biological heat production and transfer	irrelevant		
Hydraulic processes				
2.3.02.01	Resaturation/desaturation	system description		all
2.3.02.02	Thermal effects	system description		all
2.3.02.03	Gas effects	SF hazard	C, R2	N3
Mechanical processes				
2.3.03.01	Package deformation	system description		all
2.3.03.02	Material volume changes	system description		all
2.3.03.03	Package movement	irrelevant		
2.3.03.04	Stress-corrosion cracking	SF hazard	C, R1	N4
Chemical processes				
2.3.03.05	Gas explosion	irrelevant		
2.3.04.01	pH conditions	system description		all
2.3.04.02	Redox conditions	system description		all
2.3.04.03	Perturbing species' concentrations	system description		all
2.3.04.04	Corrosion	SF hazard	C	N4
2.3.04.05	Polymer degradation	system description		all
2.3.04.06	Dissolution	SF hazard	C, R1	all
2.3.04.07	Mineralisation	system description		all
2.3.04.08	Precipitation reactions	system description		all
2.3.04.09	Chelating agent effects	irrelevant		
2.3.04.10	Colloid formation	system description		all
2.3.04.11	Chemical concentration gradients	system description		all
Biological processes				
2.3.05.01	Microbial growth and poisoning	system description		all
2.3.05.02	Microbially/biologically mediated processes	system description		all
Radiological processes				
2.3.06.01	Radioactive decay and ingrowth	system description		all
2.3.06.02	Radiolysis	system description		all
2.3.06.03	Helium production	system description		all

FEP Nr	***FEP Name***	***FEP role***	***Affected Safety Function***	***Related OPERA scenario***
2.3.06.04	Radiation attenuation	system description		all
2.3.06.05	Radiation damage	system description		all
Gas generation				
2.3.07.01	Metal corrosion	SF hazard	C, R2	N3
2.3.07.02	Organic degradation	SF hazard	C, R1, R2	N3
2.3.07.03	Radon production	system description		all
2.3.07.04	Radiolysis	system description		all
2.3.07.05	Volatilisation	irrelevant		
2.3.07.06	Gas dissolution	system description		all
2.3.07.07	Gas-induced failure	SF hazard	C, R2	EGC1
Contaminant release – waste form				
2.4.01.01	Liquid wastes	SF hazard		irrelevant
2.4.01.02	Dissolution	SF hazard	C, R1	all
2.4.01.03	Diffusion	system description		all
2.4.01.04	Speciation and solubility	system description		all
2.4.01.05	Sorption and desorption	system description		all
2.4.01.06	Complexation	system description		all
2.4.01.07	Colloids	system description		all
2.4.02.01	Gaseous wastes	system description		all
2.4.02.02	Radon production	system description		all
2.4.02.03	Volatilisation	system description		all
2.4.02.04	Radiolysis	system description		all
2.4.04	Human-action-mediated release	SF hazard	C, R1, R2, R3, I1, I2	AH1
Contaminant transport – waste package				
2.5.02.01	Advection	system description		all
2.5.02.02	Dispersion	system description		all
2.5.02.03	Molecular diffusion	system description		all
2.5.02.04	Dissolution, precipitation and mineralisation	system description		all
2.5.02.05	Speciation and solubility	system description		all
2.5.02.06	Sorption and desorption	system description		all
2.5.02.07	Complexation	system description		all
2.5.02.08	Colloid transport	system description		all
2.5.03	Gas-mediated transport	system description		all

4.2.3 Repository factors

Repository factors relate to FEPs relevant to the repository as a whole, including the excavation damaged and excavation disturbed zones, as well as site investigation/monitoring boreholes, but excluding the waste packages, and the associated migration of contaminants.

Table 1-11 Listing of events and processes – repository factors

FEP Nr	***FEP Name***	***FEP role***	***Affected Safety Function***	***Related OPERA scenario***
Repository characteristics and properties				
3.1.06	Excavation damaged and disturbed zones	SF hazard	R2, I2	all
Thermal processes				
3.2.01.01	Thermal conduction and convection	irrelevant		
Hydraulic processes				
3.2.02.01	Resaturation/desaturation	SF hazard	R2, R3	N3
3.2.02.02	Piping (internal erosion) / hydraulic erosion	SF hazard	C, R2, R3, I2	AS1
Mechanical processes				
3.2.03.01	Material volume changes	SF hazard	R2, I2	AS1
3.2.03.02	Creep	system description		all
3.2.03.03	Collapse of openings	SF hazard	R2, I2	AS1
3.2.03.04	Gas explosion	irrelevant		
Chemical processes				
3.2.04.01	pH conditions	system description		all
3.2.04.02	Redox conditions	system description		all
3.2.04.03	Perturbing species' concentrations	irrelevant		
3.2.04.04	Corrosion		C, R2, I2	N4
3.2.04.05	Dissolution	irrelevant		
3.2.04.06	Mineralisation	system description		all
3.2.04.07	Precipitation reactions	system description		all
3.2.04.08	Chelating agent effects	irrelevant		
3.2.04.09	Colloid formation	irrelevant		
3.2.04.10	Chemical concentration gradients	system description		all
Biological processes				
3.2.05.01	Microbial growth and poisoning	irrelevant		
3.2.05.02	Microbially/biologically mediated processes	irrelevant		
Radiological processes				
3.2.06.01	Radioactive decay and ingrowth	system description		all
3.2.06.02	Radiolysis	system description		all
3.2.06.03	Radiation attenuation	system description		all
3.2.06.04	Radiation damage	system description		all
3.2.06.05	Criticality	SF hazard	C, R1, R2	ECC1
Gas generation				
3.2.07.01	Metal corrosion	system description		all
3.2.07.02	Organic degradation	irrelevant		
3.2.07.03	Radon production	irrelevant		

FEP Nr	FEP Name	FEP role	Affected Safety Function	Related OPERA scenario
3.2.07.04	Radiolysis	system description		all
3.2.07.05	Volatilisation	irrelevant		
3.2.07.06	Gas dissolution	system description		all
3.2.07.07	Gas-induced dilation (fracture)	SF hazard	C, R2	EGC1
Contaminant transport - Repository				
Water-mediated transport				
3.3.02.01	Advection	SF hazard	R2	SAT1
3.3.02.02	Dispersion	SF hazard	R2	SAT1
3.3.02.03	Molecular diffusion	SF hazard	R2	SAT1
3.3.02.04	Dissolution, precipitation and mineralisation	SF hazard	R1, R3	SAT1
3.3.02.05	Speciation and solubility	SF hazard	R1, R3	SAT1
3.3.02.06	Sorption and desorption	SF hazard	R1, R3	SAT1
3.3.02.07	Complexation	SF hazard	R1, R3	SAT1
3.3.02.08	Colloid transport	SF hazard	R1, R3	SAT1
Gas-mediated transport				
3.3.03	Gas-mediated transport	SF hazard	C, R2, R3	N3

4.2.4 Geosphere factors

Geosphere factors relate to FEPs relevant to the geosphere mechanically undisturbed by the construction of the repository and the associated migration of contaminants. The geosphere excludes the excavation damaged and disturbed zones surrounding the repository, and site investigation/ monitoring boreholes.

Table 1-12 Listing of events and processes – geosphere factors

FEP Nr	FEP Name	FEP role	Affected Safety Function	Related OPERA scenario
Geosphere processes				
Thermal processes				
4.2.01.01	Thermal effects of repository	irrelevant		
4.2.01.02	Thermal effects of climate change	system description		all
Hydraulic processes				
4.2.02.01	Hydraulic effects of repository	irrelevant		
4.2.02.02	Hydraulic effects of climate change	system description		all
Mechanical processes				
4.2.03.01	Mechanical effects of repository	system description		all
4.2.03.02	Mechanical effects of climate change	SF hazard	R2, R3	AGI3
Geochemical processes				
4.2.04.01	Geochemical effects of repository	irrelevant		
4.2.04.02	Geochemical effects of climate change	system description		all
Biological processes				
4.2.05.01	Biological effects of repository	irrelevant		
4.2.05.02	Biological effects of climate change	irrelevant		
Radiological processes				
4.2.06	Radiological processes	irrelevant		
Gas processes				
4.2.07.01	Gas sources	SF hazard	R3	AH1, AH2
4.2.07.02	Radon production	irrelevant		
4.2.07.03	Volatilisation	system description		all
4.2.07.04	Gas dissolution	system description		EGC1
4.2.07.05	Gas-induced dilation	system description		all
Contaminant transport - Geosphere				

FEP Nr	FEP Name	FEP role	Affected Safety Function	Related OPERA scenario
Water-mediated transport				
4.3.02.01	Advection	system description		all
4.3.02.02	Dispersion	system description		all
4.3.02.03	Molecular diffusion	system description		all
4.3.02.04	Matrix diffusion	system description		all
4.3.02.05	Dissolution, precipitation and mineralisation	system description		all
4.3.02.06	Speciation and solubility	system description		all
4.3.02.07	Sorption and desorption	system description		all
4.3.02.08	Complexation	system description		all
4.3.02.09	Colloid transport	system description		all
Gas-mediated transport				
4.3.03	Gas-mediated transport	system description		all

4.2.5 Biosphere factors

Biosphere factors relate to FEPs relevant to the biosphere, viz. the surface environment, humans and non-human biota, and the associated migration of contaminants. The biosphere factors includes the geosphere-biosphere interface such as water extraction wells, near-surface aquifers, unconsolidated sediments, and groundwater discharge zones.

In the OPERA disposal concept, no safety functions are attributed to the biosphere. Additionally, Modern2020 focuses on monitoring of the disposal facility and its surroundings. For these reasons, the screening of parameters related to processes in the biosphere is not considered in the present report.

4.3 Evaluation

Compiling the OPERA FEP database (Schelland, 2014) was the first effort so far in the Netherlands to build systematically an overview of features, events, and processes related to geological disposal in Boom Clay. The OPERA FEP Database also considered the impact of FEPs on safety functions attributed to the OPERA disposal concept, and even identified alternative evolution scenarios. In that respect, the OPERA FEP database was a significant upgrade of the knowledge base of disposal in Boom Clay.

However, the current version of OPERA FEP Database applied to the Dutch disposal concept is not mature because although it may assumed to be rather complete, it needs further detailing. To bring it in line with respect to the level of detailing of existing FEP databases for other host rocks, e.g. rock salt (Wolf, 2012) or granite (Posiva, 2012), significant additional efforts are necessary for the following reasons:

- More detailed general descriptions for each FEP are needed;
- Site-specific features, effects and impact need to be addressed;
- Assessments of the time evolutions of the FEP, both for the normal evolution scenario and the alternative evolution scenarios need to be performed;
- Assessment of the relevance and impact on barriers should be performed;
- Uncertainties in the understanding of the FEP and open questions has to be described;
- An overview of couplings to other FEPs should be given, and
- Well established and up-to-date references must be provided.

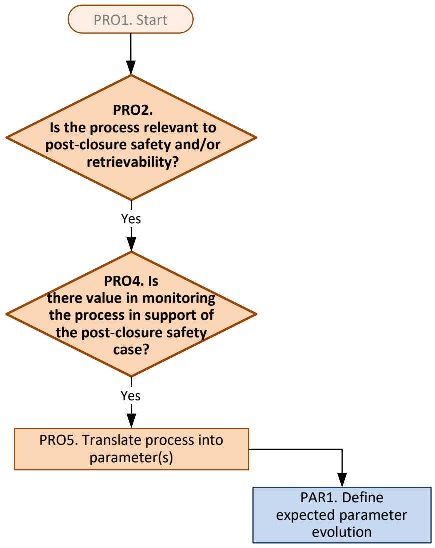
A more mature FEP database also requires to provide clear links between related FEPs. Furthermore, a larger level of detail also requires a more elaborated disposal concept, including design criteria of the various engineered barriers. With the OPERA disposal concept for the final disposal of radioactive waste in Boom Clay currently mainly in the conceptual design stages, the level of detail that can be provided by the OPERA FEP database is limited. Nevertheless, the screening of the FEP database allowed to identify and link a relevant number of processes that will be discussed further in the next chapter.

5 Safety functions and relevant processes

5.1 General screening process

In this chapter, key features and processes, and the system-specific underlying processes and parameters are established and shortly discussed, preferably based on information from the documentation generated in the OPERA programme. Although no screening is performed in this chapter, it provides and discussed the information necessary to perform the partial screening steps PRO2, PRO4, PRO5, and PAR1 of the Modern2020 screening methodology, as indicated in the figure alongside. The screening itself is discussed in Chapter 6.

In order to perform a screening, the factor-wise organised processes, based on analyses of the safety functions, related FEPs and scenarios considered that presented in the previous section, are rearranged in order to structure the existing information in a more coherent manner: the information in the remainder of this chapter is organized per disposal component, and the following components are distinguished:



- Waste form,
- Waste container,
- Backfill,
- Disposal cell plug,
- Gallery lining,
- Near-field of the host rock,
- Far-field of the host rock, and
- Shaft seal

For each of these barriers of the OPERA disposal concept the information of the previous chapter is restructured as follows:

- Safety function(s) for each barrier are identified;
- Additional functions that may be defined for a barrier are identified
- The most relevant processes potentially affecting the safety functions or other functions are described;
- Parameters are identified which are judged characteristic for the identified processes.

The tables generated at the end of each of the sub-sections below describing the various EBS's present altogether the preliminary process and parameter list for the considered scenarios. These tables are the basis of further screening of the Modern2020 methodology, in Chapter 6. The overviews generated in this chapter serve as a basis for the actual testing of the Modern2020 Screening Methodology in Chapter 6.

5.2 Waste form

5.2.1 Properties and features of the waste form

The radioactive waste in the Netherlands is classified into (Verhoef, 2014a: p.9):

- Low and Intermediate Level Waste (LILW)
- (Technically Enhanced) Naturally Occurring Radioactive Materials ((TE)NORM) and
- High Level Waste (HLW).

The HLW consists of (Verhoef, 2014a: p.9; see also Section 2.5):

- heat-generating waste (vitrified waste from reprocessed spent fuel from the Nuclear Power Plants in Borssele and Dodewaard, conditioned spent fuel from the research reactors and spent uranium targets from molybdenum production); and

- non-heat generating waste (such as hulls and ends from fuel assemblies, waste from dismantling and decommissioning nuclear facilities, legacy wastes).

The vitrified HLW results from the reprocessing of the spent fuel from the nuclear power plants. The vitrified HLW contains fission products and transuranic elements produced in the reactor core and account for over 95 % of the initial total radioactivity produced in the nuclear power process. Vitrified HLW is normally contained in stainless steel CSD-V containers. This type of canisters can hold about 400 kg of vitrified waste per package. Many countries use, at the present, borosilicate glasses for immobilisation of HLW. Borosilicate glasses have the ability to dissolve and accommodate a wide range of waste compounds, their properties can be easily modified and optimized and there is also extensive knowledge and expertise available from the glass industry regarding processing technologies and properties.

HLW is expected to require further packaging and/or conditioning prior to disposal. In OPERA the Supercontainer concept is adopted. In this concept the HLW is overpacked in Supercontainers and the waste canister, the overpack and the concrete buffer are transported and disposed of as one entity. The Supercontainer is discussed separately in Section 5.3.

The LILW is conditioned with concrete and is expected to be suitable for disposal without further packaging or conditioning. The waste form includes lightly contaminated materials (plastic, metal or glass objects, tissues and cloth) in four standardized types of packages (of 200, 600, 1000 or 1500 litres volume). The 200 and 600 litres packages consist of painted, galvanised steel drums with inside a layer of cement, embedding the waste. The 1000 and 1500 litre packages consist of full concrete packages enclosing the cemented waste.

(TE)NORM includes radioactive waste originating from the uranium enrichment facility of URENCO. Depleted uranium (DU) is intended to be disposed, although it is not yet conditioned for final disposal to allow any reuse of the material in the future, if applicable.

In OPERA it is assumed that the DU is disposed in KONRAD Type II containers. The KONRAD Type II steel containers have a thickness of 4 mm (Verhoef, 2014a: Appendix, p.2/2).

5.2.2 Safety functions related to the waste form

The waste form as a separate entity contributes to the safety function *'delay and attenuation of releases (R),* through *limitation of contaminant releases from the waste forms (R1)*, cf. Section 2.4. This safety function becomes relevant once the 'engineered containment (C)' function, which applies to the waste canister/container (see Section 5.3), fails and the waste matrix comes into contact with water.

The safety functions of the OPERA waste forms, which have to be confirmed by further analyses in the OPERA research program and beyond, are summarized in the table below.

Table 1-13 Safety functions of the OPERA Waste Forms

Safety function	Reference
Limitation of contaminant releases from the waste forms (R1)	See Section 2.4

5.2.3 Identification and description of related main processes

Dissolution of the waste form in the Normal Evolution Scenario is limited by the design and properties of the waste matrix, engineered barriers, and the geochemical environment. In addition, a significant amount of the involved waste compounds, including the radionuclides, does not or hardly dissolve in pore water (Grupa, 2016: p.43).

In (Deissmann, 2016a; Deissmann, 2016b; Filby, 2016) the dissolution rates and the radionuclide release from vitrified HLW, Spent Research Reactor Fuel and LILW under repository conditions relevant to OPERA are discussed to assess and quantify the safety function R1: '*Limitation of contaminant releases from the waste forms*' in the context of the envisaged OPERA safety case. The waste matrix dissolution/degradation processes for OPERA waste families are shortly discussed in the sections below. Gas generation due to the corrosion/degradation of waste matrix is not expected to impact the safety function (R1) of the waste matrix. However, high gas pressure may affect the integrity and consequently the safety functions of other repository components and therefore that process is shortly discussed in this section.

5.2.3.1 Dissolution of vitrified HLW in repository environment

Mechanisms of dissolution of vitrified HLW have been investigated in OPERA WP 5 (Deissmann, 2016a). In the case of vitrified HLW, leaching will start after the loss of integrity of the engineered containment provided by the Supercontainer. The dissolution and leaching of the waste form is preceded by following processes (Deissmann, 2016a: p.39):

- (fast) resaturation of the repository backfill,
- corrosion/failure of the stainless steel envelope,
- re-saturation of the concrete buffer,
- corrosion/failure of the carbon steel overpack, and finally
- corrosion/failure of the CSD-V-canister.

Release rates for vitrified waste were derived in (Deissmann, 2016a: Table 6-1). The summary of the glass waste form performance data suggested for OPERA is given in the table at the end of this section. For all other waste fractions, conservatively instantaneous release is assumed in the OPERA-PA.

The alteration and dissolution of nuclear waste glass in contact with water is controlled by several inter-related processes at the glass surface. Independent of the glass composition and the alteration conditions, the most important processes comprise (Deissmann, 2016a: p.25):

- Water diffusion,
- Ion exchange between hydrogenated species and alkalis (interdiffusion),
- Hydrolysis of covalent and iono-covalent bonds in the glass matrix,
- Formation and evolution of a surface alteration layer (gel layer),
- Silica saturation of the solution,
- Precipitation of secondary phases,
- Retention of radionuclides in the gel layer and secondary phases
- Removal of silicon from the solution by sorption, chemical reaction or transport.

The contribution of these processes to the (apparent) glass dissolution rate, which can be measured by the release of mobile species into solution, depend on glass composition and on the physical and chemical conditions at and near the glass surface.

Based on extensive studies on the dissolution of nuclear waste glasses and in particular simulated HLW borosilicate glasses, a general picture on the typical dissolution behaviour of HLW borosilicate glasses under conditions representative for geological disposal environments has been established, cf. Figure 1-12 (Deissmann, 2016a: Figure 5-1).

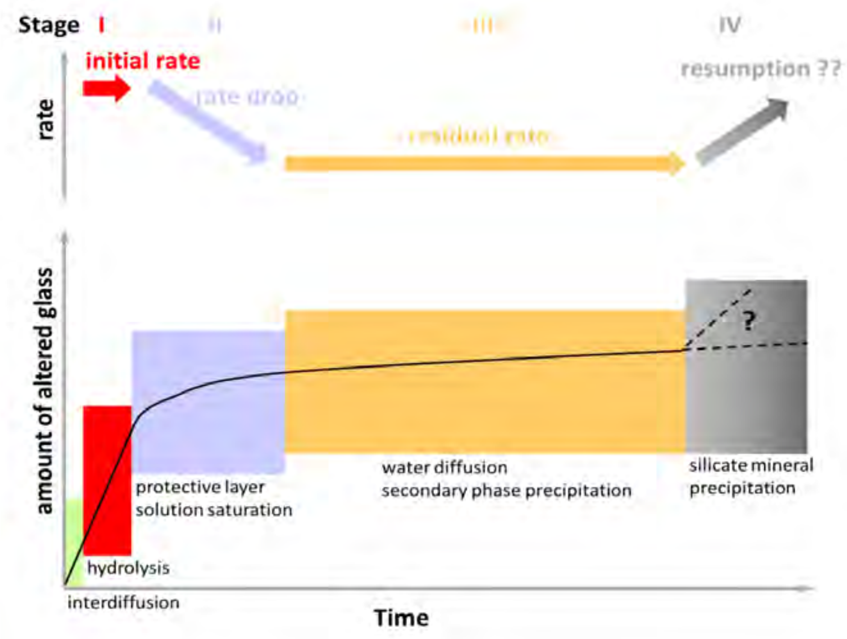


Figure 1-12 Stages of nuclear glass dissolution and related potential rate-limiting mechanisms.

The (fast) initial rate corresponds to interdiffusion and hydrolysis of the silicate network bonds. Interdiffusion (ion exchange) leads to a leaching of alkali ions from the glass network via ion exchange with H^+ ions in the aqueous solution, resulting in an increase in solution pH. Competitive to the hydrolysis of the silicate network, the interdiffusion results in the dissolution of the glass network. Due to the formation of surface layers, incongruent release of glass components at neutral to slightly alkaline conditions is expected. For example boron, which is not retained in the surface layer, is released at higher rates compared to other glass components (e.g. silicon).

The evolution of the near-field chemistry and the extent of cement alteration resulting from the exchange of cementitious materials with Boom Clay pore water will directly impact the glass dissolution rates, the formation of glass alteration layers and secondary phases, as well as the radionuclide release with time (source term).

Based on a review of the literature and a compilation of a database on glass dissolution rates under alkaline conditions, following conclusions regarding the glass dissolution rates were drawn in (Deissmann, 2016a: p.47):

- Glass dissolution rates generally depend on glass type, temperature, pH, solution composition, and the presence of cementitious materials;
- Glasses are generally less durable under high pH conditions;
- The highest dissolution rates are observed in alkali-rich KOH (NaOH/LiOH) solutions;
- Elevated calcium concentrations in solution such as in evolved cement pore waters have an antagonistic effect on the glass alteration rate due to the inclusion of calcium into the altered glass layer and/or CSH-precipitation on the glass surface;
- The presence of cementitious materials leads to a decrease of the silicon concentration in solution, for example due to CSH-formation by reaction with portlandite ($Ca(OH)_2$) resulting in higher glass dissolution rates, as long as portlandite is available.

Based on the conclusions above and on the results of the Belgian research programmes into glass dissolution under Supercontainer conditions, ranges and best estimates for the glass dissolution rates and the lifetime of the glass waste forms under Dutch repository conditions have been proposed in (Deissmann, 2016a).

Table 1-14: Summary of glass waste form performance data suggested for the OPERA PA (Deissmann, 2016a: p.41)

	Best estimate	Lower bound	Upper bound
Glass dissolution rate	0.006 g m^{-2} d^{-1}	0.00005 g m^{-2} d^{-1}	0.06 g m^{-2} d^{-1}
Cracking factor	40	5	100
Glass package dissolution rate	32.4 µm a^{-1}	0.03 µm a^{-1}	811 µm a^{-1}
Glass package lifetime	6,500 a	$6.2 \cdot 10^{6}$ a	260 a
Waste form dissolution rate	$1.5 \cdot 10^{-4}$ a^{-1}	$1.6 \cdot 10^{-7}$ a^{-1}	$3.9 \cdot 10^{-3}$ a^{-1}

5.2.3.2 Corrosion of Research Reactor Spent Fuel (RRSF) in the repository environment

The corrosion behaviour of and the radionuclide release from research reactor spent fuels (RRSF) under disposal conditions expected in a geological repository in Boom Clay in the Netherlands have been analysed in (Deissmann, 2016b).

The corrosion of plate type RRSF in the repository environment can be divided into two steps (Deissmann, 2016b: p.25): (i) corrosion of the aluminium cladding, followed by (ii) corrosion of the fuel meat containing the majority of the radionuclide inventory.

There are only limited data on corrosion behaviour of research reactor spent fuel under repository conditions. The existing experimental data indicate that RRSF corrodes after failure of the waste canisters, practically instantaneously with respect to the time scales relevant for geological disposal. Therefore, for the OPERA PA it is assumed an instantaneous corrosion and radionuclide release from the spent fuel immediately after the failure of the waste canisters.

The corrosion rates of aluminium in anaerobic, cementitious environments are associated with the generation of H_2(g). In many safety assessments for geological repositories for radioactive wastes a corrosion rate of aluminium between 0.01 and 10 mm/a has been used (see for more detail Deissmann, 2016b: Section 5.1.3).

5.2.3.3 Degradation of Non-heat generating HLW

The fraction of non-heat generating HLW consists of hulls and ends from fuel assemblies, waste from dismantling and decommissioning nuclear facilities and legacy wastes.

The hulls and ends contain the metal parts of the spent fuel assemblies made of zircaloy, inconel, stainless steel. These wastes will be contained in stainless steel CSD-C containers (Colis Standard Déchets - compacted). A CSD-C waste container usually holds 90 wt% metal parts of spent fuel assemblies and 10 wt% waste arising from fuel reprocessing (Verhoef, 2015: p. 22).

Non-heat generating HLW will also originate from dismantling and decommissioning of the various nuclear facilities in the Netherlands. It is currently assumed that this waste will be packed in the same type of containers as spent fuel, and that it will also be conditioned with concrete. The exact composition of the waste matrix is not known, it can be assumed that a significant fraction will consist of concrete and steel (Meeussen, 2014: p.14).

The legacy waste contains the wastes resulting from the nuclear research carried out in the previous decennia and consists of fuel material residues (spent uranium targets and irradiated fuel) and fission and activation products. Two types of material are considered in (Verhoef, 2015: p.24): (1) neutron-activated ferro and non-ferro metals from dismantled experiments and from claddings and other (non-fissile) parts of irradiated fuel elements; and (2) organic material contaminated with activated metal and volatile fission products such as cesium. Presently, there is no quantitative inventory of irradiated metals and organic material available. An estimation of the waste matrix composition can be found in (Verhoef, 2015: p.24).

The degradation of non-heat generating HLW was not studied in OPERA. An instantaneous release of radionuclides from waste fraction non-heat generating HLW was therefore (conservatively) assumed in OPERA.

5.2.3.4 Degradation of LILW

Depleted uranium has the largest volume of the LILW fractions. The tails remaining after the enrichment process are converted to solid uranium oxide (U_3O_8) and stored at COVRA. Currently it is assumed that the depleted uranium will be conditioned with concrete for disposal (Verhoef, 2015: p. 26), (Verhoef, 2014b: p.9).

The compacted LILW originates from nuclear power plants, industry and hospitals. This waste fraction is mainly comprised of cellulose, plastic and metal. A tentative average composition quantification of compacted LILW stored at COVRA is listed in (Verhoef, 2015: p.28).

Liquid waste from molybdenum production and liquid wastes with spent ion are conditioned with concrete and stored at COVRA and intended for final disposal. An estimation of the matrix composition of these types of wastes is given in (Verhoef, 2015: p.33&36).

The degradation processes and products of low-intermediate level waste (LILW) in the OPERA disposal concept repository in the geological host rock formation Boom Clay was investigated and discussed in (Filby, 2016). Particular LILW wastes fractions such as cellulose, plastics, rubbers, metals and depleted uranium were investigated in respect to their chemical, microbial and radiolytic degradation. Potential amounts of gas generated by metal corrosion or cellulose degradation were estimated. The main findings of the study presented in (Filby, 2016: p.117) are:

- Exact quantities and formulation of plastics, rubbers, ion exchangers and cement additives are not available. The prediction of their degradation rates and degradation products under repository conditions is therefore not possible.
- An instantaneous release of radionuclides from the compacted waste can be assumed. For processed liquid molybdenum waste, the waste with ion exchangers and depleted uranium, an instantaneous release of the radionuclides can be assumed after corrosion of the particular containers. The concentrations of the particular elements in the cementitious pore water will be controlled by their solubility.
- The solubilities determined by thermodynamic equilibrium calculations would represent the maximum released radionuclide concentration. Solubilities may be enhanced by certain organic ligands.
- Cellulose degradation kinetics has large bandwidths regarding the degradation rates. No studies regarding the degradation kinetics of other organic materials under alkaline conditions exist.

In the present OPERA disposal concept no additional engineered containment of the LILW containers is foreseen. As a consequence, the LILW waste may start to leach (slowly) relatively soon after closure (Grupa, 2016: p.18).

5.2.3.5 Gas generation

Gas generation under repository conditions depends, amongst others, on the waste category. LILW contains considerable amounts of biodegradable cellulosic material and can result in significant volumes of CH_4 and CO_2 in the first hundreds to 1000 years after disposal. HLW is expected to generate less gas and will result mainly in H_2 from anaerobic metal corrosion. Bacterial processes may then transform (in presence of carbon) H_2 into CH_4. Gas production by radiolysis is significantly smaller than by metal corrosion and organic biodegradation. The effects of temperature on gas generation are judged limited since the temperature increase of the engineered barriers and the surrounding host rock are relatively mild due to the extended surface storage period adopted in the Netherlands.

5.2.4 Expected evolution of main processes and parameters

In the OPERA performance assessment, the safety function of the waste form to limit the contaminant releases is collected in the parameter *release rate*. For illustration purpose, an overview of the waste release rates used as default values for the Central Assessment Case in OPERA is given in **Table 1-15** (Schröder, 2017c: Section 3.3.3).

Table 1-15: Overview of radionuclide release rates used for the central assessment case in the OPERA PA (Schröder, 2017c: p.21)

Disposal Section	Release rate λ_{rel} [1/a]		
Vitrified HLW	Slow	Base case	Fast
	$8.9 \cdot 10^{-6}$	$5.2 \cdot 10^{-5}$	$3.5 \cdot 10^{-4}$
Spent Fuel	∞		
Non-heat generating HLW	∞		
Depleted uranium	∞		
LILW	∞		

5.2.5 Candidate processes and parameters for monitoring

Based on the events and processes listed in Table 1-10, a preliminary list of processes related to the scenarios considered in this study (see Section 3.3) with potential hazard for the safety function *Limit contaminant releases from the waste forms* (R1) and related parameters is summarised in the table below.

Table 1-16 Processes and parameters for monitoring of the OPERA Waste Form

Safety function	Process (FEP Nr.)	Parameter	Reference
Limit contaminant releases from the waste forms (R1)	Dissolution (2.3.04.06)	pH	Deissmann, 2016a
		Temperature	Deissmann, 2016a
		Pore water composition	
		Saturation	
	Organic degradation (2.3.07.02)	pH	Filby, 2016
		Pore water composition	
		Ligand concentration	

5.3 Waste containers (OPERA Supercontainer)

Because one of the main requirements of the safety function "Containment" is to provide isolation of the waste during the thermal phase (Verhoef, 2014a: Appendix), it applies only to HLW waste fractions, which are disposed of in the so-called 'OPERA Supercontainer'. Therefore in this section only this container type is discussed.

5.3.1 Properties and features of the Supercontainer

As already mentioned in Section 2.6, a Supercontainer is foreseen to be used in the OPERA disposal concept for conditioning of the heat-generating HLW, spent fuel from research reactors, and the non-heat generating HLW (legacy waste and decommissioning waste). These waste fractions comprise 98.7% of the total activity and 99.0% of the total radiotoxicity at the time of disposal. An outline of the OPERA Supercontainer is depicted in **Figure 1-13** (Verhoef, 2014a: Figure 5-5; Arnold, 2014: Figure 2.17).

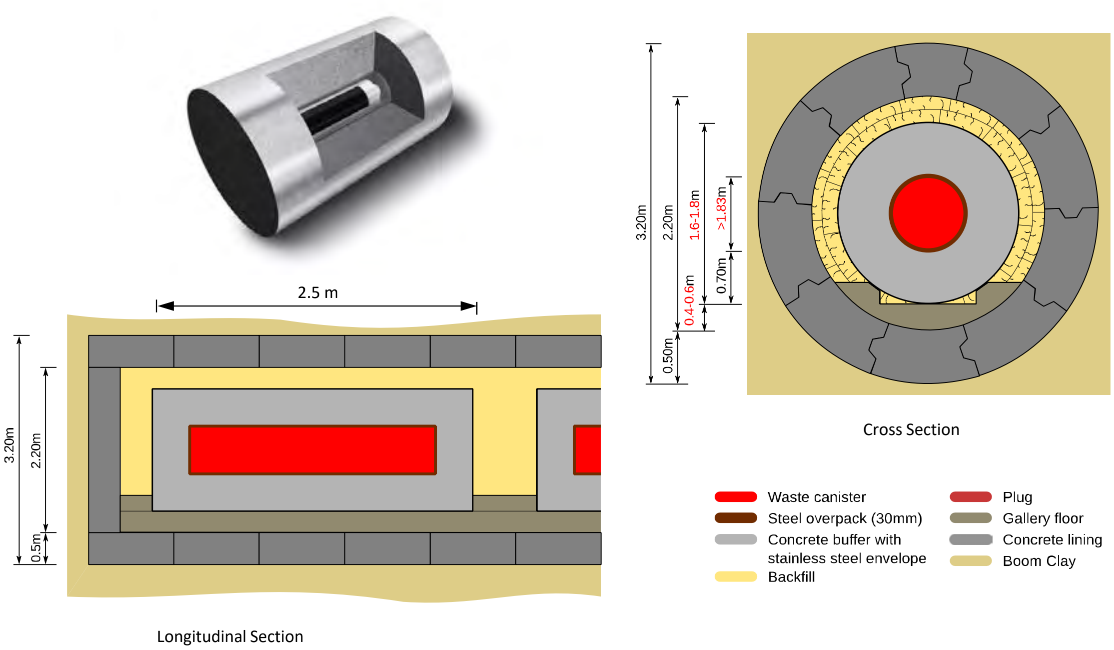


Figure 1-13 Schematic outline of the Supercontainer concept for HLW disposal in Boom Clay.

The OPERA Supercontainer is adopted from the Belgian Supercontainer concept, and consists of a carbon steel overpack, a concrete buffer and stainless steel envelope. Being smaller in size than the Belgian Supercontainer, the size of the concrete buffer of the OPERA Supercontainer is determined by the requirement of radiation shielding and the size of the waste canisters. Advantages of the use of Supercontainers include (Verhoef, 2014a: p.15):

- The construction, assemblages and quality assurance of the Supercontainer can be done above ground;
- The concrete buffer provides radiation shielding to protect the workers during waste handling in the operational phase;
- The decay heat is spread over a larger outer surface, simplifying the handling of the heat producing HLW;
- The concrete buffer impedes the corrosion of the stainless steel canisters.

The OPERA container can accommodate canisters for heat-generating vitrified HLW (CSD-V), spent fuel from the Dutch research reactors (SF), compacted high-level waste residues from reprocessing (CSD-C), and other non-heat generating HLW. The Supercontainers with a length of 2.5 meter can hold one CSD-V or CSD-C canister, whereas the Supercontainers with a length of 3.0 meter can hold two canisters with spent fuel from research reactors or other non-heat generating waste.

The present concept of the Supercontainer is foreseen to have a steel envelope for serving as a mould for construction of the concrete buffer, acting as a first barrier against aggressive species if present, providing mechanical strength and confinement, and facilitating retrievability (ONDRAF/NIRAS, 2013: p.73).

Concrete buffer thickness is a balance between among others (1) transportability and handling inside the facility, also with respect to retrievability; (2) radiation shielding and heat dissipation, as well as (3) buffer stability. Because of the longer interim storage in the Netherlands, heat generation and radiation are lower compared to the Belgian concept and package dimensions can therefore be reduced. The concrete shielding of the OPERA Supercontainer is designed to limit the potential radiation exposure to a maximum of 10 mSv per hour (maximum dose for transport of a collo).

The properties of the OPERA Supercontainer are summarized in Verhoef, 2014a (Verhoef, 2014a: Table A-5):

Table 1-17 Properties of the OPERA Supercontainer

Outer container diameter	1.9 m
Outer container length	2.5 m for 1 CSD and 3.0 m for 2 (ECN) containers
Waste container	one CSD-V-canister, one CSD-C-canister, or 2 SF containers
Concrete thickness	0.6-0.7 m
Steel overpack thickness	3 cm
Steel envelope thickness	0.4 cm
Max. dose rate at container surface	≤10 mSv/hr
Weight	Approx. 20 000 kg to maximal 24.000 kg

5.3.2 Safety functions and other functions of the Supercontainer

Table 1-18 summarizes the safety function of the OPERA Supercontainer as identified for the OPERA disposal concept from the above-mentioned references.

Table 1-18 Safety function of the OPERA Supercontainer

Safety Function	**Reference**
Prevent as long as required the release of contaminants from the waste container (C)	See Section 2.4

Table 1-19 summarizes more specific functions of the OPERA Supercontainer as identified for the OPERA disposal concept from the distinguished references, and which are judged to fit in the Modern2020 screening process.

Table 1-19 Other functions of the OPERA Supercontainer

Other functions	**Reference**
Carbon steel overpack	
Prevent contact between water and waste during the thermal phase	Verhoef, 2014a: Appendix
Concrete buffer	
Provide shielding during the operational phase	Verhoef, 2014a: p.15
Dissipate decay heat over a larger outer surface	Verhoef, 2014a: p.15
Limit the dose rate at the collo's exterior of the heat-generating HLW	Verhoef, 2014a: p.10
Provide sufficient radiological protection for (irradiated) fissile materials during the thermal phase	Verhoef, 2014a: Appendix
Impede corrosion of the stainless steel waste containers	Verhoef, 2014a: p.15
Preserve a favourable chemical environment in the immediate vicinity of the metallic overpack during at least the thermal phase	Weetjens, 2012: p.54
Adsorb deformations induced by the host rock	Arnold, 2014: p.68
Steel envelope	
Serve as a mould for construction of the concrete buffer	ONDRAF/NIRAS, 2013: p.73
Serve as a first barrier against aggressive species	ONDRAF/NIRAS, 2013: p.73
Provide mechanical strength	ONDRAF/NIRAS, 2013: p.73
Facilitate retrievability	ONDRAF/NIRAS, 2013: p.73
Sustain thermal stresses	Verhoef, 2014a: Appendix

5.3.3 Identification and description of related main processes

The loss of integrity of the engineered containment provided by the Supercontainer requires a number of subsequent steps and processes before the waste in the failed canisters can come into contact with the near field water at some point in the (far) future, such as (Deissmann, 2016a: p.39):

- (fast) resaturation of the repository backfill;
- corrosion/failure of the stainless steel envelope;
- re-saturation of the concrete buffer;
- corrosion/failure of the carbon steel overpack, and finally
- corrosion/failure of the waste canister,

The following sections provide more detail about identified processes, and related parameters.

5.3.3.1 Thermal processes

The main heat source in the repository system is provided by decay of high-level radioactive waste, but other sources including exothermic chemical reactions (short term) or persisting temperature changes at the surface may also contribute to the heat production. However, the heating effect of cement hydration reactions in the repository is expected to be minor because much of the concrete to be emplaced in the repository will have cured and cooled at the surface (Weetjens, 2012: S.4.4.1).

High-level radioactive wastes generate considerable amounts of heat through radioactive decay. In the short-term, i.e. the first decades after irradiation in a power reactor, the radionuclide couples Sr-90/Y-90 and Cs-137/Ba-137m determine the heat production. After a few half-lives of Sr-90 and Cs-137 (both have a half-life of about 30 years), the heat production is determined by the long-lived actinides (especially Pu-239, Pu-240 and Am-241). Since vitrified HLW contains relatively small amounts of actinides compared to spent fuel the heat production in vitrified HLW decreases more rapidly than in spent fuel.

Waste loading, disposal density, and thermal properties of EBS and host rock determine the required on-surface cooling time. Considering the Dutch waste categories, only vitrified HLW (CSD-V containers) produces a significant amount of decay heat. After the heat-producing radioactive waste is emplaced and the repository is closed, the disposal system will undergo a transient period on a large spatial scale and in a relatively short period, i.e. several decades. Dissipation of the heat through the engineered barriers and Boom Clay is expected to occur mainly by conduction.

The resulting temperature transients for various types of heat-producing waste were calculated in (Weetjens, 2012), resulting in estimated peak temperatures around 100°C in the concrete Supercontainer buffer close to the overpack, and an extensive zone of elevated temperature in the Boom Clay with a peak of more than 70°C within 1-2 decades. These peak temperatures depend on the properties of the waste, the design of the engineered barriers, thermal properties of the involved materials, and the spacing between the disposal galleries. The thermal disturbed zone will extend to the whole thickness of Boom Clay although the temperature change decreases rapidly with distance (Weetjens, 2012: S.4.4.1).

The temperature transients estimated in (Weetjens, 2012) relate to the Belgian context which is different from the situation in the Netherlands. Currently, in the Dutch context, the cooling time considered for radioactive waste is at least 100 years after unloading from the reactor (compared to 60 years in Belgium). Additionally, in the OPERA disposal concept the Supercontainer would hold only *one* CSD-V canister, whereas in the Belgian concept the Supercontainer would hold *two* vitrified HLW canisters. These two features *significantly* reduce the total heat output from the contained waste and the resulting temperature increase for the Dutch situation compared to the Belgian one. Provisional (unpublished) calculations indicate that in the OPERA disposal concept the peak temperatures would be limited to about 40 degrees in the concrete Supercontainer buffer, and about 30 degrees in the Boom Clay within 1-2 decades after disposal.

The limited expected temperature increase expected for the OPERA disposal concept also limits the impact of temperature dependent processes.

5.3.3.2 Resaturation

In OPERA, the evolution of the near-field conditions (e.g. regarding water saturation of the repository components, temperature evolution, and pH conditions) in the HLW/SF-section of the OPERA disposal facility have been addressed by (Kursten, 2015) and (Seetharam, 2015). The timescale of resaturation of the repository is mainly dependent on the unsaturated hydraulic properties of the EBS materials and the Boom Clay, the porosity/permeability of the cementitious materials, the hydraulic conductivity of the Boom Clay and the hydraulic gradient. The time frame of resaturation of the Supercontainer concrete and thus the ingress of corroding species at the carbon steel overpack will depend on the lifetime and failure mechanisms of the outer steel envelope. This depends on the time of failure of the outer steel envelope which, under repository conditions, will mainly be susceptible to localized corrosion, e.g. high chloride concentrations could lead to pitting corrosion. Based on reported corrosion rate data (Kursten, 2015: p.71), failure times of the outer steel envelope may range from about 1700 to 800’000 years.

5.3.3.3 pH evolution

The chemical and physical conditions in the repository near-field will be determined by the large amounts of hydrated cements for long periods of time. The degradation of the engineered barriers and the evolution of the geochemical conditions will occur due to the disequilibrium between the chemical conditions in the cementitious materials and the groundwater infiltrating into the near-field. In the long-term the cementitious materials will be leached, by which the geochemical conditions in the near field will be adjusted to the conditions of pore water in the surrounding host rock.

The evolution of the cementitious materials, pore water pH and chemistry in the repository near field under leaching conditions in the post-closure phase is commonly described by various stages, defined by different pH ranges in the pore water and associated buffering phases. In addition to the changes in the chemical conditions and the pH buffering capacity due to the dissolution of hydrated cement phases, also the physical/hydraulic properties (porosity, permeability, and tortuosity) of the cementitious barrier materials are affected.

The duration of the various stages and the timescales of pore-water evolution depend on various factors, including the pore volume of the cementitious materials and the connectivity of pore spaces, the hydraulic conductivity of the host rock and the hydraulic potentials, and the groundwater composition and the concentration of potentially deleterious components (e.g. magnesium and sulphate). The expected evolution of the pH at the interface between cement and Boom Clay is depicted in Figure 4-1 (Deissmann, 2016a: Figure 4-1). This figure shows that, from the viewpoint of the practicability of process monitoring, only the pH of "young" cement water may be feasible to determine.

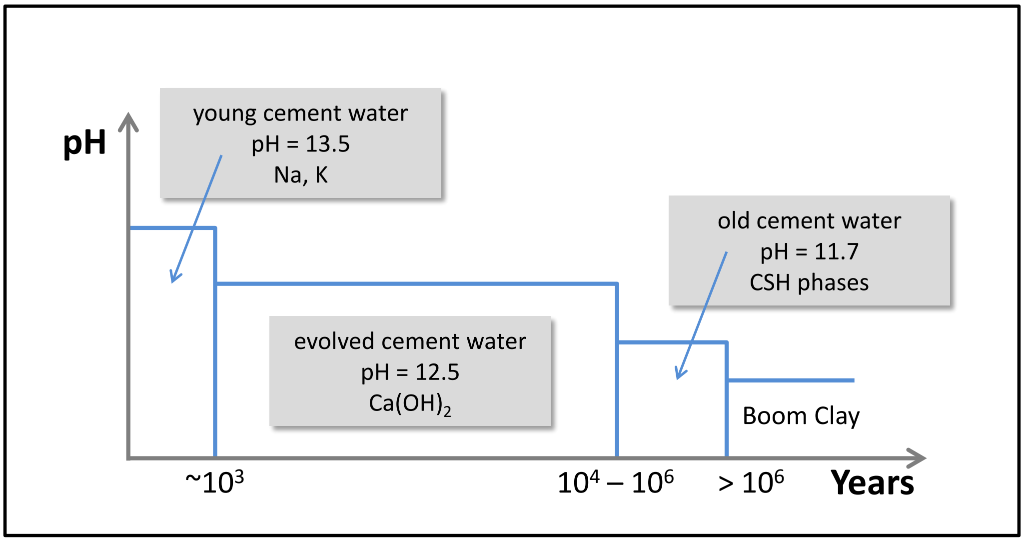


Figure 1-14 Evolution of the pH in the pore water at the interface between cement and Boom Clay.

5.3.3.4 Corrosion, chemical and mechanical degradation

(Wang, 2009) performed scoping calculations of the geochemical evolution in the cementitious repository near-field relevant for the Belgian Supercontainer concept, taking into account the reference pore water composition in the Boom Clay at Mol, Belgium. Depending on the dominant corrosion products of the metallic barriers under anaerobic conditions, i.e. either magnetite or $Fe(OH)_2$, redox potentials were estimated at the surface of the metallic barriers. The redox potentials are assumed to be around or below -800 mV as long as some uncorroded iron/steel remains. This phase was expected to be followed by the establishment of redox conditions controlled by the redox potential of the in-diffusing Boom Clay pore water at about -300 mV.

Concrete provides a highly alkaline chemical environment that leads to the formation of a thin but dense and impenetrable oxide/hydroxide layer (the so-called 'passive' film) on the surface of the steel that will protect the underlying metal (Seetharam, 2015: Section 3.4). If local breakdown of the passive film occurs (by e.g. carbonation, ingress of aggressive species such as Cl^-, etc.), corrosion products may form at the steel/concrete interface which will induce mechanical forces (expansive stresses) on to the surrounding concrete, which, eventually, can result in cracking of the concrete layer. These cracks in turn provide a pathway for the rapid ingress of aggressive agents to the steel surface, which can accelerate the corrosion process.

In a repository facility constructed in a deep geological clay formation, the environmental conditions will ultimately evolve to anaerobic conditions. Under these reducing conditions, corrosion rates are predicted to be very low and the formation of corrosion products will be rather limited.

The degradation of concrete was investigated as part of the OPERA program (Seetharam, 2015). The *chemical* degradation was found to cover major long term processes such as (i) decalcification and leaching, (ii) carbonation mainly under saturated condition, (iii) sulphate attack, (iv) chloride ingress, and (v) degradation because of interaction of cement with the waste form. The *mechanical* degradation covers major processes such as mechanical consequences associated with (i) decalcification and leaching, (ii) carbonation, (iii) sulphate attack, (iv) corrosion induced cracking, (v) long term temperature variation, and (vi) long term creep. Apart from the characteristics of the cement, aggregates and additives used in the makeup of the candidate concrete or mortar, the main drivers for these degradation processes are the native pore water composition, chemical nature of the waste form, presence of steel, saturated conditions, thermal field, availability of oxygen and diffusion.

A consequence of corrosion is the release of hydrogen gas produced by corrosion of the metallic waste or metallic parts of the EBS. If the (expansive) gas pressure exceeds the tensile strength of the surrounding concrete under the confining (overburden) pressure, local cracks can develop. Whether or not the resultant cracks form continuous or discrete pathways depends upon the existing cracks and involves complex, very long-term processes (Seetharam, 2015: Section 3.4).

Stress corrosion cracking requires a certain minimum stress level before it can occur, and could affect the physical integrity of EBS components.

The degradation of concrete components, e.g. due to decalcification and leaching, is a very slow process requiring tens of thousands of years to leach out. For the OPERA reference scenario (normal evolution scenario), it is assumed that the conditions in the Supercontainer pore water at the time of canister failure are representative for the stage II of concrete degradation (cf. **Figure 1-14**), and that the expected lifetime would be up to several 100,000 years (Deissmann, 2016a: Ch.6).

5.3.3.5 Effects of electrochemical gradients

After disposal electrochemical gradients may be present within the waste and/or the EBS and induce a number of processes (Schelland, 2014). For example, galvanic coupling refers to the establishment of an electrical current through chemical processes. Electrophoresis is the motion of charged particles in a colloid under the influence of an applied electric field. Electrochemical gradients may be established in the Supercontainer owing to the presence of various metals in the Supercontainer outer steel envelope, overpack and waste. Electrochemical effects may also arise from different local micro-environments (e.g. Eh, pH) on the surface of these metals. Natural currents occurring in the ground, known as “telluric currents”, may also create electrochemical gradients.

Galvanic coupling and electrochemical gradients may influence corrosion of the Supercontainer overpack and envelope and affect the mobility of charged radionuclide species (by electro-osmosis) and particulates (by electrophoresis) in the EBS.

5.3.3.6 Mechanical effects/processes

The stress field in the Supercontainer will be determined by the regional stress field and by local changes to the stress field caused by excavation, waste emplacement and thermal evolution. After re-saturation of the repository, the Supercontainer will be subject to hydrostatic pressure. Changes to these stresses could damage components of the EBS (Schelland, 2014).

The Supercontainer could be mechanically disturbed by physico-chemical degradation of the buffer, external forces (e.g. tunnel roof or lining collapse, rock creep or faulting in near-field rock), volume increase of corrosion products, and/or the build-up of internal gas pressure (Schelland, 2014). These disturbances could cause processes such as cracking, and movement of the overpack through the buffer. However, these processes are considered unlikely for the rigid Supercontainers (Schelland, 2014).

It is supposed in the normal evolution scenario that there are no inhomogeneities in the concrete buffer of the Supercontainer and therefore flow pathways will be absent (Schelland, 2014). A preferential pathway is seen as a consequence of a failure, rather than the cause of a failure. Preferential pathways may be formed by stress-related processes and may lead to faster migration of water to the waste packages and vice versa, or a local dominance of advection. Preferential pathways are avoided by design, at least for the thermal phase (cf. **Figure 1-6**).

5.3.3.7 Radiation effects

Radiation effects relate to any damaging effects as a result of the transfer of radiant energy from the radioactive waste containers to neighbouring materials, including the buffer and other components of the EBS. Examples of relevant effects are ionisation, radiolytic decomposition of water, radiation damage to waste matrix or Supercontainer materials, and helium gas production due to alpha decay. Radiation may affect the mineralogy and structure of the materials.

In the OPERA disposal concept the effects of radiation are considered small (1) due to the extended surface storage period, (2) the isolating properties of glass (in the case of vitrified HLW) and steel, and (3) the presence of the concrete Supercontainer.

The main contribution to radiation effects comes from gamma-emitting nuclides. However, the level of gamma radiation decreases rapidly. A first estimate of the duration of radiolysis effects in the Supercontainer is about 300 years, which is ten times the half-life of Cs-137, the main source of gamma radiation (ONDRAF/NIRAS, 2013: p.177). Radiolysis of concrete pore water may in principle influence redox conditions and generate hydrogen, oxygen, and other oxidising radicals. However, the effects of these oxidising radicals will be transient, and limited as a result of the extended surface storage period in the Netherlands.

5.3.3.8 Biological processes

Microbes may survive under alkaline conditions and areas of enhanced microbial activity may develop. Microbes and metabolites of microbes may form complexes with some radionuclides. Dissolved in the pore water, these metabolites may decrease sorption on the solid phase and affect the solubility of the radionuclides concerned (Schelland, 2014). However, microbial activity is highly unlikely considering the unfavourable conditions close to the overpack owing to the high pH, enhanced temperature and the small size of the pores in the buffer concrete (Kursten, 2015: p.23).

5.3.4 Expected evolution of main processes and parameters

Table 1-20 summarizes a range of failure times for the Supercontainer to be used for the performance assessment calculations under the assumption of a pH of 12.5 (Neeft, 2017). From this table it is clear that detection of an "expected" failure of Supercontainers is likely beyond a practical time period for monitoring. Note however that for the alternative evolution scenarios EEC1 and ECC1 an early containment failure is assumed (see Section 3.3).

Table 1-20: Supercontainer failure times to be used in the NES *central assessment case* (N1)

	Time of Supercontainer failure $t_{failure}$ [a]
Early container failure case (**EF**)	1000
Failure base case (**DV**)	35’000
Late container failure case (**LF**)	70’000

5.3.5 Candidate processes and parameters for monitoring

Based on information provided by the Belgian and Dutch programs on geological waste disposal a number of processes and related parameters were identified that play a role in safety aspects of the OPERA Supercontainer. **Table 1-21** summarizes the candidate processes and parameters for the monitoring of the OPERA Supercontainer based the safety functions of the Supercontainer as given in Table 1-18. Table 1-22 gives a condensed overview of these features for the various parts of the Supercontainer based on the functions of the Supercontainer identified in Table 1-19.

Table 1-21 Candidate processes and parameters for monitoring of the OPERA Supercontainer, related to safety functions

Safety Function	Process	Parameter	Comment	Reference
Prevent as long as required the release of contaminants from the waste container (C)	• Creep • Stress • Corrosion	• Pressure • H_2 generation	Long-term process, except for early containment failure	Schelland, 2014 (EBS)
	• Biological processes	• Gas generation	Due to microbe metabolism; considered less relevant for Supercontainer	Schelland, 2014; Kursten, 2015: p.23

Table 1-22 Candidate processes and parameters for monitoring of the OPERA Supercontainer, related to other functions

Function	Process	Parameter	Comment	Reference
Carbon steel overpack				
Prevent contact between water and waste during the thermal phase	• Mechanical disturbance	• Stress (pressure)	Overpack welds may be subject to “cold cracking”	Schelland, 2014 (EBS)
	• Steel corrosion	• H_2 generation • Chemical conditions in buffer pore water • Electrochemical gradients	After water ingress	Verhoef, 2014a: Appendix; Schelland, 2014
	• Stress corrosion cracking	• H_2 generation • Pressure • Stress	Localized phenomenon; related to welding	Kursten, 2015: S.3.3 Schelland, 2014
	• Volume increase	• Mechanical stress	Due to formation of corrosion products	Schelland, 2014
	• Water ingress	• Humidity • water presence	Resaturation after emplacement (few decades) Flooding (AES)	Schelland, 2014
Concrete buffer				
Provide sufficient radiological protection during the operational and thermal phase	• Radioactive decay	• Dose rate	Mostly relevant during waste emplacement (shielding)	Verhoef, 2014a: p.15 and Appendix
Dissipate decay heat over a larger outer surface	• Heat transport	• Temperature	T-effects limited (extended storage)	Verhoef, 2014a: p.15
Impede corrosion of the stainless steel waste containers	• Cracking	• Stress	Corrosion-induced cracking	Verhoef, 2014a: p.15; Seetharam, 2015: S.3.4
	• Geochemical evolution	• Redox potential	Pore water / concrete interaction	Deissmann, 2016a; p.23
Preserve a favourable chemical environment in the immediate vicinity of the metallic overpack	• Corrosion	• pH • pore water chemistry	High pH environment Aerobic (short term) Anaerobic (longer term)	Verhoef, 2014a: Appendix; Schelland, 2014

Function	Process	Parameter	Comment	Reference
during at least the thermal phase				
Adsorb deformations induced by the host rock	• Deformation of the buffer • thermal expansion • creep	• Pressure	Potential formation of preferential pathways	Arnold, 2014: p.68
Sustain thermally induced deformations during the thermal phase	• Thermal expansion • creep	• Pressure • Temperature	Potential damage of the SC	ONDRAF/NIRAS, 2013: p.204
Steel envelope				
Serve as a first barrier against aggressive species	• Steel corrosion	• H_2 generation • Chemical conditions in buffer pore water • Electrochemical gradients	Due to interaction with Boom Clay pore water	Verhoef, 2014a: Appendix Schelland, 2014
Provide mechanical strength	• Creep • Failure of steel envelope • crack development	• Pressure • Stress	Due to external forces (Boom Clay, overburden)	ONDRAF/NIRAS, 2013; p.73; Schelland, 2014
Sustain thermal stresses	• Creep	• Temperature • Pressure	T-effects limited (extended storage)	Verhoef, 2014a: Appendix

5.4 Backfill

5.4.1 Properties and features of the backfill

In the OPERA concept (Verhoef, 2014a: p.13) the disposal drifts are backfilled with grout and hydraulically sealed off using a plug (see **Figure 1-15**).

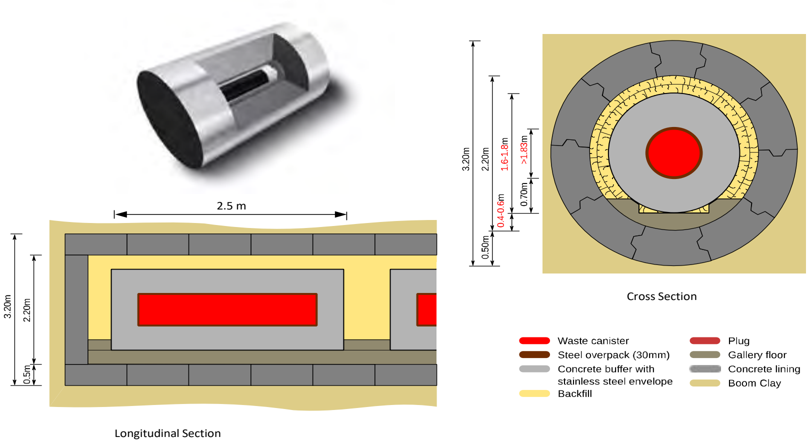


Figure 1-15 Artist impression of the HLW waste sections (from (Verhoef, 2014a: p.14)).

The backfill is a key component of most geological disposal concepts and, consequently, a detailed understanding of its long-term behaviour and how it interacts with the waste package is essential. The specific safety functions provided depend on the choice of backfill material(s) and the role of this barrier within a particular disposal system. The required characteristics of the buffer/backfill are highly dependent on the role that this barrier plays in specific disposal concepts and it is therefore difficult to define these properties at a generic level (NEA, 2012b: p.124). Factors that might be considered include (NEA, 2012b: p.124):

- The strength of the material;

- Its permeability to ingress by ground- and/or pore water and gas;
- The surface area of the material, and its ability to provide sites for sorption processes;
- The ability of the material to chemically condition the near-field environment, for example, by buffering the pH and/or the redox potential, so that it remains within a particular range over long time periods.

Requirements for chemical composition of all cementitious materials for the OPERA disposal concept were defined in (Verhoef, 2014b).

The EBS materials must have a low hydraulic conductivity ensuring transport of contaminants by diffusion only. At the same time, a low hydraulic conductivity reduces the gas permeability which may be detrimental in case of excessive formation of gas. High-pH concrete favours the longevity of the steel components but at the same time its leachates may have detrimental effects on the Boom Clay properties and the durability of the waste matrix.

5.4.2 Safety functions and other functions of backfill

Functions of the backfill are to enclose the emplaced waste during the operational phase and to prevent the waste packages coming into contact with water in the unlikely case of flooding of the facility (Verhoef, 2014b: p.4). In the OPERA concept, the backfill material which fills the void between the Supercontainer and concrete lining primarily serves to hold the Supercontainer in place, and to eventually adsorb deformations induced by the host rock, to contain radionuclides, to transport the potential heat from the Supercontainer and to create a favourable geochemical environment to limit corrosion and leaching (Arnold, 2014: p.67). The backfill should also prevent cave-in of the Supercontainer when - in the post-closure phase – the concrete segments in the lining no longer provide sufficient mechanical support (Verhoef, 2014b: p.9).

The presence of backfill and seals will ensure that transport within the repository after closure will be diffusion-dominated (ONDRAF/NIRAS, 2013: p.34).

From the characteristics and requirements for backfill given in (Verhoef, 2014a: p.13) the following functions of the of the backfill can be deduced: (1) provide additional support to the disposal drifts, and, in a later stage, the secondary galleries; (2) facilitate retrievability; and (3) match the thermal properties of the surrounding clay and enable sufficient dissipation of the decay heat from the containers in the heat-generating HLW-section into the Boom Clay. To ensure retrievability backfill should be used which can be relatively easily excavated. The suitability of foam concrete made with Portland cement as a backfill material is investigated in OPERA (Verhoef, 2014b).

The gas formation and transport is extensively studied in many national programs on geological disposal of radioactive waste. However, the gas formation and gas transport properties under in-situ conditions are still a subject of investigation. Formation of gas within a geological repository is unavoidable and in case the generated amount of gas exceeds the amount than can be evacuated by diffusion, a gas phase may form and consequently a two-phase flow through the engineered barriers and/or host formation may occur. This may lead to the formation of discrete gas pathways through the engineered barriers and host formation and impact the hydraulic and mechanical properties of the engineered barrier and possibly even parts of the host formation. Consequently, the safety functions of the EBS, including the backfill, and host rock may be impaired.

The safety function of the OPERA backfill, Limit the water flow through the disposal system (R2), is indicated in Table 1-23.

Table 1-23 Safety function of the OPERA backfill

Safety function	**Reference**
Limit the water flow through the disposal system (R2)	see Section 2.4

The functions of the OPERA backfill specified in (Verhoef, 2014a: p.13), (Verhoef, 2014b), (ONDRAF/NIRAS, 2013) and (Arnold, 2014: p.67) are summarized in the table below.

Table 1-24 Other functions and design objectives of the OPERA backfill

Function	Reference
Provide additional support to the disposal drifts, and, in a later stage, the secondary galleries	Verhoef, 2014a: p.13
Hold Supercontainer in place and adsorb deformations induced by the host rock	Arnold, 2014: p.67
Minimise the impacts of external events such as earthquakes, by absorbing shear displacements so that they do not rupture the package	NEA, 2012b: p.124
Facilitate retrievability	Verhoef, 2014a: p.13
Match the thermal properties of the surrounding clay and enable sufficient dissipation of the decay heat from the container into the Boom Clay	Verhoef, 2014a: p.13
Ensure diffusion-dominated transport within the repository after closure	ONDRAF/NIRAS, 2013: p.34
Limit the migration of chemical and microbial species, which might enhance canister degradation, to the package surface	NEA, 2012b: p.123
Provide favourable geochemical environment to limit corrosion of the containers and subsequent leaching of radionuclides	Verhoef, 2014b: p. 5; Arnold, 2014: p.67
Keep the gas pressure below the magnitude at which preferential pathways within the host rock would start to develop.	Norris, 2013: p.17

5.4.3 Identification and description of related main processes

The backfill needs to remain mechanically stable as well as chemically compatible with other repository components for the long term. The backfill should also contribute to a preferential radionuclide migration through the host formation.

The performance of the cementitious backfill will evolve due to several processes. The processes in the concrete can be of physical (e.g. physical damage, aggregate expansion, crystallisation, cracking), chemical (e.g. hydration, reaction with groundwater solutes, carbonation, reaction with wastes and waste degradation products), biological (bacterial corrosion) or thermal nature. The main processes and associated backfill properties are shortly discussed in the following. The key processes affecting cementitious materials were discussed in a Workshop organised by the OECD/NEA Integration Group for the Safety Case, Radioactive Waste Management (NEA, 2012b). The perceived significance of the key processes affecting cementitious materials is summarised in Table 1 in (NEA, 2012b: p.23) and reproduced in the table below.

Table 1-25 Perceived significance of key processes affecting cementitious materials

Key process	Effects of limited impact	Effects of higher impact
Radiation	-	Pore water composition, saturation
Mechanics (cracks)	Early structural failure of barriers, seepage	Mechanical and transfer properties Chemical evolution
Waste chemical composition	-	Solid phase composition
Corrosion products	Radionuclide sorption on cements	Mechanical and transfer properties (gas production)
EBS composition	Composition of element pore water	Chemical composition/cement formulation
Hydraulic conditions	-	Pore and groundwater composition

The main effect of radiation would be on the pore water composition, in particular on the redox conditions. The significance of this process in cementitious backfill is however limited because of a limited radiation field because of (1) the presence of the OPERA Supercontainer, and (2) the extended surface storage period.

The mechanical evolution of the cementitious materials depends mainly on the boundary conditions and concrete type and considered structure (NEA, 2012b: p.24). The mechanical properties can be achieved by design and an appropriate choice of material.

The physico-chemical processes of the backfill may have an impact on its permeability and diffusion properties. The chemical evolution depends on the composition of the deposited wastes and used materials. The expansion of the corrosion products may cause a significant mechanical damage.

Hydraulic conditions affect the fluid flows as well as pore water composition, chemical evolution and radionuclide transport and the consequences of hydrological changes are difficult to assess without site-specific information (NEA, 2012b: p. 24). Because of a lack of knowledge regarding the influence of microbial processes on cementitious materials, these processes could not be assessed.

Migration through the backfilled tunnels and shafts represents a potential pathway of the released contaminants to the biosphere. In (ONDRAF/NIRAS, 2009: p.32) is stated that although the backfill will have a higher permeability than the Boom Clay, there are no significant hydraulic pressure gradients expected to drive flow following repository saturation, and significant advective contaminant transport through the backfill is not expected. The transport along backfilled tunnels and shafts is therefore expected to be slow and diffusion-dominated.

The main processes and associated backfill properties will be shortly discussed in the following.

5.4.3.1 Chemical processes and properties

The following chemical processes have been identified to impact the concrete (NEA, 2012b: p.15):

- leaching
- reaction with groundwater solutes
- hydration and crystallisation
- reaction with waste, waste degradation products and non-cementitious waste forms

The chemical processes in concrete due to the ingress of Boom Clay pore water cause a decrease in the pore water pH. The rate of the pH evolution is however difficult to quantify (NEA, 2012b: p.25). The high-pH (alkaline) pore water from cementitious materials favours the longevity of the steel components but at the same time may have detrimental effects on the Boom Clay properties and the durability of the waste matrix, especially vitrified HLW.

5.4.3.2 Mechanical evolution

Although the physical evolution of concrete barriers under repository conditions is adequately known in broad terms, existing disposal programs so far lacked explicit representations of time-dependent physical degradation of cementitious barriers (NEA, 2012b: p.19). Representations of time-dependent changes were attempted mainly in safety cases for disposal facilities for LLW and ILW and were usually represented by step changes rather than gradual ones (NEA, 2012b: p. 19-20). However, the uncertainties regarding the long-term physical evolution of cementitious structures are not considered critical in a safety case (NEA, 2012b: p. 19).

5.4.3.3 Microbial processes

Microbes are likely to be present in a disposal facility but their effect on concrete corrosion is uncertain (NEA, 2012b: p.29). Microbial activity can enhance the corrosion rate. However, the high pH provided by cementitious materials will inhibit the microbial activity. Gas bubbles trapped in voids may provide niches were microbial activity is allowed to develop.

It is assessed that biological activity, increasing the inorganic carbon concentration in the pore water, has a negative effect on concrete durability (NEA, 2012b: p.238).

5.4.3.4 Radiation

The processes related to the radiation of cementitious materials as well as their consequences are not yet fully understood. The radiolysis of the cementitious materials pore water affects in particular its redox conditions. The significance of radiation related processes depends on the wastes and the intensity of the radiation field, and on various other competing factors that may control or influence the chemistry of the pore waters (NEA, 2012b: p.23-24).

The effect of radiation on the backfill properties will be negligible in the present Dutch context because of the radiation shielding provided by the OPERA Supercontainers.

5.4.3.5 Gas generation and migration

Gas generation and migration can potentially alter the hydraulic and mechanical properties of the repository (possibly the thermal and chemical properties as well) (Norris, 2010: p.4). Consequently, these processes could affect the safety function of the host rock to retard and spread in time the release of radionuclides (Norris, 2010: p.5).

Within a repository, gas is generated as result of chemical processes (anaerobic corrosion of metallic components, (microbial) degradation of organic matter, radiolysis, radioactive decay etc.). The gas generation rate depends on the waste components, but also on the repository design. For both vitrified HLW and spent fuel, the gas source term comes primarily from the corrosion of the C-steel overpack and to a smaller extent from the stainless steel envelope. The iron support to insert the spent fuel assemblies may also be a significant gas source (Norris, 2010: p.9). The vitrified waste itself is not considered to contribute to the gas generation. The radiolysis of the buffer components is a potential source of gas. Corrosion of the galvanised steel drums and potentially reinforcement bars in the concrete monolith are considered as major potential gas source term. Other potential gas sources include radiolysis of bituminised wastes (sludges from reprocessing and other sources), corrosion of various metals present in the waste, such as aluminium, zinc, zircaloy, cast iron, steel and microbial degradation of the organic materials (Norris, 2010: p.9).

After emplacement of waste and backfilling of the disposal tunnels and galleries, the repository will be gradually filled with water and the EBS materials will be resaturated. The resaturation rate depends on the initial saturation degree and hydraulic properties of EBS materials, and also on hydraulic gradient in the host rock and the thermal evolution of the repository.

An overview of the stages in gas migration is given in (Norris, 2010: p.14):

Table 1-26 Summary of distinct stages in gas migration (from Norris, 2010**: p.14)***

<table>
<tr><th colspan="2">Stage</th><th>Description</th><th>Gas migration</th><th>Conditions</th><th>Degree of liquid saturation S_l</th></tr>
<tr><td colspan="2">I</td><td>Gas can be dissolved in the liquid phase as soon as it is produced</td><td>Diffusive transport of dissolved gas</td><td>[gas] < solubility</td><td>S_l=1, saturated porous medium</td></tr>
<tr><td colspan="2">II</td><td>Formation of free gas phase, liquid starts to be expelled</td><td>Diffusive transport of dissolved gas</td><td>P_l <P_g<(P_l+gas entry value)</td><td>1- S_{gr} <S_l<1 Desaturation of EBS and host clay</td></tr>
<tr><td colspan="2" rowspan="2">III</td><td>Pores have desaturated to allow gas to start flowing</td><td>Principally advective flow but diffusive transport continues</td><td>(P_l+gas entry value)<P_g < breakthrough pressure of clay</td><td>Desaturation of EBS and host clay continues</td></tr>
<tr><td colspan="4">Note: For some host rocks at limited depths or with higher air entry value, (Pl + gas entry value) could be greater than minimal component of the principal tensor of total stresses and the system could go abruptly from stage II to stage IV.</td></tr>
<tr><td rowspan="4">IV</td><td rowspan="2">1st Hypo-thesis</td><td>Gas breakthrough occurs in the EBS and host clay.</td><td>Non-Darcian flow through preferential pathways</td><td>Pg ≥ breakthrough pressure of clay</td><td>Depends on the newly formed pore space, but further desaturation likely to be small</td></tr>
<tr><td colspan="4">Cyclic behaviour: Pg drops due to the release of gas after breakthrough. After the preferential pathways are closed owing to the self sealing capacity of the Boom Clay, Pg will build up again ... The cyclic behaviour goes on until the gas production rate becomes small enough for that the dissolved gas to be evacuated via the pore system, which may be desaturated initially but gradually saturates again.</td></tr>
<tr><td rowspan="2">2nd Hypo-thesis</td><td>Microfractures will form to release gas</td><td>Advective flow with deformation dependent flow parameters</td><td>P_g ≥ breakthrough pressure of clay</td><td>Depends on the newly formed pore space</td></tr>
<tr><td>Propagation of macrofracture</td><td>Non-Darcian flow through preferential pathways</td><td>When the combined effect of pore water displacement and formation of small-scale fractures no longer counterbalances the gas production rate and gas pressure.</td><td>Depends on the newly formed pore space</td></tr>
</table>

* Stage I & II are characterized by single phase flow and transport; stage III & IV by two-phase flow and transport. S_l = liquid saturation, S_{gr} = residual gas saturation, P_l = liquid pressure, P_g = gas pressure.

The use of appropriate backfill and sealing materials that ensure a release of a part of the gas along the engineered features of the facility would be a suitable design measure to limit gas pressure in the disposal cells and galleries (Norris, 2010: p.97).

5.4.3.6 Thermal processes and properties

The thermal loading from the heat-generating HLW may induce perturbations on each barrier. The compressive stress in the concrete components may increase due to thermal loading and become larger than the compressive strength imposed by the load of the host rock.

The concrete backfill should have a thermal conductivity that would ensure a Supercontainer temperature lower than 100ºC (Verhoef, 2014b: p. 8-9). In (Arnold, 2014) it was shown that the temperature rise will be limited due to the extended period of interim storage adopted in the Netherlands, and therefore the influence of the thermal load on the properties and evolution of the backfill will be limited as well.

5.4.4 Expected evolution of main processes and parameters

In the OPERA performance assessment model the backfill has not been modelled as a separate component (Schröder, 2017c). Reasons being that is that the delay of radionuclide migration provided by the EBS/backfill is small compared to the host rock. Furthermore, backfill material for the Dutch repository has not yet been specified (foamed concrete is proposed). Additional work is therefore required to be able to evaluate the evolution of the backfill in more detail.

5.4.5 Candidate processes and parameters for monitoring

Based on the information gathered in the previous sections a preliminary list of processes and parameters for backfill monitoring is given in **Table 1-27** and Table 1-28.

Table 1-27 Processes and parameters for monitoring of the OPERA backfill related to safety functions

Safety function	Process	Parameter	Comment	Reference
Limit water flow through the disposal system (R2)	(re-)saturation	pore pressure relative humidity	Gap between backfill and lining; leakage	ONDRAF/NIRAS, 2013: p.34
	diffusion dominated transport	hydraulic conductivity/ permeability	Slow process, difficult to establish	
		relative humidity		
		pore pressure		

Table 1-28 Processes and parameters for monitoring of the OPERA backfill related to other functions

Function	Process	Parameter	Comment	Reference
Provide additional (mechanical) support to the disposal drifts, and, in a later stage, the secondary galleries	mechanical load	stress	Requirement, QA; Controlled by chemical composition/ cement formulation	IAEA, 2014: Table I-1; Arnold, 2014: S.2.5
		strain		
		compressive strength		Verhoef, 2014b: S.4.3
Hold Supercontainer in place and adsorb deformations induced by the host rock	deformation	deformation	monitoring	
	container displacement	displacement	monitoring	
Facilitate retrievability	backfill excavation	compressive strength	Requirement, QA	Verhoef, 2014b: S.4.3
Match the thermal properties of the surrounding clay and enable sufficient dissipation of the decay heat from the container into the Boom Clay	thermal load (temperature evolution)	temperature	Limited temperature effects in OPERA concept (extended storage)	Verhoef, 2014a: p.13
	heat dissipation	thermal conductivity	Requirement, QA	
Keep the gas pressure below the magnitude at which preferential pathways in the host rock would start to develop.	gas formation	oxygen concentration	Due to corrosion	Norris, 2013: p.17; Jobmann, 2013: p.67
		hydrogen concentration		
		gas pressure		
	gas migration out of repository	gas pressure	Build-up of gas pressure needs to be verified	
	gas exchange with main galleries	Oxygen/ hydrogen concentration		
Provide favourable geochemical environment to limit corrosion of the containers and subsequent leaching of radionuclides	Boom Clay pore water composition	pH	Requirement, QA; Controlled by chemical composition/ cement formulation	Verhoef, 2014b: S. 5.1; Arnold, 2014: p.67

5.5 Disposal cell plugs

5.5.1 Properties and features of the disposal cell plugs

After the emplacement of the waste packages, the disposal drifts are backfilled with grout backfill and hydraulically sealed off using a plug (Verhoef, 2014a: p.13).

As part of OPERA Task 3.2 "*Design Modification*", the Delft University of Technology carried out a scoping study of the design requirements for plugs and seals as well as scoping calculations for the specific conditions expected in the Dutch geological context. The aim was to provide an initial design and approximate sizing of a plug system for the sealing off of disposal drifts of the OPERA disposal concept (see Section 2.6), and an assessment on the key issues, e.g. hydraulic conductivity, swelling pressure of the bentonite seal and material creep, so that a detailed design and performance assessment may be carried out at subsequent stages (Yuan, 2016b: p.3). The generic term *plug system* was used for a system providing mechanical support and hydraulic resistance, where the functions are however considered separated.

Following these considerations and other international radioactive waste programmes, two components of the plug system have been distinguished (see also Figure 1-16): (i) a concrete plug to mechanically support the bentonite seal and backfill, and transfer the loads into the surrounding host rock, and (ii) a bentonite seal to control water flow.

Two variations of conceptual plug designs have been assessed:

(A) with the concrete plug installed inside the tunnel lining;

(B) with the tunnel lining removed along the length of the concrete plug.

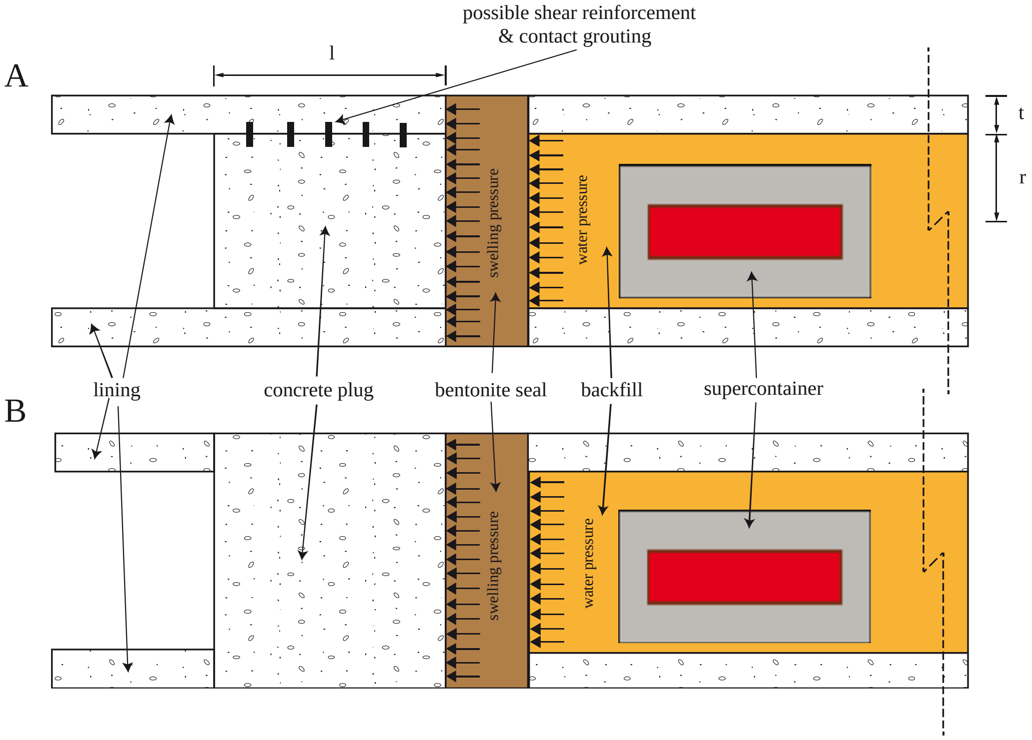


Figure 1-16 Conceptual plug designs considered in OPERA.

An important function of the concrete plug is to withstand the hydrostatic water pressure as well as the effective stresses of the surrounding rock and overburden. The bentonite seal, which is assumed to be (partially) desaturated upon instalment, cannot prevent water ingress unless it has reached sufficient saturation, so until that time the concrete plug should prevent leakage. After bentonite resaturation, the requirement of the concrete plug to be watertight is no longer necessary. Upon saturation the bentonite seal should prevent axial flow from the deposition tunnel, and seal off any cracks in the concrete plug that may be formed during the instalment of the plug system.

5.5.2 Safety functions and other functions of the disposal cell plug

The (safety) functions of the plug system, which have to be confirmed by further analyses in the Dutch research program, are summarized in Table 1-29 and Table 1-30 below.

Table 1-29 Safety functions of the OPERA plug system

Safety Function	Reference
Limit water flow through the disposal system (R2)	See Section 2.4

Table 1-30 Functions of the OPERA plug system and plug system components

Function	Reference
Concrete plug	
Mechanically support the bentonite seal and backfill	Yuan, 2016a: p.17
Carry effective stresses from the host rock	Yuan, 2016a: p.17
Prevent leakage until bentonite resaturation	Yuan, 2016a: p.17
Bentonite seal	
Prevent axial water flow from the deposition tunnel	Yuan, 2016a: p.17
Withstand a high hydraulic gradient	Yuan, 2016a: p.17
Seal cracks in the concrete plug upon resaturation (swelling)	Yuan, 2016a: p.17
Reseal the EDZ through swelling upon resaturation	Yuan, 2016a: p.17
Plug system	
Hydraulically seal off the disposal drift	Verhoef, 2014a: p.13
Keep the backfill in place	Yuan, 2016a: p.16
Limit erosion of backfill from the deposition tunnel	Yuan, 2016a: p.16
Limit and retard radionuclide releases in the event of canister failure	Jobmann, 2013: p.71

5.5.3 Identification and description of related main processes

A large effort considering the assessment of plugs and seals under repository conditions was performed in the EU FP-7 project DOPAS, *Full-Scale Demonstration of Plugs and Seals* (e.g. Rübel, 2016). The DOPAS Project comprised a set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories.

In (Rübel, 2016), the considered processes comprise the following hydraulic and geomechanical evolution of the seals and sealing materials:

- Hydraulic state evolution of the seal
  - o Flow rates of fluid through the seal with time
  - o Temporal evolution saturation state of the sealing pore space
  - o Temporal evolution of the pore pressure of fluids in the seal
- Mechanical state evolution of the seal
  - o Temporal evolution of the mechanical stress and load of the seal
- Hydraulic and mechanical coupled evolution of the seal
  - o Temporal evolution of seal permeability
  - o Temporal evolution of the sealing porosity
  - o Temporal evolution of the total pressure in the seal

- Chemical evolution of the sealing and the sealing material
  - Mineral phase changes in sealing material

5.5.4 Expected evolution of main processes and parameters

In the OPERA performance assessment model the disposal cell plugs have not been modelled as a separate component (Schröder, 2017c), one of the reasons being that the plugs for the Dutch repository have not yet been specified in detail. Additional work is therefore required to establish design criteria for the plugs and to evaluate their evolution.

5.5.5 Candidate processes and parameters for monitoring

Taking into account the above-mentioned topics an identification of processes and parameters relevant for maintaining the intended functions of the OPERA plug system is provided in **Table 1-31** and Table 1-32 below.

Table 1-31 Candidate processes and parameters for monitoring of the OPERA plug system related to the safety function of the barrier

Safety function	Process	Parameter	Comment	Reference
Limit water flow through the disposal system (R2)	Advective flow through the plug system and the EDZ between the plug components and host rock	Hydraulic conductivity of the concrete plug, bentonite seal and the EDZ at their interface with the host rock	Likely less relevant in the NES May be relevant in case of flooding	Schelland, 2014
		Leakage through the plug		
		(Closed) interface between the plug components and host rock		
	Gas induced dilation (fracture) of the plug components	Gas pressure		Schelland, 2014
		Gas permeability		

Table 1-32 Candidate processes and parameters for monitoring of the OPERA plug system related to other functions of the barrier

Function	Process	Parameter	Comment	Reference
Concrete plug				
Mechanically support the bentonite seal and backfill	Mechanical load as result of mechanic, hydraulic and swelling pressure from the bentonite seal and backfill	Total load (pressure) on the concrete plug at the interface concrete plug /bentonite seal	total load < 7 MPa (2 MPa swelling pressure in the bentonite seal + 5 MPa pore water pressure)	Yuan, 2016a: p.17,21; IAEA, 2014: Table I-1
		Compressive strength	55 MPa	Yuan, 2016a: p.23
		Stresses (punching shear stress)		Yuan, 2016a: p.23
		Deformation		
	Horizontal displacement as results of mechanical load from bentonite seal and backfill	Displacement		DOPAS
Carry effective stresses from the host rock	Mechanical load as result of lithostatic, hydraulic and swelling pressure of bedrock	Total load on concrete plug at the interface plug / host rock	Refer to 500 m depth	Yuan, 2016a: p.17; IAEA, 2014: Table I-1
		Stresses (punching share stress)		

Function	Process	Parameter	Comment	Reference
		Compressive strength	55 MPa	Yuan, 2016a: p.23
Prevent leakage until bentonite resaturation	Advective flow through the concrete plug and the EDZ at the interface between the concrete plug and host rock	Leakage	Likely less relevant in the NES May be relevant in case of flooding	Yuan, 2016a: p.17; IAEA, 2014: Table I-1
		Closed concrete / host rock interface		Yuan, 2016a: p.23
		Hydraulic conductivity of the concrete plug, EDZ and the interface between them	the hydraulic conductivity of the concrete plug and EDZ must be comparable with the hydraulic conductivity of the host rock	Yuan, 2016a: p.23
		Hydraulic gradient	Likely less relevant in the NES (hydraulic gradient absent) May be relevant in case of flooding	Yuan, 2016a: p.23; IAEA, 2014: Table I-1
	Gas induced dilation (fracture) of the concrete plug	Gas pressure		
		Gas permeability		
Bentonite seal				
Prevent axial water flow from the deposition tunnel	Diffusion through bentonite seal	Hydraulic conductivity		Yuan, 2016a
	Resaturation / desaturation	Relative humidity		
		Swelling pressure		
		Pore pressure		
	Advective flow through bentonite seal and the EDZ between the bentonite seal and EDZ	Leakage		Yuan, 2016a: p.17; DOPAS
	Gas induced dilation (fracture) of the bentonite seal	Gas pressure		
		Gas permeability		
Withstand a high hydraulic gradient	Hydraulic gradient	Hydraulic gradient	Likely less relevant in the NES (hydraulic gradient absent) May be relevant in case of flooding	Yuan, 2016a: p.23
Seal cracks in the concrete plug upon resaturation (swelling)	Swelling of the bentonite seal	Swelling pressure of bentonite	Cracks formed during concrete hardening heat resulting in volumetric expansion and stresses	Yuan, 2016a: p.17; IAEA, 2014: Table I-1
	Redistribution of bentonite mass	Density of bentonite		
		Hydraulic conductivity of bentonite		
Reseal the EDZ through swelling upon resaturation	Swelling	Swelling pressure of bentonite	See also Section 5.7	Yuan, 2016a: p.17; IAEA, 2014: Table I-1
	Redistribution of bentonite mass	Density of bentonite		
Plug system				
Limit water flow through the disposal system (R2)	Advective flow through the plug system and the EDZ between the plug components and host rock	Hydraulic conductivity of the concrete plug, bentonite seal and the EDZ at their interface with the host rock Leakage through the plug (Closed) interface between the plug components and host rock	Likely less relevant in the NES May be relevant in case of flooding	See also Section 2.4
Hydraulically seal off the disposal drift	Diffusive transport regime through the plug and the EDZ between	Peclet number Transport regime	Low hydraulic conductivity Likely less relevant in the NES	Verhoef, 2014a: p.13;

Function	Process	Parameter	Comment	Reference
	the plug components and host rock		May be relevant in case of flooding	IAEA, 2014: Table I-1
Limit erosion of backfill from the deposition tunnel	Erosion of bentonite	Hydraulic conductivity of the bentonite seal	Attributed to excessive seepage around the plug Likely less relevant in the NES May be relevant in case of flooding	Yuan, 2016a: p.5,16
Limit and retard radionuclide releases in the event of canister failure	Diffusion dominated migration through the plug	Hydraulic conductivity	Only relevant for very early canister failure Otherwise long term process	Jobmann, 2013: p.71
	Retardation of radionuclides	Sorption capacity of the bentonite seal		
	Gas mediated transport			see Section 2.4

From the various consulted studies and documents, is can be concluded that the most relevant safety function of the disposal cell plugs is to limit water flux through the disposal cells. For the OPERA disposal system this function is achieved by:

- applying concrete (short-term isolation) and swelling clay (longer-term isolation);
- a dead-end topology of the disposal cells.

Only in case of an early flooding, i.e. before complete resaturation of the disposal cell backfill has occurred, a relevant pressure gradient along the plug is expected. However, the selection of properties of the concrete (or any other hydraulically isolating material) can impair the consequences of such an event.

The option of retrievability of the waste canisters and ease of construction have provided guidance for the preliminary design of the OPERA plug system. Retrievability implies that tunnels may be re-entered after backfilling.

For the OPERA plug system it is noted that a number of aspects require further detailed design and investigation to improve the concept, viz. the hydraulic conductivity of the involved components and the swelling pressure of the bentonite seal, as well as other aspects, e.g. geochemical evolution, concrete shrinkage and material creep.

5.6 Lining

5.6.1 Properties and features of the lining

During the excavations of the tunnels and disposal drifts the pressure exerted by the overlying rock will lead to convergence of the open spaces in the Boom Clay. In order to minimise the convergence of the excavated tunnel galleries and provide the necessary stability over the envisaged operational period a concrete support structure is required (Arnold, 2014: p.102).

In the OPERA disposal concept, the concrete support is proposed have a thickness of 0.5/0.55 m (Verhoef, 2014a: Table A-4), although, as noted by in (Arnold, 2014: p.263), the thickness of the lining may be reduced during detailed design. The disposal drifts are supported by concrete wedge-shaped blocks. **Table 1-33** provides details of the concrete support (lining) in the OPERA disposal concept.

Table 1-33 Dimensions of the shafts, galleries and tunnels (Table A-4 in (Verhoef, 2014a))

	Number	Length [m]	Diameter[1] [m]	Concrete Support Thickness [m]	Gallery Spacing [m]
Shaft	2	500	6.2/5.0	0.60	1110
Main Gallery	1	7200	4.8/3.7	0.55	N.A.
Secondary Galleries	5	1100	4.8/3.7	0.55	260
Disposal Tunnels					
Heat-generating HLW	47	45	3.2/2.2	0.50	50
Spent fuel	6	45	3.2/2.2	0.50	50
Non-heat generating HLW	36	200	3.2/2.2	0.50	50
LILW and DepU	65	200	4.8/3.7	0.55	50

[1] Excavated diameter/Inner diameter of the gallery support

The mechanical support during construction and the operational phase of a geological disposal facility is provided by the concrete lining (see also Figure 1-9 and Figure 1-13). Concrete segments made with Portland fly ash cement are proposed (Verhoef, 2014b: p.1).

The potential mechanical support should be larger than the host rock pressure at a depth of 500 meter in Boom Clay, about 10 MPa. The hardened properties e.g. compressive strength of the concrete and thickness of the lining determine both whether sufficient support can be achieved (Verhoef, 2014b: p.6).

Mechanical support by the gallery lining, drifts and floor plate is expected to be needed at least during construction and the operational phase of the facility. The considered period for emplacement of waste is 40 years (Verhoef, 2014a: p.7). Additionally, to facilitate retrieval of waste over the period of a century, the lining should provide mechanical support for about 150 years.

For the post-closure phase, a limited of the use of metal such as steel is preferred in order to limit the corrosion of steel and the resulting potential formation of hydrogen gas. Unreinforced concrete segments are therefore considered for the transport galleries and the disposal drifts (Verhoef, 2014a: p.7).

At the intersections e.g. between the disposal drifts and access gallery, reinforcement may be necessary. In (Arnold, 2014), the behaviour of a single tunnel and the required spacing between adjacent tunnels were investigated. The results suggested that at tunnel intersections, the symmetry of the stress field in the tunnel lining and in the surrounding Boom Clay will be lost, and therefore the lining at the tunnel crossings will be subjected to bending and torsion stresses. Moreover, the host rock behaviour at the intersection is a complex, three-dimensional problem. This aspect has been investigated in (Yuan, 2016a). The results from that study demonstrated that the construction of perpendicular tunnel openings in Boom Clay at a depth of 500 m is technically feasible, without substantially increasing the damage of the clay or without substantial reinforcement. Local reinforcement around the tunnel opening is likely to be required and the construction sequence should be studied further in detail prior to construction.

The permeability in concrete segments proposed for the lining is usually sufficiently small to consider it impermeable during the construction phase and the operational phase. It is therefore required to have no degradation of the concrete lining by ingress of sulphates carried by Boom Clay pore water with a concentration comparable to seawater for a period of at least 150 years (Verhoef, 2014b: p.6). Any leakage is expected to occur at the joints of the concrete segments.

5.6.2 Safety functions and other functions of the lining

The (safety) functions of the lining are summarized in Table 1-34 and Table 1-35 below.

Table 1-34 Safety functions of the concrete lining of the OPERA disposal concept

Safety function	Reference
Limit water flow through the disposal system (R2)	Section 2.4, and Verhoef, 2014b: p.6

Table 1-35 Functions of the concrete lining of the OPERA disposal concept

Function	Reference
Provide sufficient support to prevent collapse of the excavated volume for a sufficient period (about 150 years)	Verhoef, 2011a: p.8 (Verhoef, 2014b: p.6)

5.6.3 Identification and description of related main processes

The most relevant processes concerning the lining of the OPERA disposal system, discussed in the following sections, are:

- Hydraulic: Prevent water ingress from the surrounding Boom Clay;
- Mechanical: pressurization of the lining due to the convergence of the excavated volumes of Boom Clay;
- Chemical: sulphate attack and the formation of an alkaline plume.

5.6.3.1 Hydraulic processes

The main function of the concrete gallery linings is to provide sufficient mechanical support to prevent collapse of the excavated volume, and to a lesser extent to limit water flow through the disposal system (safety function R2, cf. Section 2.4).

In the CORA program, the concrete lining of the disposal and transport galleries were assumed impermeable for water flow (Van de Steen, 1998: p.13). Also in more recent efforts, the concrete lining has been assumed impermeable for hydraulic transport (Arnold, 2014: p.202).

5.6.3.2 Mechanical behaviour

Consolidation and creep of Boom Clay after emplacement of the concrete lining result in loads on the lining which will increase with time. The dimensioning of the lining must consider this load increase if retrievability of the waste is required.

A yet unresolved problem with models predicting pore pressure, permeability evolution, pressure on the lining, and convergence is that system parameter values are obtained from laboratory test results but also by back-analysis of in-situ measurements. It is difficult at the present state of knowledge to assess their predictive capability (ONDRAF/NIRAS, 2013: p.124).

Parameters identified relevant for the mechanical behaviour of the liner are:

- Boom Clay pore pressure around the lining
- Pressure on the lining
- Compressive stress in the concrete
- Compressive stress in the concrete lining segments
- Total stress close to the concrete lining
- Compression strength (collapse load)

5.6.3.3 Sulphate attack

Sulphate attack is the geochemical process in which dissolved sulphate species reacts with cement components with the precipitation of sulphate minerals.

During the construction phase, sulphate attack, originating from both pyrite oxidation and the native Boom Clay water, on concrete liners remain an important concern (Wang, 2009: Section 2.3). After repository closure, there is no supply of oxygen and hence sulphate attack is only possible due to the native Boom Clay water, which is rich in sulphates.

After the repository closure, and after resaturation of the concrete barriers, sulphate attack is diffusion driven and it will take a very long time for sulphate species to diffuse through the backfill and then to the concrete buffer. Initially sulphate can also advect towards the cementitious components with the resaturation water and the time scale depends on the capillary properties of the material.

The consequences of sulphate attack can be reduced significantly by using favourable cement properties. For example, the cement used for the lining segments installed in the connecting gallery of the HADES URF in Mol is a Highly Sulphates Resistant (HSR) cement, CEM II/B-V 42.5 (Arnold, 2014: Section 3.6).

5.6.4 Expected evolution of main processes and parameters

In the OPERA performance assessment model the lining has not been modelled as a separate component (Schröder, 2017c), one of the reasons being that the lining for the Dutch repository has not yet been specified in detail. Additional work is therefore required to establish design criteria for the lining and to evaluate its evolution.

5.6.5 Candidate processes and parameters for monitoring

An overview of processes and parameters for lining monitoring is given in **Table 1-36** and **Table 1-37**.

Table 1-36 Candidate processes and parameters for monitoring of the OPERA lining related to the safety function of the barrier

Safety function	Process	Parameter	Comment	Reference
Limit water flow through the disposal system (R2)	• diffusion	• Hydraulic conductivity (permeability)	Slow process, difficult to measure	See Section 2.4
		• Porosity	QA, Controlled by chemical composition/ cement formulation	Arnold, 2014: p.103
	• saturation	• Pore pressure	See also Section 5.7	
	• advection	• Leakage rate	In case of leaking liner	
		• Pressure gradient		
		• Peclet number		

Table 1-37 Candidate processes and parameters for monitoring of the OPERA lining related to other functions of the barrier

Function	Process	Parameter	Comment	Reference
Provide sufficient support to prevent collapse of the excavated volume for a sufficient period (about 150 years)	• Pressure load on the lining	• Total pressure on the lining • host rock pressure	10 MPa at 500 m Boom Clay Determination of collapse load on lining	Verhoef, 2014b: p.6; Arnold, 2014: S.4.7
		• Compressive stress in the concrete lining segments	Determination of collapse load on lining	Arnold, 2014: S.3.6, S.4.7
		• Total stress close to the concrete lining		
	• Deformation	• Pressure on the lining	Extensively investigated in OPERA WP3.1	Jobmann, 2013: Table 5.12; Arnold, 2014
	• Sulphate attack	• Sulphate concentration		Wang, 2009: Section 2.3
	• Formation of alkaline plume	• pH	No negative impact on diffusion properties of Boom Clay	Wang, 2010

5.7 Host rock near field

5.7.1 Properties and features of the host rock near field

In the OPERA disposal concept the host rock near field is defined as the part of the geological host formation whose characteristics have been or could be altered by the excavation works, the presence of the repository and its contents (Grupa, 2016: Section 3.1.1).

5.7.2 Safety functions and other functions of the host rock near field

The main, overall functions of the near field (normal evolution scenario) are (cf. Section 2.4):

- Limitation of the water flow through the disposal system[19] (R2)
- Retardation of contaminant migration to the environment of the contaminants released from the waste packages (R3).

Table 1-38 and **Table 1-39** summarize in more detail the (safety) functions of the Boom Clay near field adjacent to the engineered structures of the disposal facility.

Table 1-38 Safety functions of the host rock near field

Safety function	Reference
Limit water flow through the disposal system (R2)	Section 2.4
Retard migration of the contaminants released from the waste packages (R3)	Section 2.4

[19] A repository together with, in the case of geological disposal, the host formation in which it is built (Smith, 2009: Annex 1).

Table 1-39 Functions of the host rock near field

Function	Reference
Enable resaturation after desaturation phase	Yu, 2010: Ch.4
Serve as a buffer to store gas which may be generated by corrosion of metals (aerobic, anaerobic)	Grupa, 2016: Section 3.1.1
Allow dispersion of gas into the clay preferably by diffusion only	Grupa, 2016: Section 3.1.1
Allow healing of damaged zones	Yu, 2010: Ch.4
Enable sufficient dissipation of the decay heat from the waste container into the Boom Clay	Verhoef, 2011a: p.13
Preserve natural diffusion and dispersion potential of surrounding formations	(Jobmann, 2013: p.29)

5.7.3 Identification and description of related main processes

Key processes to monitor the evolution of the near field of a clay-based repository refer to verifying the dissipation of heat from the disposal cell, the deformation and loading of rock on the disposal cell liners, fluid (liquid and/or vapour) influx around the disposal cell, air exchange between disposal cell and access tunnel (Jobmann, 2013: Section 5.3.2). In addition, verifying the self-healing of any damaged clay in the near field is important in relation to ensuring the return to ambient conditions (permeability, porosity, humidity).

Due to the excavation of the tunnel galleries the Boom Clay host rock will undergo a major stress release and redistribution. The contractant and/or dilatant strains resulting from this differential stresses may potentially induce micro and macro shear fractures which will influence the repository performance (Arnold, 2014: Section 2.5.1.2).

Boom Clay is a transversely isotropic material, with a smaller stiffness in the direction perpendicular to the bedding plane. The damaged zone around an excavated gallery parallel to the bedding plane in Boom Clay is related to the initial anisotropic stress of the clay and the subsequent development of an anisotropic plastic zone around the gallery. In the near field of the gallery, a larger deviatory stress along the horizontal profile due to a sudden release of radial stress during excavation induces a plastic zone about three times deeper along the horizontal profile than that in the vertical profile.

An important safety-relevant process which may be induced by the pressure relief following the excavations is a significant decrease of the pore (interstitial) pressure in the near field, potentially causing a change in the plastic zone around the tunnels (Yuan, 2015: Section 4.5). This effect is strengthened by the heat input from emplaced waste containers, which is however limited for the OPERA disposal concept. Analyses showed that in this plastic zone around the repository the permeability will increase. On the other hand the sealing behaviour of Boom Clay may reduce the formation of such a plastic zone as well as its impact, but this has yet to be experimentally determined.

Upon the installment of a supporting concrete liner, the convergence of the Boom Clay around the tunnel is halted and the pressure increases again, within several years, to the ambient value (e.g. Arnold, 2014: Fig. 2.47).

After the temperature and pore pressures peak, unloading occurs and due to consolidation the material is likely to be denser, stiffer and stronger. This implies that after the thermal period, the Boom Clay properties may have mechanically improved (Yuan, 2015: Section 4.5).

The impact of the increase in temperature on the tunnel stability seems to be limited. A moderate increase in both the maximum cavity pressure and moment is observed, and should be taken into account in the detailed design of the liner, but neither are sufficiently large to suggest that the construction is not feasible. Additionally, these additional stresses and moments only occur after repository closure, and therefore may affect the ability to retrieve the waste, but would not affect the operational phase of the repository.

As part of the OPERA programme, it was established that the evolution of the near-field pore pressure is almost independent of the thermal input from the waste (Yuan, 2015: Section 4.5). This is due to the (near) linear thermal expansion of water and the (near) incompressibility of water, implying that Boom Clay pore water can transfer pressure relatively easily throughout the domain. It was estimated that the extent where the pore water pressure is elevated as a result of heat input from the waste is greater than that of the temperature.

A number of longer term mechanical features include creep and sealing behaviour. Both processes are likely to aid the sealing of any zones of increased permeability, and creep may lead to an increased maximum stress on the tunnel. For a complete mechanical understanding these processes could be included in future analysis.

The effects of the formation of an *alkaline plume* as a result of chemical interactions between Boom Clay host rock pore water and concrete has recently been investigated in Belgium (Wang, 2010).

During the construction and exploitation phase of a Boom Clay based repository, localized chemical perturbations to the Boom Clay along the fracture planes exist. Oxidation of pyrite at the surface of open cracks locally modifies the chemistry of the pore water. Within the oxidized zone, calcite, which accounts for the buffering capacity of the clay, may (partly) be dissolved into the acid water. The oxidization affected zone is only limited to the surface of open cracks, the extent of which is estimated at about ¼ of the gallery diameter. The acid pore water will not persist very long as the alkaline environment will be dominant with the backfilling of the cementitious material in the gallery. When the pore water reaches the concrete material (backfilling and buffer), the interactions between the Boom Clay and cementitious material will lead to the development of an alkaline plume into the surrounding clay through diffusion. The affected thickness is expected to be less than 2.5 m in the long term.
The overall conclusion of (Wang, 2010) was is that the alkaline plume perturbation to Boom Clay is expected to be limited. The magnitude of the perturbation to Boom Clay was assessed to be comparable to studies performed in Switzerland and France on clays of similar properties. In-house experiments at the HADES URL demonstrated that no negative impact of an alkaline plume on diffusion properties of Boom Clay.

5.7.4 Expected evolution of main processes and parameters

The evolution of the near field in Boom Clay has been studied extensively in the EU-FP6 project TIMODAZ (e.g. (Yu, 2010)). Additional efforts related to the EDZ evolution in the OPERA disposal concept are reported in (Arnold, 2014). A summary of the most relevant aspects is provided in the following (see also (Yu, 2010: Section 3.1)).

During the excavation of the disposal gallery, a fracture zone is inevitably formed as a result of the mechanical failure caused by stress redistribution. Beyond this fracture zone, a damaged zone (DZ) with enhanced hydraulic conductivity due to effective stress variation is observed around the gallery into the Boom Clay up to about 1.7 times the gallery diameter. The increase in hydraulic conductivity of the DZ is limited to one order of magnitude. In-situ test results show that no transmissive interconnected fracture network exists beyond a few centimetres into the Boom Clay. Furthermore, the fractures do not play an important role in the enhancement of the hydraulic conductivity in DZ because self-sealing of the fractures was observed to occur in a relatively short time: the permeability of the DZ recovers close to the undisturbed Boom Clay value within a few years.

In case of instant installation of the concrete lining, convergence can be limited to a few centimetres, thereby effectively avoiding further development of the fractures. The consolidation under the hydraulic gradient towards the inner surface of the gallery and the confining pressure acting on the EDZ imposed by the liner fasten the sealing process. On the other hand, the ventilation of the repository induces limited desaturation in the clay formation close to the tunnel wall.

Besides the hydro-mechanical disturbances to the Boom Clay during the construction and exploitation phase, there exist localized chemical perturbations to the Boom Clay along the fracture planes. Oxidation of pyrite at the surface of open cracks locally modifies the chemistry of the pore water. Within the oxidized zone, calcite, which accounts for the buffering capacity of the clay, may (partly) be dissolved into the acid water. However, the oxidization affected zone is only limited to the surface of open cracks, the extent of which is estimated at about ¼ of the gallery diameter. The acid pore water will not persist very long as the alkaline environment will be dominant with the backfilling of the cementitious material in the gallery. When the pore water reaches the concrete material (backfilling and buffer), the interactions between the Boom Clay and cementitious material will lead to the development of an alkaline plume into the surrounding clay through diffusion. The affected thickness is expected to be less than 2.5 m in the long term.

The heat production in the waste containers in the OPERA disposal concept is considered limited due to the extended surface storage period. Consequently, any heat-up in the Boom Clay after canister emplacement will be limited, and temperature effects on Boom Clay properties will be moderate.

After the limited peak temperature in the Boom Clay, estimated at about 30°C, a recovery of the temperature to the initial value follows. It is estimated that after about 100 years, the temperature of the host clay near the gallery lining will have dropped below 25°C. The laboratory tests in the TIMODAZ project show that there is no significant increase of the permeability of the DZ caused by elevated temperatures.

The enlarged plastic strain due to the excavation induced by creep of the near field Boom Clay will contribute to the sealing of the fractures. After the (limited) thermal and hydraulic transient, the stress state and pore water pressure within the Boom Clay will recover to their initial state. This slow process is expected to have no negative impact on the host clay.

As soon as oxygen is depleted in the EBS, gas will be produced continuously through anaerobic corrosion of the metals (package of the waste as well as other iron components). Besides this, degradation of organic matters (e.g. kerogen) contained in the Boom Clay may produce carbon dioxide. The gas imposes a potential risk of creating connected pathways (e.g. fissures or cracks) and localized enhanced gas flow in the clay host rock if it cannot be evacuated timely through diffusion. The uncertainties however related to gas flow and the potential formation of pressure-induced dilatant pathways are considerable, and should further be reduced by experimental and theoretical efforts.

PA calculations undertaken to date illustrated that enhanced radionuclide transport through EDZ would not have a significant influence on the dose in the biosphere in the long term, even with very conservative scenarios and assumptions, including the enhancement of the permeability of the EDZ with several orders of magnitude (in combination with an inversion of the hydraulic gradient) and disregarding the barrier functions of EDZ (e.g. ANDRA, 2005b: Section 5.5.6.1). The self-sealing that is consistently observed further strengthens this conclusion.

In the framework of the TIMODAZ project, no significant modification of the safety-relevant properties of Boom Clay, especially self-sealing capacity, has been found, even at elevated temperatures. On the contrary, several aspects related to thermal disturbance have been found to be beneficial to the safety functions of clay host formations, such as thermal induced creep, plastic deformation and re-consolidation. On the other hand, the questions related to the evolution of the EDZ in case of gas pressure build-up are not yet answered satisfactorily.

A summary of the most relevant mechanical, hydrological, thermal, and chemical evolutions of the near field during the various phases of repository implementation in Boom Clay is depicted in Figure 1-17 (Sillen, 2010). It is noted that this overview is not exhaustive and that it was constructed for a repository at a depth of 220 m, i.e. in the Belgian context.

Important differences between the Belgian concept and the OPERA disposal concept are the greater depth foreseen for the Dutch repository, and the anticipated limited temperature effects due to the extended surface storage in the Netherlands. These aspects may influence the magnitude of some processes, such as deformation and self-healing, or dryout and resaturation of the Boom Clay.

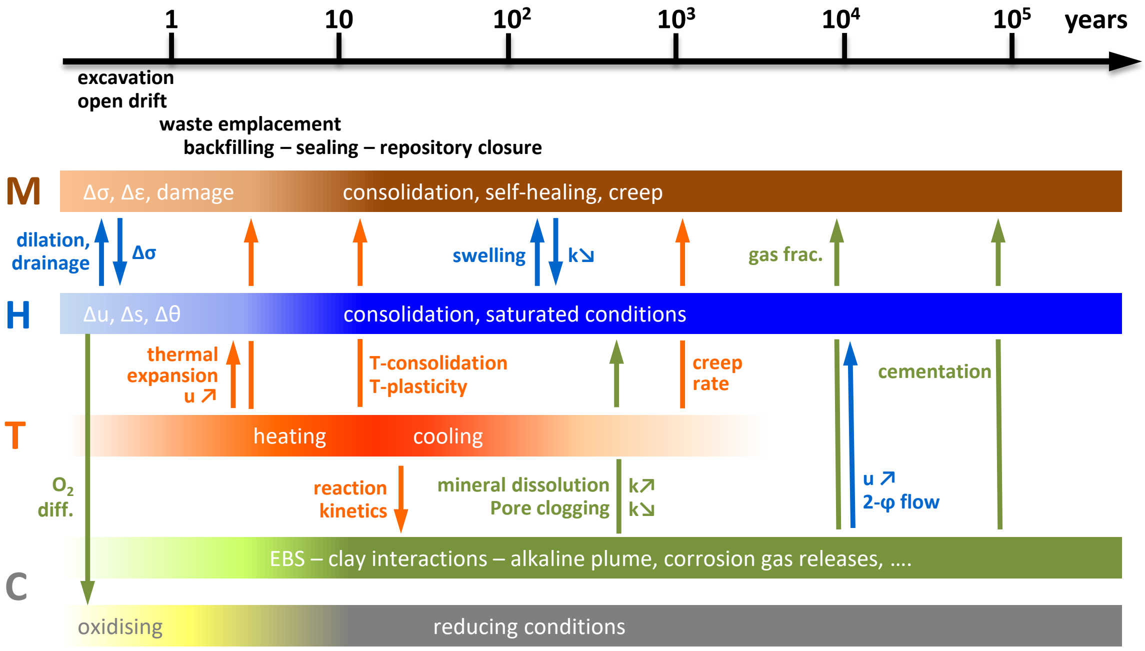


Figure 1-17 Schematic of the Boom Clay near field evolution

In summary, the TIMODAZ project concluded the following about safety-relevant aspects related to the near-filed (EDZ) of a repository in Boom Clay (Yu, 2010: Section 2.2):

- Evidences of the self-sealing capacity of Boom Clay at room temperature;
- No significant negative thermal impacts on permeability;
- No negative impacts on self-sealing capacity of clay at elevated temperatures;
- No negative impacts on cation exchange capacity.

5.7.5 Candidate processes and parameters for monitoring

Summarizing, monitoring of the temperature in the host rock near field may contribute to verifying process models that predict:

- The decrease of waste form activity
- Characteristics and evolution of the engineered barrier
- Evolution of the near field
- Overall host rock properties

Consequently, understanding of the near field conditions that may impact the repository's safety call for the monitoring of:

- Near-field temperature distribution;
- Near-field desaturation, which may be enhanced by ventilation;
- Near-field resaturation and pore (interstitial) pressure to ambient conditions;
- Near-field deformation and gap closure with disposal cell liner;
- Loading distribution on the disposal cell liner.

Table 1-40 and Table 1-41 provide an overview of processes and parameters identified for monitoring the Boom Clay host rock near field under the conditions of the OPERA disposal concept.

Table 1-40 Candidate processes and parameters for monitoring of the host rock near field

Safety function	Process	Parameter	Comment	Reference
Limit water flow through the disposal system (R2)	• Advection • Diffusion • Resaturation	• Pressure gradient • Permeability • Pore pressure	Generic features	
Retard migration of the contaminants (R3)	• Diffusion	• Concentration gradient • Pressure gradient	Long-term process for RN transport	(Jobmann, 2013: S.5.1.3)

Table 1-41 Candidate processes and parameters for monitoring of the host rock near field

Function	Process	Parameter	Comment	Reference
Preserve natural diffusion and dispersion potential of surrounding formations	• Diffusion	• Concentration gradient • Pressure gradient • Permeability	Small gradients, problematic to determine accurately in situ	(Jobmann, 2013)
Limit chemical perturbation of host formation water (pH, Eh)	• Oxidation • EBS dissolution	• pH, Eh	Inevitable, but limited consequences in the long term	(Jobmann, 2013: S.5.2.2, Table 5.3, 5.4)
Enable resaturation	• Resaturation, water ingress	• Humidity • Pore pressure	Short term process (decades)	TIMODAZ, NF-PRO
Enable healing of damaged zone	• Healing	• Pressure	Short-term process (decades)	TIMODAZ, NF-PRO
Enable sufficient dissipation of the decay heat from the waste container into the Boom Clay	• Heat transfer	• Temperature	Limited heat production in OPERA concept (long-term storage)	Verhoef, 2011a: p.13

5.8 Host rock far field

5.8.1 Properties and features of the host rock far field

The main focus in the OPERA Research Programme is on the Boom Clay as potential host rock (Verhoef, 2014a). These clays are officially referred to as Rupel Clay Member (Vis, 2014) were formed 30 to 34 million years ago during the Oligocene. The composition of the clay in the Netherlands subsurface is variable; both vertically and laterally trends in grain size are visible. In the northern part of the Netherlands the calculated permeability of the clay reaches the lowest values, whereas in the southern and south-eastern parts of the Netherlands the permeability is higher and more variable. Faults are present which transect the clay layer from bottom to top.

As part of OPERA Work Package 4.1, *Geology and geohydrological behaviour of the geosphere*, the Boom Clay subsurface of the Netherlands was characterized based on existing information (Vis, 2014) on the following aspects:

- Regional-scale geometry and overburden;
- Lithological characterization;
- Regional-scale geohydrological setting;
- Geohydrological characterization.

An important finding of the study was that fault properties such as horizontal and vertical offset, geohydrological properties, and connectivity are presently not well defined but may be vital with respect to Safety Functions of the disposal system.

The mineralogical and geochemical characterization of the Boom Clay in the Netherlands was investigated in OPERA Work Package 5.2, *Properties, evolution and interactions of the Boom Clay* (Koenen, 2014). It was found that the Boom Clay in the southern part of the Netherlands has coarser, silty upper and lower parts. The central part is finer grained and more clay-rich with occasional silty layers. This is consistent with the cyclic alternation of clay- and silt-rich layers found in the Belgian Boom Clay. In the Southeast of the Netherlands, the Boom Clay has higher carbonate content than in the Southwest. The Boom Clay in the north of the Netherlands is significantly different from the Southeast and Southwest. There, the Boom Clay is fine grained and clay- and carbonate-rich over the total depth interval. Both the pyrite and organic carbon content are important parameters due to their reactivity and potential impact on the safety function '*Retardation of contaminant migration to the environment of the contaminants released from the waste packages (R3)*'.

By definition the effects of the repository are limited or negligible in the far field of the host rock. Any noticeable effects of the repository on the host rock will mainly occur in the host rock near field. The present section therefore concentrates on the state of the host rock under the influence of external processes, not caused by processes occurring in the repository itself.

For practical, dedicated monitoring of the repository, only external processes operating on decennial to centennial time scales can be considered; long-term processes or events like glaciation processes occurring after more than 50 ka are out of scope. On the other hand, some aspects of monitoring might be part of longer term regional monitoring activities by governmental bodies, for example on groundwater quality, climate, sea level and flooding protection.

5.8.2 Safety functions and other functions of the host rock far field

The main, overall functions of the near field (normal evolution scenario) are (cf. Section 2.4, and Table 1-42):

- Retardation of contaminant migration to the environment of the contaminants released from the waste packages (R3);
- Reduction of the likelihood of inadvertent human intrusion (I1);
- Ensuring stable conditions for the disposed waste and the system components (I2).

Table 1-42 Safety functions of the Boom Clay host-rock far field

Safety function	**Reference**
Retardation of contaminant migration to the environment of the contaminants released from the waste packages (R3)	Section 2.4
Reduction of the likelihood of inadvertent human intrusion (I1)	Section 2.4
Ensuring stable conditions for the disposed waste and the system components (I2)	Section 2.4

Table 1-43 Functions of the Boom Clay host-rock far field

Function	**Reference**
Very low advection due to very low permeability and low hydraulic gradients	Verhoef, 2014a: p. 6
No permanent bypass, e.g. permeable fault	ONDRAF/NIRAS, 2013: Annex A1
Limited availability of mobile water	ONDRAF/NIRAS, 2013: Annex A1
Chemical buffering capacity	Verhoef, 2014a: p. 6
Propensity for plastic deformation and self-sealing of fractures	Verhoef, 2014a: p. 6
Geochemical characteristics that favour low solubility of radionuclides	Verhoef, 2014a: p. 6

Function	Reference
High capacity to retard the migration of radionuclides towards the accessible environment, e.g. through sorption capacity and due to a diffusion-dominated transport	Verhoef, 2014a: p. 6

5.8.3 Identification and description of related main processes

The following processes are considered to play a potential role in assessing the performance of the host-rock far-field in relation to the safety of the disposal system.

5.8.3.1 Hydraulic processes

The difference in the hydraulic head between top and bottom of a 100 m thick Boom Clay layer amounts to 0.003 and 0.015 m; the upward groundwater flow is about 0.06 to 1.75 mm per year (Verweij, 2016a: p.33). The hydraulic gradient only slightly changes in the vicinity of a fault or a deep well. Locally near faults the gradient can be upward instead of downwards (Verweij, 2016b: p.34).

5.8.3.2 Chemical processes

Boom Clay displays a significant buffer capacity with regard to chemical perturbations (ONDRAF/NIRAS, 2013: S. 4.1.2.2). Chemical perturbations affecting the pH, redox potential (Eh) and partial pressure of carbon dioxide can be buffered by the minerals present in the Boom Clay, mainly pyrite and carbonates, and by organic matter. The carbonates regulate the pH and the partial pressure of carbon dioxide while the pyrite and organic matter control the redox potential.

Currently, there is no indication that the mineral composition of the Boom Clay Member is changing on a decennial to centennial time scale.

5.8.3.3 Sorption processes

The migration of radionuclides through the host rock plays an important role in the long-term safety of disposal facilities in clay. Due to the slow transport of radionuclides in the host rock, most radionuclides will have decayed before they can enter the surrounding aquifers. For the generic OPERA disposal concept in Boom Clay, the delayed transport of radionuclides through the host rock is assumed as the most important safety function on the long-term (Schröder, 2017b: p.1). Since sorption of radionuclides is an important aspect in the migration process it is important to understand the basic processes behind the migration and sorption of radionuclides in the host rock sufficiently well to be able to make a credible quantitative assessment of the long-term effects of deep disposal of radioactive waste in Boom Clay.

In (Schröder, 2017a), general aspects with respect to the modelling of radionuclide sorption in Boom Clay for the purpose of PA calculation as part of the OPERA Safety Case are summarized, and key processes with respect to the understanding of adsorption processes are shortly reviewed, e.g.:

- Speciation, relating to the distribution of an element over different chemical bindings or forms;
- Redox chemistry, describing the altering speciation of elements under variable oxygen concentrations;
- Colloids, or small particles (<0.5 µm), which can be present in solution, contributing to mass transport by diffusion and advection, if applicable;

- Adsorption reactions, which can relate to sorption in the electrostatic double layer of a particle, often expressed as “ion exchange”, or to specific interactions with surface groups of the sorbent, often expressed as “surface complexation”.

5.8.3.4 Mechanical processes

Faults or fractures in the Boom Clay may not be detected because of limitations in the resolution of site-characterisation techniques or inherently limited quality assurance (Grupa, 2016: Section 4.6). Hydraulic properties of faults may also adversely be altered as a consequence of unforeseen geologic events such as movement along the fault plane and the formation or increase of a fault gauge. Fault movement may influence the integrity of the EBS as well.

The existence or formation of faults mostly affects the following safety functions:

- Retardation of contaminant migration (R3). Due to the potentially enhanced transport of water the migration of contaminants may also be enhanced.
- Ensuring stable conditions for the disposed waste and the system components (I2).

The possible consequences of faults and fractures in Boom Clay in the Dutch context has been explored in OPERA 4.1.2 - *Future evolution of the geological and geohydrological properties of the geosphere* (Ten Veen, 2015).

It appears that for the Netherlands, based on historical records, large seismic events are not expected to have more than a limited effect on the regional landscape. However, it is possible for fault scarps of a few meters to occur as a consequence of repeated large-scale fault movements associated with multiple seismic events of varying magnitude. The possibility of exposing the Boom Clay can easily be discarded if the total expected vertical offset does not exceed the depth position of the Boom Clay in the Netherlands within the next 1 Ma. Also, the accumulated effect of multiple seismic events in a seismically active area resulting in, for example, modified drainage patterns, may not be particularly significant from a geological perspective.

Seismic events potentially have an effect on the delay and/or attenuation of radionuclides transport due to possible changes in groundwater flow patterns through faults and fractures. These groundwater flows, if reaching the surface, might have a contaminating effect at the location of the geosphere-biosphere interface. This is a complex process that is relatively unpredictable although it can be generalized by stating that the only way for upward transport of deep fluids is through permeable faults. Renewed fault movement tends to increase the permeability of a damage zone parallel to the fault core, which may facilitate the deep circulation of fluids.

It is also important to realize that fault activity can be enhanced by loading and unloading of the lithosphere by sediment, water or ice. For instance, small changes in pore water volume occurring when a porous medium is mechanically compressed (loaded) or expanded (unloaded), both result in changes in pore water pressure. In highly permeable rock these transient changes in fluid pressure will quickly dissipate. However, in low-permeability units like shale or Boom Clay the effects of loading and unloading can induce anomalous fluid pressures that require thousands of years to return to equilibrium conditions.

5.8.3.5 Thermal processes

The present-day temperature conditions in the subsurface of the Netherlands may not be in equilibrium with the current boundary conditions; they are in a transient state reflecting in greater or lesser extent paleo boundary conditions (e.g. paleo surface temperatures). The reported average geothermal gradient in the Netherlands amounts 31.3°C/km (Verweij, 2016a: p.20). In addition, taking into account the limited heat output from the disposed waste, thermal processes in the host rock far field will likely not be relevant for the safety of the disposal system.

5.8.4 Candidate processes and parameters for monitoring

An overview of candidate processes and parameters for monitoring the Boom Clay host rock in the far field is provided in Table 1-44 and Table 1-45.

Table 1-44 Candidate processes and parameters for monitoring the Boom Clay host rock in the far field related to safety functions of the barrier

Safety function	Process	Parameter	Comment	Reference
Retardation of contaminant migration to the environment of the contaminants released from the waste packages (R3)	Advection	Hydraulic head gradient	no measured data on pressure and groundwater flow available	(Vis, 2014: Ch.3)
	Diffusion	Concentration gradient	small gradients over a large extension	Preliminary PA results
Ensuring stable conditions for the disposed waste and the system components (I2)	N/A	N/A		

Table 1-45 Candidate processes and parameters for monitoring the Boom Clay host rock in the far field related to other functions of the barrier

Function	Process	Parameter	Comment	Reference
Very low advection due to very low permeability and low hydraulic gradients	Advection	Hydraulic head gradient	no measured data on pressure and groundwater flow available	(Vis, 2014: Ch.3)
	Compaction	Strain Pore pressure Fluid flux	Long-term compaction of the Dutch subsurface is ongoing	(Vis, 2014: S.3.3)
No permanent bypass, e.g. presence of fault	Seismicity	Seismic energy	May induce faults. Plastic properties of Boom Clay may counteract fractures	(Vis, 2014: S.4.3)
	Deformation	Stress/Strain	Can be beneficial for self-healing of fractures	(Vis, 2014: S.1.3)
	Advection	Hydraulic head gradient	Presence of faults can be minimized by siting	(Vis, 2014: Ch.3)
Chemical buffering capacity	Chemical buffering	pH, Eh	Buffering by minerals present in the Boom Clay - pyrite and carbonates - and by organic matter	(Koenen, 2014: S.6.2); ONDRAF/NIRAS, 2013: S. 4.1.2.2
Propensity for plastic deformation and self-sealing of fractures	Deformation	Stress/Strain	May counteract fractures/ faults	(Vis, 2014: S.1.3)
Geochemical characteristics affect solubility of radionuclides	Solution/ precipitation	Species concentration	Dissolved organic matter increases the solubility of some radionuclides by several orders of magnitude	ONDRAF/NIRAS, 2013: S. 3.3.9.1
Sorption capacity to retard the migration of radionuclides	Solution/ precipitation	Species concentration	Dissolved organic matter increases the solubility of some radionuclides by several orders of magnitude	ONDRAF/NIRAS, 2013: S. 43.3.9.1
Absence of profound erosion	Erosion	Boom Clay thickness	Very slow process; geological time scale	Vis, 2014: S. 1.5.2
Limited seismicity	Seismicity	Seismic energy	May induce faults. Plastic properties of Boom Clay may counteract fractures.	(Vis, 2014: S.4.3)

5.9 Shaft seal

5.9.1 Properties and features of the shaft seal

As already mentioned in Section 2.6, two vertical shafts are foreseen in the OPERA disposal concept for connecting the underground facility and the surface and underground facilities, see Figure 1-7. The shaft dimensions of the OPERA concept are based on a design previously proposed as part of the Dutch CORA program (CORA, 2001: Ch.5). One shaft is intended for transferring the radioactive waste containers from the surface to the underground, and one for the transport of workers and equipment. Table 1-46 summarizes the dimensions of the shafts.

Table 1-46 Dimensions of the shaft of the OPERA disposal concept

	Number	Length [m]	Diameter [m] inner/excavated	Concrete Support Thickness [m]	Spacing [m]
Shaft	2	500	5.0/6.2	0.6	1110

In the past, limited efforts were performed in the Netherlands concerning the design, construction and performance of shafts considered for a geological disposal facility in Boom Clay. These efforts were however only generic and tentative, and did not include any specific information about the design and performance of shaft seals, e.g. (CORA, 2001: Ch.5; Van de Steen, 1998: S.2.2). (Wakker, 2010) mentioned that for the final closure of the facility the galleries and shafts have to be backfilled and closed, but no specifications for the shaft seals were provided.

As part of the OPERA program, the stress response of Boom Clay due to the excavation of the shaft in Boom Clay was calculated in (Arnold, 2014: Section 4.7), and it was found that the plastic zone can extend to a maximum of 6.0 m around the shaft at 500m depth. In addition, the liner collapse load, i.e. the pressure exerted by the Boom Clay on the shaft lining, decreases when increasing the cavity radius: Also in (Arnold, 2014) no specifications about any backfilling and/or sealing of the shafts were provided. After repository closure, any retrieval of already emplaced waste containers would essentially involve re-opening the repository by the original shafts or by creating new ones, after which the retrieval is possible.

5.9.2 Safety functions and other functions of the shaft seal

The main safety functions of a shaft sealing system are to limit water flow from the overlying rock, and, in the long term, to delay migration of contaminants upon their release from the waste packages, see also Table 1-47. In addition, the shaft should provide stable THMC (thermo, hydro, mechanical and chemical) behaviour during the required lifetime (Table 1-48).

Table 1-47 Main safety functions of the shaft sealing system

Safety function	**Reference**
Limit water flow through the disposal system (R2)	Section 2.4

Table 1-48 Other functions of the shaft sealing system

Function	**Reference**
Provide stable THMC (thermo, hydro, mechanical and chemical) behaviour during required lifetime	(ONDRAF/NIRAS, 2013: Table 22)

5.9.3 Identification and description of related main processes

Facility closure

When the facility is closed the shafts (and ramp) will be refilled and sealed (Verhoef, 2014a: p.7). Since there is no specific information about the shafts of the OPERA disposal concept is available yet, only generic features of the shafts can be proposed. In principle, the shaft contains the following features:

- A concrete lining, which is installed during the construction of the shafts and which is necessary for support of the surrounding Boom Clay and layers of the overburden;
- Backfill, which is installed during the closure of the shafts;
- A shaft seal, which may consist of several overlying layers and various materials, depending on their intended functions.

The design of the shaft seals and their installation have to be feasible and consistent with the Dutch safety strategy. This includes, among other considerations, the requirements that (Verhoef, 2014c: p.1):

- The geological disposal facility has to be designed, operated and closed such that the process is reversible and the waste is retrievable;
- The materials and implementation procedures will not unduly perturb the safety functions of the host formation, or of any other component;
- The various disposal galleries and sections, and the geological disposal facility as a whole, will be closed (access routes backfilled and sealed) following a progressive, step-wise closure procedure.

Although there are numerous examples of tunnel and shaft sealing available from the mining industry, these designs may be less well applicable to a geological facility for the disposal of radioactive waste because of the strict requirements placed on the long-term performance of repository seals. Nevertheless, various conceptual designs of tunnel and shaft sealing systems are available, for example for salt formations that for the Morsleben radioactive waste repository in Germany, and in France that for the repository in Callovo-Oxfordian clay (Jobmann, 2013). Conceptual seal designs typically employ a sequence of various load-bearing and impermeable materials, including crushed rock, concrete, asphalt, and bentonite clay.

Shaft sealing elements

A shaft seal may be constructed from several components and/or compounds to ensure that the overall performance of the seal system will meet requirements imposed by the regulatory body. For example, the design adopted in the Shaft Seal Experiment as part of the RESEAL-II project was executed in the HADES facility in Belgium and consisted of several layers of concrete, bentonite, resin, and sand, as depicted in Figure 1-18 (ONDRAF/NIRAS, 2013: p.227).

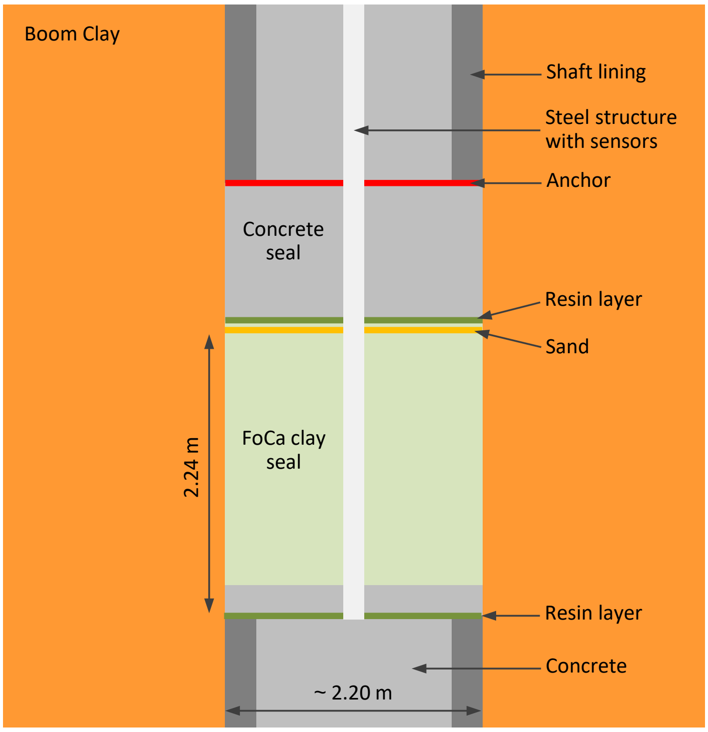


Figure 1-18 Schematic overview of the Shaft Sealing Experiment design in the HADES URL.

In the Shaft Seal Experiment the functions of the various layers were as follows (Van Geet, 2009: p.48):

- The resin layers served to render the seal water and gas tight towards the underlying grout;
- The compacted FoCa[20] swelling clay has favourable properties with respect to saturation time, swelling pressure, hydraulic conductivity and ability to be compacted;
- The sand acts as a filter allowing an axial water injection from the top of the seal;
- The reinforced-anchored concrete plug was installed to block the seal axially.

It was concluded in RESEAL-II and additional efforts performed in Belgium that the shaft sealing system in a Boom Clay environment has yet further to be improved. The experiences gained from the Belgian Shaft Seal Experiment are certainly beneficial for further developing such a system.

Based on the outcomes of the RESEAL-II project, the following requirements for shaft seals for closing a Boom Clay based repository, were identified in the Belgian RD&D Plan (ONDRAF/NIRAS, 2013: Table 22):

- Hydraulic conductivity similar to that of the host formation;
- Self-sealing of shaft seal components, in case the concrete shaft lining would be removed upon repository closure;
- Knowledge of hydration time and hydration mechanisms;
- Homogenised mixture after saturation;
- No preferential gas flow through the seal;
- No preferential migration of radionuclides at the interface seal/Boom Clay;
- Stable THMC (thermo, hydro, mechanical and chemical) behaviour during required lifetime.

An important issue influencing the design of shaft seals will be a decision on whether these components should be gas permeable, to prevent gas build-up and pressurisation in the repository (ONDRAF/NIRAS, 2013: Section 5.4.2). In Belgium, there is a programme of ongoing RD&D to characterise the mechanisms by which gas is produced and the volume of gas that may be

[20] FoCa clay: Fourges-Cahaignes clay

generated (together with the gas generation rate), in order to improve understanding of the potential impact of gas generation on the long-term evolution of the disposal system.

In the Belgian RD&D Plan is was recommended to define which materials should be used as seals, taking into account retrievability and how to install seals in the disposal galleries, access gallery and shafts, taking into account retrievability. In addition, it will be checked whether a large-scale seal (in the waste shaft) can be constructed with features similar to Boom Clay (ONDRAF/NIRAS, 2013: Section 5.4.2).

Taking into account the experiences in other waste disposal programmes, and the scarce information provided in relevant Dutch documents, the aspects mentioned above might be used when developing a shaft seal in a later stage.

5.9.4 Candidate processes and parameters for monitoring

In addition to the safety functions mentioned in Table 1-47, it is apparent that the processes occurring in the lining of the repository's galleries (Section 5.6) and the host rock near field (Section 5.7) would also apply to the shaft. The respective sections provide additional details for these features of the shaft system. Table 1-49 and Table 1-50 provide an overview of (internal) processes and parameters identified for monitoring of the shaft.

Table 1-49 Candidate processes and parameters for monitoring the shaft related to safety functions of the barrier

Safety function	Process	Parameter	Comment	Reference
Limit water flow through the disposal system (R2)	• Swelling of clay/ bentonite	• Pore pressure • Swelling pressure	For (swelling) clay parts of the shaft	(Van Geet, 2009: S.2.2)
	• Resaturation • Advection • Diffusion	• Pressure gradient • Permeability • Pore pressure • Relative humidity	Water flux from overlying rock formations	(Jobmann, 2013: S.5.2.1)

Table 1-50 Candidate processes and parameters for monitoring the shaft related to other functions of the barrier

Safety function	Process	Parameter	Comment	Reference
Provide stable mechanical behaviour during lifetime	• Deformation	• Total stress • Displacement		(ONDRAF/NIRAS, 2013: Table 22)

6 Testing of Modern2020 Screening Methodology

This chapter tests the Modern2020 screening methodology as outlined in (White, 2017: Chapter 6), and depicted in Figure 1.3. In the remainder of this chapter, the various steps of the screening workflow are followed, considering the selected example case of the OPERA Supercontainer. The screening steps are discussed in a sequential manner, following the Modern2020 workflow, and each step is shortly evaluated thereafter.

In general, it can be noted that many elements of the OPERA safety case were available at the moment of screening (disposal concept, safety functions, FEP-list, scenario definitions, process studies, etc.). However, the outcomes of the OPERA PA at the moment of writing are insufficiently consolidated to be accounted for in the screening, and uncertainty/sensitivity analyses that allow to break down overall system behaviour into safety function- or barrier-level were not available.

6.1 PRO1. Start of the screening

Modern2020 D2.1 cited:

PRO1. Start

The starting point is 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.

6.1.1 Initial identification of processes

Start of the Modern2020 screening process are the raw inventories of identified processes and parameters (“preliminary process list”) which have been based on the OPERA FEP Database (Schelland, 2014), the disposal outline and the safety functions defined in OPERA and are summarized in the previous chapter.

The procedure for compiling a preliminary list of parameters has been described in Section 1.4, and summarized in Figure 1-19.

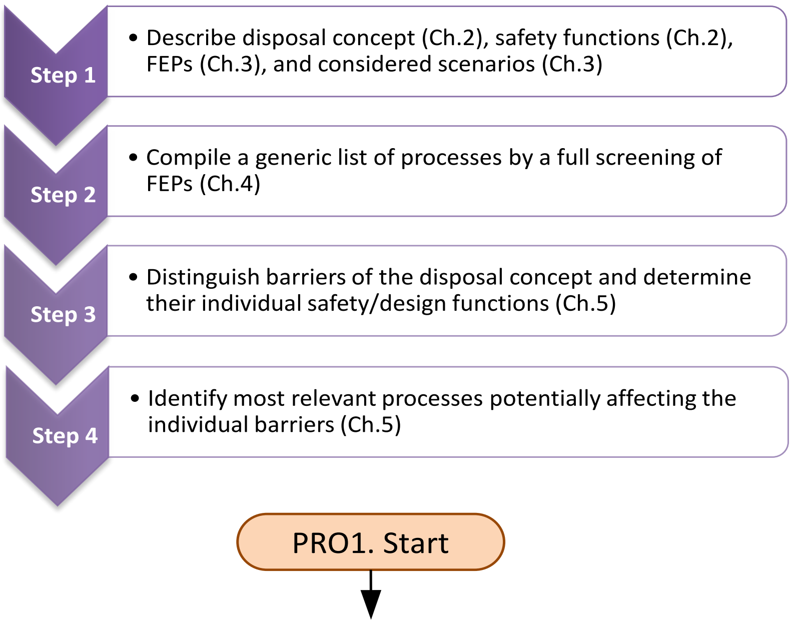


Figure 1-19 Steps taken for identifying the most relevant processes to consider in the Modern2020 screening process - PRO1 *Start*.

The processes and parameters that represent the *preliminary process list* are summarized in Chapter 5, together with the more detailed descriptions of processes and related parameters for each of the engineered barriers considered. A preliminary list of processes and parameters was generated, following a structured, barrier wise approach: for each barrier considered, general properties and features are summarized and the related safety functions and other functions are described. Based on the screening of the FEP-list in the previous chapters, the related main processes have been identified and described. Taking into account the expected evolution rates of the individual processes in time, a list of processes and related parameters has been identified which are considered to evolve sufficiently fast to allow monitoring on a realistic time scale. This results then in the preliminary list of processes and parameters that forms the input of the Modern2020 Screening in the second stage described below.

While the previous chapters gives an overview on all relevant barrier components, the remainder of this chapter focuses on the processes and parameters of a single example case: the OPERA Supercontainer. The list of processes and parameters which were identified as candidates for monitoring of the OPERA Supercontainer are summarized in Section 5.3.5 of this report. Table 1-22 in Section 5.3.5 comprises a raw list of candidate processes for monitoring of the OPERA Supercontainer. That list contains several duplicate processes and/or processes which are closely related. Cleaning of that list and merging these (duplicate) processes results in Table 1-51 listing the processes which are taken forward in the subsequent screening process:

Table 1-51 Supercontainer processes considered for further screening

Notation	Process
	Carbon steel overpack
SC-1	Mechanical disturbance of carbon steel overpack as a result of corrosion (stress corrosion cracking, cold cracking, welding)
SC-2	Steel corrosion following water ingress, resaturation
	Concrete buffer
SC-3	Thermal evolution
SC-4	Water ingress – resaturation, flooding
SC-5	Geochemical evolution due to pore water/concrete interaction
SC-6	Mechanical load evolution due to external forces
SC-7	Mechanical load evolution due thermal processes (expansion)
SC-8	Corrosion induced cracking of concrete buffer
	Steel envelope
SC-9	Steel corrosion due to interaction with Boom Clay pore water
SC-10	Mechanical load evolution as a result of external forces
	Supercontainer
SC-11	Release of radiation

6.1.2 Evaluation of Step PRO1.

The present report identifies processes relevant for the performance of the various barriers of the OPERA disposal concept. The step-wise procedure depicted in Figure 1-19 leads to the lists of processes as well as parameters for a set of scenarios currently considered in the OPERA safety case. These processes and parameters are summarized in the respective tables in Chapter 5 of this report.

The inventories of processes and parameters as outlined in Chapter 5 will provide the necessary input for the next steps in the screening methodology. The inventory can also serve for further detailing of design criteria for the various engineered barriers, and provides topics for further analysing safety-relevant processes.

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

6.2.1 Notes to Step PRO2.

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

In Modern2020 Deliverable D2.1 the following guiding questions provide guidance for determining the relevance of processes identified in PRO1 for further consideration (White, 2017: Section 6.2.3):

<u>Main question:</u>

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

<u>Supplementary Guiding Questions:</u>

- *PRO2.1 Is the process related to one or more safety functions of any element of the repository system?*
- *PRO2.2 Is the process related to any safety function indicator?*
- *PRO2.3 Is the process linked to a parameter modelled in the safety assessment that has a significant impact on system performance (dose/risk)?*
- *PRO2.4 Is the process related to system performance that could lead to a decision to retrieve waste or otherwise reverse the disposal process?*

With respect to the Supplementary Guiding Questions, the following applies for the screening of the OPERA disposal concept:

- **PRO2.1:** Following the line set out in the previous chapter, all processes are related to either safety functions or other functions identified for the considered barriers of the OPERA disposal concept. Whether the latter group is indispensable related to safety is difficult to establish in the current phase, also because some of them are related to operational safety which is not covered in the current OPERA Safety Case. For the present analysis it is assumed that the functions identified for the various engineered barriers are in one or the other way related to a safety function of the related barrier, although not explicitly determined at this moment. Therefore, the generic answer to this question is “yes”.
- **PRO2.2:** No safety function indicators have yet been defined in the Dutch research programme[21]. Currently, insufficient quantitative information is available to define meaningful quantitative safety function indicators and/or safety function indicators criteria or alike. Therefore the generic answer to this question is “no”.
- **PRO2.3:** From the OPERA programme, no quantitative link between the safety assessment and parameters is available at this moment, i.e. there is no explicitly defined “system performance” that provides an envelope of parameter evolutions that has been classified as ‘safe’. The screening performed here is therefore based on expert judgement, focussing on long-term safety rather than a predefined “system performance”.
- **PRO2.4:** No guidelines or regulations are currently defined with respect to how a decision to retrieve waste or otherwise reverse the disposal process has to be supported by monitoring. The screening performed here is therefore based on expert judgement, and in order to avoid repetition with respect to the previous question, focus is given on the question whether monitoring is expected to support any decision on retrieval of waste.

In the following sections the questions PRO2.3 and PRO2.4 are addressed for processes identified as relevant for the functioning of the OPERA Supercontainer. The information in the next subsections is organized scenario/what-if case-wise. As discussed above the main focus of the OPERA Safety Case concerns the long-term safety; the accompanying safety assessment thus builds on a set of scenarios and what-if cases relevant for the long-term safety. Altered scenarios

[21] Although a generic set of safety function indicators was defined in OPERA (Rosca, 2013; Schröder, 2013), these were used as a tool for analysing PA outcomes rather than providing criteria in support of monitoring activities.

are currently less well described and only very preliminary PA calculation results are yet available from OPERA.

The screening itself is performed in two steps: in the first step it is questioned whether the safety function is relevant for the long-term safety in the considered scenario. If yes, the related functions/processes are assessed. If not, the screening is stopped and all functions/processes are marked as “not applicable” (n.a.).

6.2.2 Results of screening of OPERA Supercontainer processes

PRO2.1

As discussed in the previous section, the generic answer to PRO2.1 is “yes”

PRO2.2

As discussed in the previous section, the generic answer to PRO2.2 is “no”.

PRO2.3

The following Table 1-52 addresses the questions related to PRO2.3 for the OPERA Supercontainer, for the Normal Evolution Scenario (NES), and the Alternative Evolution Scenarios (AES) selected for the present analysis (see Chapter 3). Next to the safety function of the Supercontainer, denoted here as “SF-1”, also other functions of the Supercontainer identified are assessed.

Table 1-52 Processes – scenario matrix for the OPERA Supercontainer for question PRO2.3 (impact on system performance)

Supercontainer Processes	Normal Evolution Scenario (NES)	Altered Evolution Scenario (AES): Abandonment of the facility (AA1)	Poor Sealing scenario (AS1)	Excessive early containment failure scenario (EEC1)	Excessive gas generation scenario (EGC1)	Criticality event (ECC1)
*Supercontainer Safety Function **SF-1** – Engineered Containment*						
SF-1 – Prevent contaminant release	no	yes	yes	yes	no	no
Carbon steel overpack						
SC-1 - Mechanical disturbance	*n.a.*	+	+	*n.a.*	*n.a.*	*n.a.*
SC-2 - Steel corrosion		+	+			
Concrete buffer						
SC-3 - Thermal evolution	*n.a.*	o	o	*n.a.*	*n.a.*	*n.a.*
SC-4 - Water ingress		o	o			
SC-5 - Geochemical evolution		+	+			
SC-6 - Mechanical load (external forces)		o	o			
SC-7 - Mechanical load (thermal processes)		o	o			
SC-8 - Corrosion induced cracking		o	o			
Steel envelope						
SC-9 - Steel corrosion	*n.a.*	o	o	*n.a.*	*n.a.*	*n.a.*
SC-10 - Mechanical load		o	o			
Supercontainer						
SC-11 - Release of radiation	OP	OP	OP	OP	OP	OP

n.a. : not applicable
\+ : clear link
o : indirect impact or impact can currently not be excluded
OP : during the operational phase

The following arguments apply to the assessment whether a process has impact on the system performance:

- For the NES all identified processes will occur, either early after disposal or at later stages after closure of the facility. Consequently, these processes have impact on the long-term safety. However, following the line of argumentation that the NES represents a safe evolution covered by the safety case, in case of the NES their impact is taken into account in the design of the disposal concept and therefore the limited impact is covered by the safety case. This is indicated with "*n.a.*" in Table 1-52. This interpretation excludes the ability to monitor evolutions that are "unexpected" in the sense that these are not covered by any of the scenarios. However, it still makes sense to proceed that way in this part of the screening, otherwise the conclusion would be that no single process can be excluded, when it comes to the ability to monitor a yet undefined future evolution.
  However, in general it can be concluded on basis of the current system understanding that for future evolutions/scenarios where the host rock's barrier function is not compromised, the performance of the Supercontainer's containment function has little impact on the long-term safety. Examples of quantitative assessments of the impact of system parameters and processes on the dose rate to the biosphere for a disposal concept in Boom Clay are provided in Figure 1-20 (EC-FP6 project PAMINA (Schröder, 2009: Ch. 6)) and Figure 1-21 (Preliminary result of OPERA performance assessment) and are shortly discussed below.

  In a probabilistic performance assessment executed in the PAMINA project, the impact of several parameters on the performance of a simplified disposal system for vitrified HLW was analysed. Three parameters were assessed: the clay content in disposal cell plug, the diffusion coefficient in Boom Clay and the glass dissolution time (Table 1-53). Despite the significant variation of model parameters the total dose rate to the biosphere remains orders of magnitude below reference values (0.1 mSv/a). Note that although the glass dissolution rate is only partly influencing the safety function "Engineered containment", in this case, where immediate failure of the container has been assumed, it provides some evidence that container failure time has a limited effect on the dose rate as long as diffusion of radionuclides is the main migration process through the host rock.

Table 1-53 Variation of model parameter and distribution – PAMINA (Schröder, 2009)

parameter	minimum	maximum	distribution
clay content in plug [%]	0	100	uniform
$D_{a\ clay}$ [m²/a]	$1.26 \cdot 10^{-3}$	$1.26 \cdot 10^{-2}$	uniform
glass dissolution time [a]	100	10’000	uniform

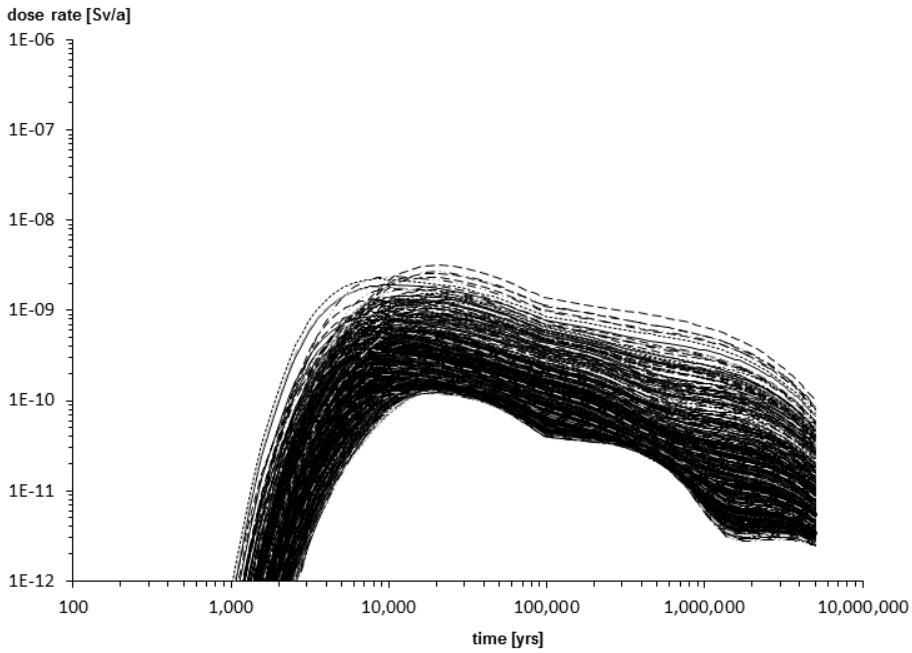


Figure 1-20 Evolution of the dose rate in the biosphere – impact of clay content in disposal cell plug, nuclide diffusion coefficient in Boom Clay and glass dissolution time.

As part of the performance assessment of the OPERA disposal concept uncertainty analyses are in progress in which, next to other factors, the time of failure of the OPERA Supercontainer (cf. **Table 1-20**) on the dose rate in the biosphere is being assessed. The preliminary results given in Figure 1-21 show that, considering the envelope of Supercontainer failure times assumed for the NES (1500 - 700’000 years), the peak values of the dose rate are only little affected when container failure would occur earlier or later than the best estimate value (central value).

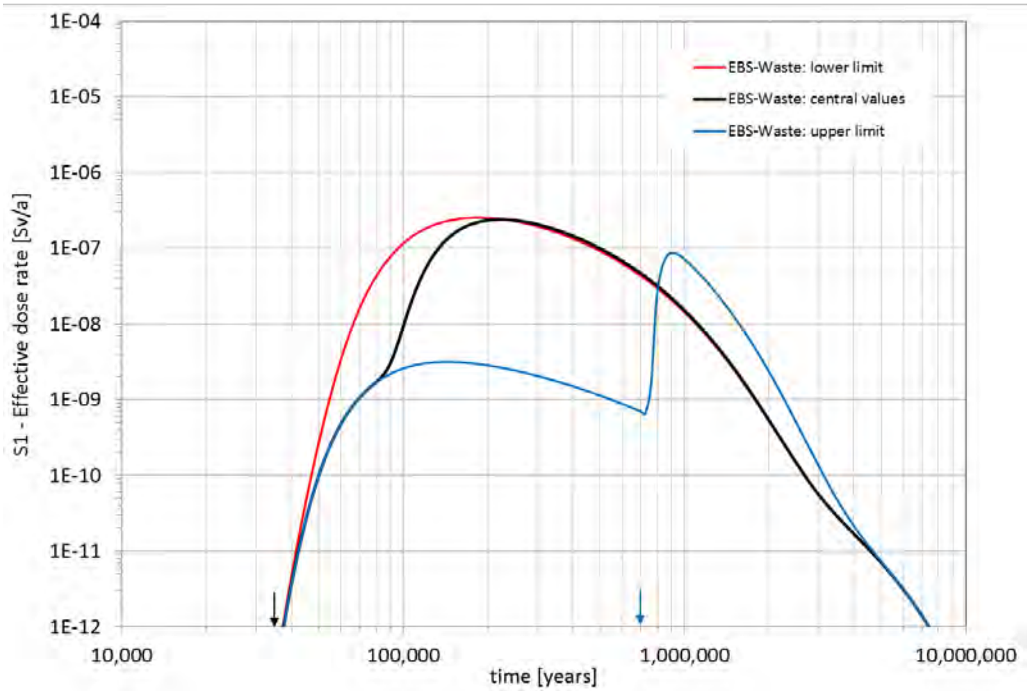


Figure 1-21 Preliminary OPERA test calculation results: effect of time of failure of the OPERA Supercontainer on the dose rate in the biosphere. The arrows indicated the failure times of the OPERA Supercontainer (lower limit of 1500 years is not visible in the graph).

- For the alternative scenarios AA1 (*Facility abandonment*) and AS1 (*Poor sealing*), the Supercontainer's safety function SF-1 is judged to have impact on the long-term safety. Table 1-52 identifies the processes which are related to this safety function.
- The alternative scenario EEC1, *Excessive early containment failure*, has impact on the Supercontainer safety function SF-1. However, because in this scenario an early failure is assumed in a generic manner, no specific process can be attributed to it.
- For the alternative scenarios EGC1, *Excessive gas generation*, and ECC1, *Criticality event*, it is judged that these scenarios do not relevantly impair the barrier function of the host rock. Like for the NES, it is assumed that the failure time of the container has no relevant effect on the long-term safety in this case.
- Although not part of the OPERA safety case, is can be easily judged that during the operational phase, the release of radiation (Process SC-11) has impact on the system performance and (operational) safety.

PRO2.4

The following Table 1-54 addresses the questions related to PRO2.4 for the OPERA Supercontainer:

- PRO2.*4 Is the process related to system performance that could lead to a decision to retrieve waste or otherwise reverse the disposal process?*

Table 1-54 Processes – scenario matrix for the OPERA Supercontainer for question PRO2.4 (relation to decision to retrieve waste)

Supercontainer Processes	Normal Evolution Scenario (NES)	Altered Evolution Scenario (AES)				
		Abandonment of the facility (AA1)	Poor Sealing scenario (AS1)	Excessive early containment failure scenario (EEC1)	Excessive gas generation scenario (EGC1)	Criticality event (ECC1)
*Supercontainer Safety Function **SF-1** – Engineered Containment*						
SF-1 – Prevent contaminant release	no	*n.a.*	yes	yes	no	no
Carbon steel overpack						
SC-1 - Mechanical disturbance	*n.a.*	*n.a.*	+	*n.a.*	*n.a.*	*n.a.*
SC-2 - Steel corrosion	*n.a.*	*n.a.*	+	*n.a.*	*n.a.*	*n.a.*
Concrete buffer						
SC-3 - Thermal evolution	*n.a.*	*n.a.*	-	*n.a.*	*n.a.*	*n.a.*
SC-4 - Water ingress	*n.a.*	*n.a.*	o	*n.a.*	*n.a.*	*n.a.*
SC-5 - Geochemical evolution	*n.a.*	*n.a.*	o	*n.a.*	*n.a.*	*n.a.*
SC-6 - Mechanical load (external forces)	*n.a.*	*n.a.*	+	*n.a.*	*n.a.*	*n.a.*
SC-7 - Mechanical load (thermal processes)	*n.a.*	*n.a.*	-	*n.a.*	*n.a.*	*n.a.*
SC-8 - Corrosion induced cracking	*n.a.*	*n.a.*	o	*n.a.*	*n.a.*	*n.a.*
Steel envelope						
SC-9 - Steel corrosion	*n.a.*	*n.a.*	+	n.a.	n.a.	n.a.
SC-10 - Mechanical load	*n.a.*	*n.a.*	+	n.a.	n.a.	n.a.
Supercontainer						
SC-11 - Release of radiation	OP	OP	OP	OP	OP	OP

n.a. : not applicable
\+ : clear link
o : indirect impact or impact can currently not be excluded
OP : during the operational phase

For the assessment whether monitoring of a process could support a decision to retrieve waste or otherwise reverse the disposal process the following arguments apply:

- For the NES no waste retrieval or reversal of operations apply, arguing that as long as the evolution is covered by the (range defined by the) parameter evolution defined in the NES, retrieval of the waste is not applicable.
- In case of abandonment of the facility, AA1, by definition no waste retrieval or reversal of operations apply.
- The scenario AS1, poor sealing, may lead to an impairment of the safety provided by other elements of the disposal. Here, additional disturbances of the safety functions of the Supercontainer could justify a decision for waste retrieval or reversal of operations.
- An excessive early failure of Supercontainers, scenario EEC1, could in principle lead to a decision for waste retrieval or reversal of operations. The OPERA safety assessment treats this scenario as a theoretical exercise by assuming an early time of Supercontainer failure instead of the result of specific processes. Therefore, an assessment of the individual related processes is not applicable for this scenario. However, monitoring of the processes indicated for AS1 might help to identify whether an (excessive) early failure might have occurred, and support decision on retrieval of the waste.
- For the alternative scenarios EGC1, excessive gas generation, and ECC1, criticality event, it is judged that the scenario does not impair relevantly the barrier function of the host rock. Like for the NES, it is assumed that in this case the failure time of the container has no relevant effect on the long-term safety in this case. Monitoring on related processes is therefore judged not to have added value in support of a decision on retrieval or reversal of operations.

6.2.3 Evaluation of Step PRO2.

For PRO2 , the following general considerations related to the guiding questions mentioned in the previous sections can be given:

- **PRO2.1:** The processes identified in Chapter 5 relevant to the evolution of the OPERA disposal system have been selected based on their potential impact on safety functions of (components of) the individual barriers. Consequently, the answer to the supplementary question PRO2.1 would always be "yes". In the present context, the screening process is performed separately for each barrier, either engineered of natural. Taking this into account, the supplementary question PRO2.1 is proposed to be reformulated as follows, in analogy with (Jobmann, 2017):
  PRO2.1 Is the process related to one or more safety functions of the barrier under consideration?

- **PRO2.2:** For the OPERA disposal concept, only a few indicators and criteria for design have been established, which are, however, not directly related to the long-term safety. Examples are a temperature criterion (<100ºC in the host rock; Verhoef, 2014a: p.12), or a limit value for the potential radiation exposure (maximum dose rate of 10 mSv/h at the surface of all waste canister; Verhoef, 2014a: p.15). Consequently, detailed answers to this particular question that allows to safely exclude processes could not be provided. The PRO2.2 question thus does not lead to excluding any process considered relevant for the OPERA Supercontainer, or any other barrier of the OPERA disposal system.

- **PRO2.3:** A number of processes identified in this report have been investigated in the OPERA programme. With the OPERA safety assessment still ongoing, processes and parameters can only qualitatively, or indirectly, be linked to the barriers performance. "Indirectly" modelled processes in the OPERA safety assessment refer to, for example, processes affecting the timing of the release of radionuclides from the waste package. Where applicable, an evaluation of the related processes has been performed.

- **PRO2.3:** Like other disposal designs, the OPERA disposal system relies on the multi-barrier principle and the failure of a single barrier like the OPERA Supercontainer as a result of a particular process does not automatically imply that a significant impact of the system performance in terms of dose and/or risk will occur, neither that the disposal system has become unsafe. A significant impact on system performance can only be expected if the multi-barrier system is compromised, as a result of a combination of processes. That aspect can only be considered on basis of detailed PA results and uncertainty analyses, which are not available at the moment of writing.

- **PRO2.4:** The Dutch policy on radioactive waste disposal currently provides insufficient criteria to analyse on basis of which monitoring results or activities already emplaced waste might be retrieved or the disposal process might be reversed. Criteria for waste retrieval or reversal of operation still need to be established in the Netherlands. In additional, considering the multi-barrier principle, it has to be established whether the failure of a single barrier due to the impact of a single process or a combination of processes would justify a complicated reversal of operations or even waste retrieval.

6.3 PRO3. Park process

6.3.1 Notes to step PRO3.

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

6.3.2 Evaluation of step PRO3.

Detailed assessments of all relevant processes potentially affecting the safety, both for the operational and post-closure phases, are yet to be performed. In addition, explicit criteria need to be developed which could serve as a basis for the decision to reverse operations or to retrieve (parts of) already emplaced waste containers. As a consequence, there are presently no "Parked processes" applicable to the OPERA disposal concept.

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

6.4.1 Notes to Step PRO4.

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

In Modern2020 Deliverable D2.1 the following guiding questions provide guidance to this step (White, 2017: Section 6.2.3):

- **PRO4. Is there value in monitoring the process in support of the post-closure safety case?**
    - *PRO4.1: 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 include materials science, procedure development, full-scale experiments, natural analogues and fundamental scientific understanding.)*

- *PRO4.2: 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)?*
- *PRO4.3: Could the changes to the repository system resulting from the process be quantifiable during the monitoring period?*
- *PRO4.4: Could any uncertainty that would be addressed by monitoring the process be more readily addressed by changes to the repository design?*
- *PRO4.5: Could monitoring the process support repository design improvements?*
- *PRO4.6: Could monitoring the process result in greater system understanding that would be incorporated in a periodic update to the post-closure safety case?*

6.4.2 OPERA Supercontainer

The questions related to step PRO4 have been evaluated for the processes identified for the Supercontainer (SC-x) in Table 1-55. In our understanding the answer to PRO4 should be "yes", if any of the sub-questions is answered positively. The only exception is question PRO4.3: if one expects measurable changes only beyond the timeframe during which monitoring can be performed, one may argue that this should lead to an immediate "no" as answer to the overall question. However, because the assessment of this aspect is based on expert judgement rather than detailed technical analyses, it is not used as a criterion for parameter exclusion.

The topic "confidence" (PRO4.2) is a complex one to assess: it is from current Dutch perspective not possible to exclude that measurement of a parameter can contribute to confidence, even if from expert views no relevant contribution of the data is expected. This means that, from the Dutch perspective, PRO4.2 might also 'overrule' PRO4.3.

In Table 1-55 the sub-questions are marked ("✓") which can be most easily answered with "yes", whereas PRO4.3 is answered independently, and not affecting the overall outcome of question PRO4.

Table 1-55: Processes – subquestion matrix for the OPERA Supercontainer

	PRO4.1	PRO4.2	PRO4.3	PRO4.4	PRO4.5	PRO4.6	PRO4
Carbon steel overpack							
SC-1 - Mechanical disturbance	✓		no				yes
SC-2 - Steel corrosion		✓	no				yes
Concrete buffer							
SC-3 - Thermal evolution		✓	yes				yes
SC-4 - Water ingress		✓	no				yes
SC-5 - Geochemical evolution	✓		no				yes
SC-6 - Mechanical load (external forces)	✓		yes				yes
SC-7 - Mechanical load (thermal processes)		✓	yes				yes
SC-8 - Corrosion induced cracking		✓	no				yes
Steel envelope							
SC-9 - Steel corrosion		✓	yes				yes
SC-10 - Mechanical load	✓		yes				yes
Supercontainer							
SC-11 - Release of radiation		✓	no				yes

6.4.3 Evaluation of step PRO4.

In the current stage of the Dutch programme, the questions summarized under PRO4 are obviously too early for providing substantiated answers: one motivation of the question is to eliminate processes and parameters from the list for which one considers sufficient understanding to be present. However, the question of what can be considered an adequate level of monitoring, is not only a technical one, and it is therefore from our point of view not possible to exclude any parameters at this step.

Question PRO4.3 is somewhat different than the others since it relates to the evolution of the repository system. That topic is part of PAR1 – *Define expected parameter evolution.*

6.5 PRO5. Translate process into parameter(s)

6.5.1 Notes to Step PRO5.

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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).*

The translation from processes to parameters has already been performed in detail in Chapter 5 of the present report. In the following subsection, as example the processes and related parameter for the OPERA Supercontainer are summarized.

6.5.2 OPERA Supercontainer

In Section 5.3.5, parameters representative of processes relevant for the OPERA Supercontainer were identified. Table 1-56 summarizes the processes and parameters.

Table 1-56: Processes and parameters identified as candidates for monitoring for the OPERA Supercontainer

Notation	Process	Parameter
Carbon steel overpack		
SC-1 - Mechanical disturbance	Mechanical disturbance of carbon steel overpack as a result of corrosion (stress corrosion cracking, cold cracking, welding)	Pressure Stress
SC-2 - Steel corrosion	Steel corrosion following water ingress, resaturation	Redox potential pH Gas generation Pore water chemistry H_2 concentration Electrochemical gradients
Concrete buffer		
SC-3 - Thermal evolution	Thermal evolution	Temperature
SC-4 - Water ingress	Water ingress – resaturation, flooding	Saturation Water content
SC-5 - Geochemical evolution	Geochemical evolution due to pore water/concrete interaction	Redox potential pH Pore water chemistry
SC-6 - Mechanical load (external forces)	Mechanical load evolution due to external forces	Pressure Stress
SC-7 - Mechanical load (thermal processes)	Mechanical load evolution due thermal processes (expansion)	Pressure Stress
SC-8 - Corrosion induced cracking	Corrosion induced cracking of concrete buffer	Stress
Steel envelope		
SC-9 - Steel corrosion	Steel corrosion due to interaction with Boom Clay pore water	Redox potential pH Gas generation Pore water composition H_2 concentration Electrochemical gradients
SC-10 - Mechanical load	Mechanical load evolution as a result of external forces	Pressure Stress
Supercontainer		
SC-11 - Release of radiation	Potential radiation exposure	Dose rate

6.5.3 Evaluation of step PRO5.

In step PRO5, processes can be broken down in a straightforward manner into parameters as indicators for these processes, based on the work summarized in Chapter 5.

6.6 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. By doing so, understanding of the evolution of the parameter values over the monitoring period can be developed, and requirements for monitoring the parameters can be determined. This is needed in order to evaluate in the next step (TEC1) whether the potential options for monitoring are suitable, e.g. to understand if techniques are available with sufficient precision, accuracy and long-term reliability to monitor the scale of potential changes over the monitoring period. This, in most cases, requires presentations with quantified uncertainties to ensure that responses to monitoring data account for the expected performance of the facility. Thus, in essence, in PAR1 not only parameter evolutions need to be established, but also related uncertainty ranges.

It was found useful to subdivide question PAR1 into five sub-questions, in order to provide a more discriminative answer on the parameter evolutions and their bandwidths:

- *PAR1.1: What is the timescale over which a significant parameter evolution is expected?*
- *PAR1.2: What is the expected, most likely evolution of a parameter?*
- *PAR1.3: What is the expected uncertainty range?*
- *PAR1.4: What is a "safe envelope" of a parameter evolution for which no adverse effects on safety are expected?*
- *PAR1.5: For which parameter evolutions, adverse effects on the safety cannot be excluded?*

For the OPERA disposal concept, there is some information available concerning the time evolution of a number of processes, but currently limited information is available to link overall safety with individual parameter evolutions. This includes in particular alternative evolution scenarios. Consequently, defining the expected evolution of parameters for the OPERA disposal concept in Boom Clay is only possible in a qualitative manner.

With respect to sub-question PAR1.1, Figure 1-22 below gives an indication of the evolution in time for the most relevant THMCR processes foreseen for the OPERA disposal system under the conditions of the Normal Evolution Scenario (NES). As time progresses, these processes tend to revert towards either the original or a new state of equilibrium.

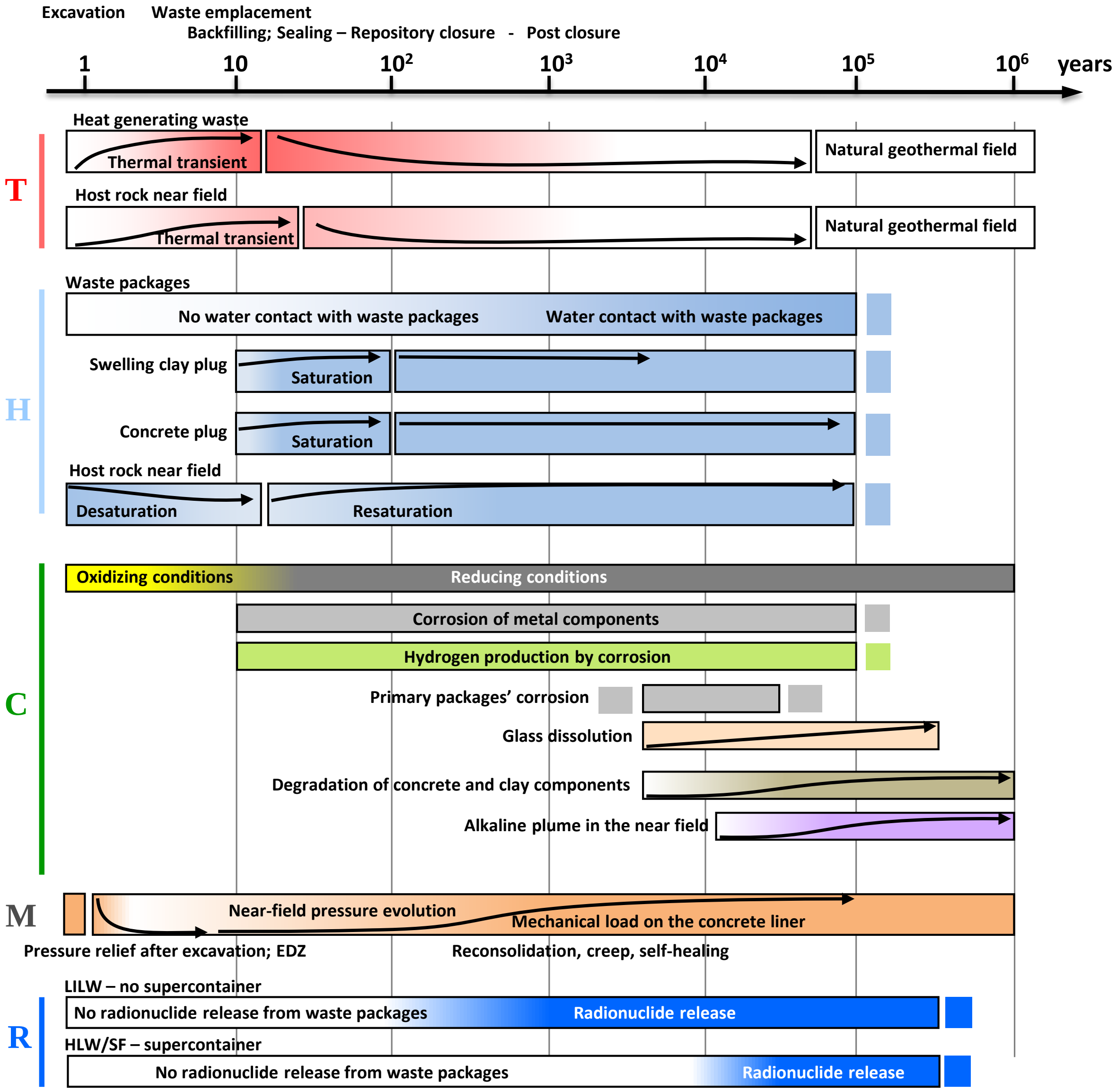


Figure 1-22 General overview of processes for the evolution of the OPERA disposal concept.

The following broad-brush sketch applies to the timing of the various THMCR processes:

- Thermal loading of the EBS and the host rock occurs over a timescale of several hundred years, although in the repository and its vicinity it peaks within only a few decades. Because of the extended surface storage period adopted in the Netherlands, the heat output from the heat-producing waste has already decreased significantly, and the temperature increase in the EBS and the host rock will be very limited.
- The period of desaturation of the host rock near field upon the excavation and operation of the facility is limited to several decades following the excavations. Hydraulic processes in the repository and the Boom Clay host rock take place over a timescale of several hundred years at maximum, when total saturation of the repository is reached.
- Apart from the redox transient, which appears a short-lived phenomenon when considered on a million-year timescale, the chemical processes develop mainly after thousands and tens of thousands of years and last from tens of thousands of years to hundreds of thousands or even a million years. More specifically, the metal components and the concrete/steel Supercontainer corrode over a period lasting from a few thousand years to a several tens of thousands of years. The corrosion and dissolution of vitrified HLW may take even longer.

- Mechanical processes, which are largely dependent on the hydraulic processes and the chemical degradation of the repository components, extend primarily over the same timescales as those processes. The plastic nature of the Boom Clay favours its relatively fast natural creep to the original state.
- Radionuclide release is largely dependent on chemical processes such as the availability of water, corrosion of metal containers, aqueous dissolution of packaging matrices (e.g. the glass in vitrified waste) or dissolution of spent fuel from the research reactors. Accordingly, the timescale for this process extends from a few tens of thousands of years to several hundred thousand years or more. Once released, radionuclides migrate into the Boom Clay host rock layer by diffusion over a period of several hundred thousand years or longer.

The above-mentioned considerations have been summarized in the following table.

Table 1-57 PAR1: Expected parameter evolution for the OPERA Supercontainer

	PAR1.1	PAR1.2	PAR1.3	PAR1.4	PAR1.5
Carbon steel overpack					
SC-1 - Mechanical disturbance	thousands of years	not defined	not defined	*n.a.*	*n.a.*
SC-2 - Steel corrosion	thousands of years	generally known	generally known	*n.a.*	*n.a.*
Concrete buffer					
SC-3 - Thermal evolution	immediate				
SC-4 - Water ingress	thousands of years	generally known	generally known	*n.a.*	*n.a.*
SC-5 - Geochemical evolution	thousands of years	generally known	generally known	*n.a.*	*n.a.*
SC-6 - Mechanical load (external forces)	years	not defined	not defined	*n.a.*	*n.a.*
SC-7 - Mechanical load (thermal processes)	immediate	not defined	not defined	*n.a.*	*n.a.*
SC-8 - Corrosion induced cracking	thousands of years	not defined	not defined	*n.a.*	*n.a.*
Steel envelope					
SC-9 - Steel corrosion	tens of years	known	known	*n.a.*	*n.a.*
SC-10 - Mechanical load	years	generally known	generally known	*n.a.*	*n.a.*
Supercontainer					
SC-11 - Release of radiation	ten thousands of years	known	known	known for NES, not yet defined for AES	none for the NES, not yet defined for AES

6.7 PAR2. Identify monitoring strategy and technology options

In this step, options for monitoring the parameters 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 as part 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.

From the current point of view, two aspects with respect to the development of a monitoring strategy are relevant:

- There is an *a priori* preference for *in-situ* monitoring in a disposal facility, with other options considered as well: either additionally to *in-situ* monitoring of the disposal, or as alternative option, i.e. in case *in-situ* monitoring of a particular parameter in a particular disposal compartment is judged to be not feasible (TEC1) or is “parked” for other reasons in the steps thereafter. This includes monitoring in pilot facilities, demonstrators in URL’s, or experiments performed in a lab-environment.
- The number of sensors and locations to be monitored need to be clarified. This depends on requirements of redundancies, expected uncertainties vs. performance requirements and expected heterogeneities, e.g. in the host rock.

From the Dutch national programme, no guidance can be given here. However, it can be argued that it is important to understand the feasibility of *in-situ* monitoring (and its limitations) in the current stage, because other monitoring options might have a more important role for the Netherlands than for other, faster progressing countries: the policy of long-term interim storage allows performing experiments and demonstrators in laboratory and URLs over relevant time scales, in advance of any decision on host rock or siting.

6.8 TEC1. Is option technically feasible?

Sections 6.2.2 and 6.2.3 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*
> *In Modern2020 Deliverable D2.1 the following guiding questions provide guidance to this step (White, 2017; Section 6.2.3):*
>
> - *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?*

Considering the Dutch policy of long-term interim surface storage, no emphasis has been put so far on investigating the technical feasibility of monitoring processes and parameters. Consequently, this aspect has less urgency in the Netherlands. On the other hand, extending the surface storage period allows performing R&D in laboratory and URLs over longer time scales. However, as indicated in the previous section, the level of detail necessary to evaluate the feasibility of technological option is too high to make a quantitative assessment here: to be able to do so, detailed quantitative information is required on parameter evolutions that can be considered as safe.

However, Table 1-58 is a first attempt to assess the technical feasibility of monitoring processes, which are considered to be relevant for the performance of the OPERA Supercontainer. A rough estimate of the anticipated timescales for the identified processes has been added to this table (cf. Figure 1-22).

Table 1-58 TEC1: Expected feasibility to measure parameter evolution for the OPERA Supercontainer. Indication of relevance is based on PRO2.

Process	Parameter	Relevance	Timescale [a]	Generally feasible?
	Carbon steel overpack			
SC-1	Pressure	+	0-100	+
	Stress	+	0-100	+
SC-2	Redox potential	+	10-100	depends on timescale & presence of water
	pH	+	10-100	depends on timescale & presence of water
	Gas generation	+	10-100	depends on timescale & presence of water
	Pore water chemistry	+	10-100	?
	H_2 concentration	+	10-100	depends on timescale & presence of water
	Electrochemical gradients	+	10-100	depends on timescale & presence of water
	Concrete buffer			
SC-3	Temperature	o	0-100	+
SC-4	Saturation	o	0-100	+
	Water content	o	0-100	+
SC-5	Redox potential	+	10-100	depends on timescale & presence of water
	pH	+	10-100	depends on timescale & presence of water
	Pore water chemistry	+	10-100	?
SC-6	Pressure	+	0-100	+
	Stress	+	0-100	+
SC-7	Pressure	o	0-100	+
	Stress	o	0-100	+
SC-8	Stress	o	0-100	+
	Steel envelope			
SC-9	Redox potential	+	0-100	depends on timescale & presence of water
	pH	+	0-100	depends on timescale & presence of water
	Gas generation	+	0-100	depends on timescale & presence of water
	Pore water chemistry	+	0-100	?
	H_2 concentration	+	0-100	depends on timescale & presence of water
	Electrochemical gradients	+	0-100	depends on timescale & presence of water
SC-10	Pressure	o	0-100	+
	Stress	o	0-100	+
	Supercontainer			
SC-11	Dose rate	OP	0-100	+

6.9 TEC2. Take option forward

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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*

In principle this particular step is considered obsolete since, in case TEC1 is answered with "Yes", then the next step would be either PAR3, or PRO6.

6.10 TEC3. Park option

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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).*

Considering the present Dutch policy of long-term interim surface storage, this step is less relevant. In case an option is considered presently not feasible but sufficiently relevant to develop further, there would be sufficient time left prior to final disposal to develop the particular option, or to consider another option.
A remark to step TEC3 is that its follow-up is not further clarified in the Modern2020 screening process.

6.11 PAR3. Are there any feasible options for this parameter?

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

This step in the Modern2020 seems already partially established in TEC1, in which the feasibility has been assessed. In case of a "No" answer to step TEC1, step PAR3 may come into play. However, in case of a "Yes" answer to TEC1, the next step of the flowchart would be PRO6.
Taking this into consideration, we propose to modify the Modern2020 flowchart as follows:

- In case of a "No" answer to TEC1, it seems more appropriate to investigate other feasible options, i.e. go to PAR3, than to park the particular option. We therefore propose to remove TEC3 from the flowchart.
- In case of a "Yes" answer to TEC1, one could immediately go forward to PRO6 instead of following the obsolete route through PAR4. In that case step TEC2 could be removed as well.
- Similar to what is mentioned under TEC1, a generic preference for monitoring options under *in-situ* conditions was noted.

The resulting modifications are depicted in Figure 1-23.

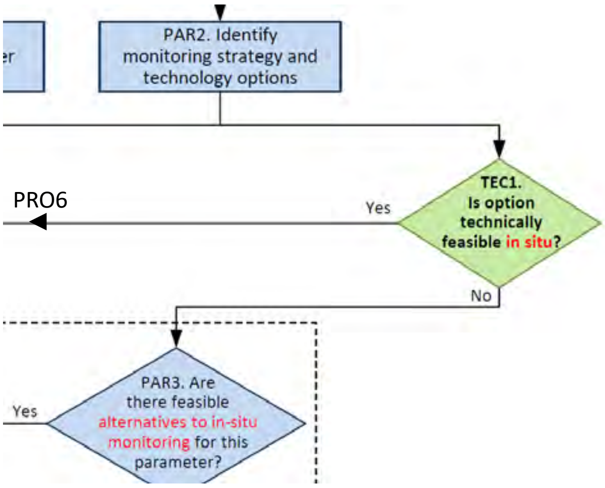


Figure 1-23 Proposed modification of the Modern2020 flowchart (1) – TEC.

6.12 PAR4. Take parameter forward

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

PAR4 seems an obsolete step in the Modern2020 flowchart: In case the answer to PAR3 is a "Yes", one could by-pass PAR4 and immediately go to PRO6.

6.13 PAR5. Park parameter

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

PAR5 has not been regarded at present. Considering the Dutch policy of long-term surface storage the parking of parameters is judged less relevant since sufficient time would be left until disposal to search for feasible options. On the other hand, parking of parameters can have value to administer a list of parameters that could be dealt with in the future.

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

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

This question is a valid one since measuring the evolution of a particular parameter may not always sufficiently characterize the evolution of a single process occurring in a barrier of the disposal system. For example, the presence of water alone in the concrete buffer of the Supercontainer is not an indication of the process corrosion. For providing more certainty about identifying a process, additional information is then necessary. For example, the process corrosion of the Supercontainer may be identified by measuring the following parameters:

- Presence of water
- Electrochemical gradients
- H_2 concentrations
- Chemical composition of buffer pore water.

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

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

In the Netherlands, no reconsideration of options is applicable. Considering the representation of PRO7 in the Modern2020 flowchart it is noted that this step includes three options, each leading to a different route back in the scheme:

- “Reconsider process”
- “ Reconsider monitoring strategy”
- “ Undertake further R&D on monitoring technologies

The single route back from PRO7 leads either to PRO2, or PAR1/PAR2. However, at the intersection point where this route back splits into the two routes to PAR1 and/or PAR 2, no decision step is indicated. Consequently, we propose the modification to step PRO7 indicated in Figure 1-24, taking into account the three distinct routes that may apply for the iteration:

- “Reconsider process”, which may lead back to PRO2;
- “Reconsider monitoring strategy”, which may lead back to PAR2;

- "Undertake further R&D on monitoring technologies", which may lead back to TEC1.

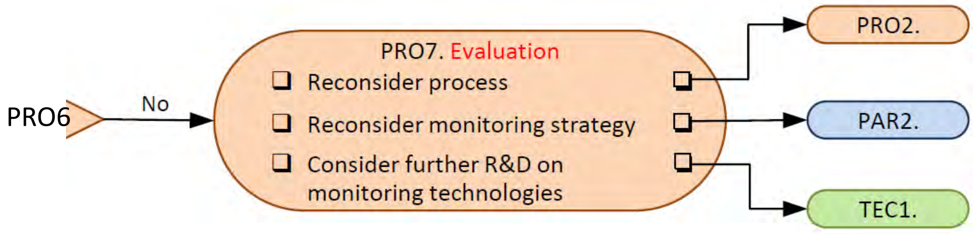


Figure 1-24 Proposed modification of the Modern2020 flowchart (2) – PRO7.

It should be noted that most likely more than one route will be considered. However, the adapted scheme points to the fact that in order to be able to proceed in a programme often a decision is necessary rather than keeping all options open.

6.16 PRO8. Cross-compare parameters

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

It is acknowledged that individual barriers are no stand-alone features that are independently affected by a particular process. Processes which affect barriers of the disposal system can occur simultaneously and/or subsequently, and they may influence each other. As a consequence, the Modern2020 screening process needs to be established for the integrated system which includes all barriers.

However, the present exercise in the framework of Modern2020 focuses only on the OPERA Supercontainer, thereby neglecting processes that may occur in other barriers, and that may impede, delay or accelerate the degradation of the Supercontainer.

The cross-comparison of processes affecting the performance of all barriers has therefore still to be performed, a process that is acknowledged and will be taken forward in subsequent geological disposal programmes.

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

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

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

This question is not applicable since no monitoring plan has been established yet. However, a first list of parameter has been established for the OPERA Supercontainer:

Table 1-59 List of parameters identified for the OPERA Supercontainer

Process	Representative Parameter	Time Scale [a]
Carbon steel overpack		
SC-1 - Mechanical disturbance	Pressure Displacement	0 – 100's
SC-2 - Steel corrosion	Redox potential H_2 presence	10's – 100's
Concrete buffer		
SC-5 - Geochemical evolution	pH Redox potential Pore water chemistry	10's – 100's
SC-6 – Mechanical load (external forces)	Pressure Displacement	0 – 100's
Steel envelope		
SC-9 - Steel corrosion	Redox potential H_2 presence	0 – 100's
SC-10 - Mechanical load	Pressure Displacement	0 – 100's

6.18 PAR7. Take parameter forward to monitoring programme design stage

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

Table 1-59 above summarizes the list parameters identified for the OPERA Supercontainer to carry forward, e.g. for consideration in a future monitoring programme design stage in the Netherlands.

6.19 PAR8. Park parameter

Section 6.2.2 of Modern2020 D2.1 (White, 2017) provides the following explanation to this step.

> *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.*

This step is not considered, if only because presently there is no monitoring plan available in the Netherlands.

6.20 Proposed modification of the Modern2020 flowchart

Following the proposed modifications of steps of the Modern2020 flowchart, Figure 1-25 depicts the complete overview. The most distinct modifications compared to the base flowchart (Figure 1.3) concern the removal of TEC2/TEC3, the removal of the seemingly obsolete step PAR4, and the identification of the iteration loops originating from PRO7.

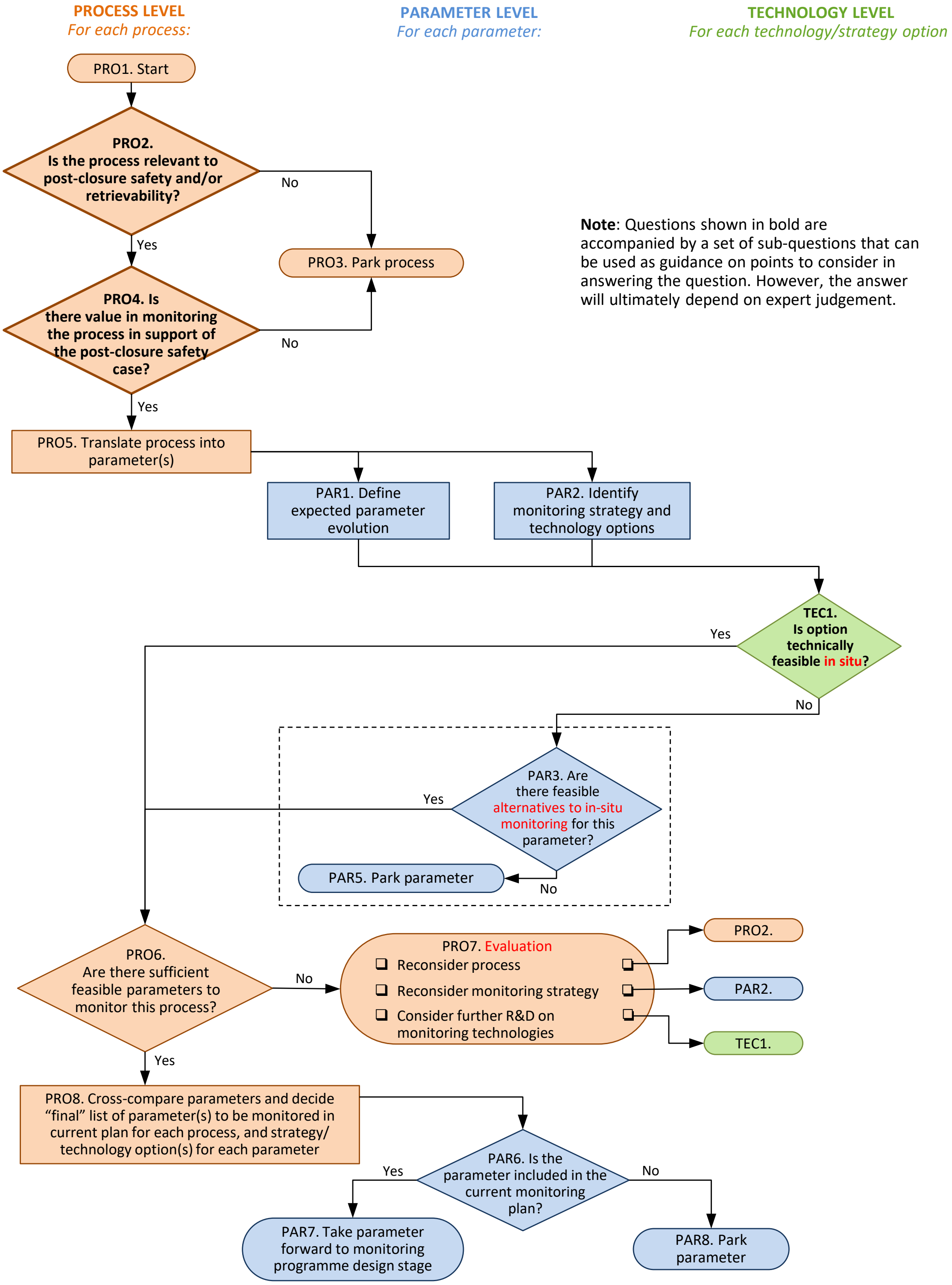


Figure 1-25 Proposed modification of the Modern2020 flowchart.

7 Conclusions and recommendations

This report addresses the following objectives of Modern2020 WP2, Task 2.2:

- Test the methodologies - developed in Task 2.1 of the Modern2020 project to identify EBS and host-rock monitoring parameters for the national programme on geological disposal in the Netherlands;
- Develop further understanding of EBS and host rock evolutions in the Dutch OPERA concept for the geological disposal of radioactive waste to inform the development and implementation of dedicated monitoring programmes.

The present contribution reflects the current ability of the Dutch national programme to define an actual monitoring programme and discusses its benefits at various stages of implementation.

The geological disposal programme in the Netherlands is at an early stage; the current OPERA Safety Case is under development and focuses on how to provide evidence for the long-term safety of a generic, location independent disposal concept. The main barrier - the host rock - has many favourable properties, and is expected to provide sufficient safety for most long-term scenarios. Consequently, in the Netherlands less focus is given to design and performance evaluations of EBS components, while more efforts are directed in deeper understanding of the migration behaviour of radionuclides in the host rock of interest, the Boom Clay. One of the challenges of this study was to compile and structure the relevant information that is currently available. The following activities have been executed for this report:

- Processes have been identified which are judged most relevant in affecting the various components of the Dutch disposal concept, more specifically the engineered barrier system and the Boom Clay host rock;
- Parameters have been identified which provide indications of processes relevant or the safety of the disposal system, and which may be monitored in practice by using the screening methodology developed in Task 2.1 of Modern2020;
- The expected evolution of the most relevant processes occurring in the disposal system during the period when monitoring is expected to be possible has been described;
- The Modern2020 screening methodology for establishing monitoring parameter lists for the Dutch disposal concept has been evaluated, and proposals for modifications have been elucidated;
- Uncertainties and lacunas concerning process understanding of the Dutch concept for geological disposal have been identified.

The screening of processes and parameters potentially relevant for monitoring is mainly based on the disposal concept, system descriptions, safety functions, scenario descriptions, FEP database, and process understanding developed during the OPERA research programme. A thorough inventory has been compiled of processes and parameters potentially affecting the OPERA disposal system. In the analysis, the following barriers were distinguished:

- Waste form;
- Waste container;
- Backfill;
- Disposal cell plug;
- Gallery lining;
- Near-field of the host rock;
- Far-field of the host rock;
- Shaft seal.

For some of these barriers, such as the OPERA Supercontainer, sufficient information exists to establish an inventory of relevant processes and parameters. Other barriers are only at a very generic stage of development, e.g. the disposal cell plug, or even not considered in the current OPERA disposal concept, e.g. the shaft seal. The breakdown of safety functions into an inventory of processes and parameters was helpful in understanding the relevance of clear design criteria that need to be established in geological disposal programmes following OPERA.

Each of the steps of the Modern2020 screening methodology has been assessed with the focus on the OPERA Supercontainer. The assessment of the subsequent steps also resulted in proposals for the alternative descriptions of the various steps of the screening methodology as well as the additional questions that have been formulated for most of the steps.

It was found that executing and documenting the various steps of the Modern2020 screening methodology in a structured and reproducible way is rather labour-intensive. All main engineered barriers of the Dutch disposal concept had to be described and the main processes impacting their performance had to be identified. However, within the scope of project, the actual screening could only be performed for the OPERA Supercontainer as example case, although the information collected in Chapter 5 allows to extend the screening to the other barriers in a future project.

Since at present there is limited information available concerning alternative evolution scenarios (AES) of the disposal system, a qualitative assessment of the evolution of monitorable parameters as indicators of the selected AES's has been described when possible. It was also chosen to set up the parameter screening in a way that allows to add other scenarios in a later stage, when additional information comes available.

Hardly any quantitative design criteria for the barriers of the OPERA disposal concept have been defined yet. As a consequence, the testing of the Modern2020 screening methodology could only be performed with sufficient adequacy up to step PAR2 - *Identification of monitoring strategy and technology options for specific parameters*.

The knowledge to perform the subsequent steps TEC1/2/3 (feasibility of technology options) is presently less developed in the Netherlands; due to the policy of long-term interim storage, the actual implementation of a disposal facility is far away, and Dutch research activities in e.g. URLs are limited. However, more important in order to improve the knowledge on technical limitations of monitoring would be to give a better quantitative description of which parameter evolutions could potentially lead to an impairment of the long-term safety.

Following the proposed modifications of steps of the Modern2020 flowchart, Figure 1-25 depicts the adjusted overview. The most distinct modifications compared to the base flowchart (Figure 1.3) concern the removal of TEC2/TEC3 (go/no-go decision for technology option), the removal of the seemingly obsolete step PAR4 (decision on inclusion of parameter in follow-up process studies), and the re-iteration loops originating from PRO7 (reconsider screening).

In summary, the application of the screening exercise to the OPERA disposal concept is found a useful exercise. The workflow contains a comprehensive and detailed collection of relevant questions, which help focussing on what kind of knowledge is necessary to support evidence for safety, and what aspects need to be considered when further refining design criteria. The lessons learned will serve as a basis to further evolve the OPERA disposal concept.

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Appendix G: TURVA 2012 Test Case (Posiva)

Contents

Comment to this report guideline

The objective with the test case report is to describe the testing of methodologies identified in Task 2.1 (Deliverable D2.1) when identifying EBS and host-rock monitoring parameters. The application of the parameter screening methodology is a central point of the task (addressed in Chapter 4). Monitoring of parameters shall also be put in a context of the WMO´s national programme, repository system, safety functions and utilisation of the monitoring data. This need to be described although not to its full extension but rather as supporting information to provide insight and appreciation on the system as a whole (addressed in Chapter 2-6).

Specific issues have been identified (Appendix 1) which the WMO shall attempt to address, and if not addressed explain why. The Parameters issues are at the core and should be addressed with relatively high level of detail including underlying considerations and motivations for adopted approaches. System description and Added value issues aim at providing the relevant framework to support the Parameter issues, these may be described in less detail but with a clear and logical coupling to the monitoring parameters. The Decision support issues are far downstream in the process and may not have been so much developed among some of the Test cases. An attempt to address these is still important as it will give input to Task 2.3.

It is recognised that disposal programmes as well as EBS-monitoring programmes are at different level of development for the participating WMO´s and that this level will govern the degree and extent to which issues are possible to address for the WMO. Test case may cover complete EBS or only a part of it.

The writing should be as specific for the test case as possible. It should describe the work and workflow from safety functions to monitored parameters including motivations.

The language should be at the level for the intended audience for the report being knowledgeable people in the field of nuclear waste disposal, predominantly from waste management organisations and regulators.

Bulleted issue in this guidelines are not in any chronological order to address and some issues may be addressed under different chapters e.g. added values may be covered in Chapter 3 (Objectives) and in Chapter 6 (Confidence building).

The report is not a deliverable within the project and will not be published but it will be classified as a public document. It is an objective to put the Summary from this report in to the Task report which constitutes deliverable D2.2. //

Executive summary

Posiva has undertaken the MoDeRn2020 WP2 Task 2.2 by establishing a work group to test the methodology developed in the project. The task was to identify processes and parameters of the EBS's to be potentially monitored during the operational phase of a high-level nuclear waste repository in crystalline rock. The objective of the group was to perform screening by utilising screening methodology provided already in Task 2.1 by White et al. (2017). In addition, the guide to perform Task 2.2 was used. With given start points and tools, it was decided that the task group would start the work from Posiva's performance targets, which are set in manner that as completed, they provide the safety functions of the disposal facility for long-term safety. A template was drafted using given tools mentioned, and each performance target was gone through using both the template and the screening methodology chart.

The topic is relevant to Posiva at the moment as Posiva will submit the operational licence application for the high-level nuclear waste repository of Olkiluoto around the year 2020. Before submitting the application, Posiva's monitoring programme shall be updated to also include the plan for monitoring the performance of the EBS, required by the national legislation and nuclear safety guides.

The project provided a list of parameters, which need to be monitored. Majority of the work is conducted with quality assurance and quality control, as the direct monitoring of EBS's during operational phase is challenging and in most cases, impossible. The operation phase is short in comparison to long-term evolution of the EBS and the site, for which reason any monitoring activity can only provide limited information on the long-term behaviour of the repository system. The EBS and the disposal facility are designed in robust manner providing passive safety, without an aim to use post-closure monitoring or active post-closure maintenance. Due to this passive safety approach, also in this project the focus is set to QA and QC, as well as to full-scale and/or in-situ tests, which can provide confidence in materials and design and compatibility of different components. Verifying the performance of the engineered barriers is seen as a topic strongly related to material development and quality control.

After completion of the test screening process, recommendations are presented to simplify the screening methodology chart. Several late-stage screening steps at the end of the chart seemed redundant and provided the same answer. As a whole, the screening methodology was found very useful, especially the first steps until determination if the parameter is technically feasible. It was especially good that the expected evolution of the system was taken into consideration in the method, as discussions of it led to better identify the correct process needed to be monitored, as this was not in all cases as straight forward as thought beforehand.

As a conclusion, the project produced the list of monitoring parameters as intended. The results of this work are used as an input to other Modern2020 work packages and tasks, especially for WP4, Task 4.1. This work and the resulting monitoring parameters and processes have been defined purely for the purpose of testing the screening methodology, developed in MoDeRn2020 Task 2.1 and the work, or its results do not represent Posiva's actual operational monitoring programme plans.

1 Introduction

The focus of the Modern2020 Project is monitoring during the operational period in support of demonstration of post-closure safety. Aspects of monitoring after final closure are for consideration by the WMO. It is an implicit principle of the Screening Process that any monitoring after full closure of a repository would be a continuation of monitoring prior to full closure. Therefore, the process that is developed here is equally applicable to all phases of monitoring. Closure entails that deposition is completed and galleries backfilled. Once monitoring is put in place during the operational period it is up to the WMO and its regulatory framework to decide on discontinuation.

Monitoring programmes based on these safety cases are at different levels of development. Preliminary parameter lists exist for the Cigéo and Olkiluoto repositories. For the other programmes, preliminary parameter lists will to some extent be developed within Task 2.2.

The general objective of Task 2.2 is to test the methodologies for screening monitoring parameters identified and developed in Task 2.1. Specific objectives are:

• Describe specific objectives for monitoring of the barrier system in different national programmes, based on generic objectives for monitoring identified in MoDeRn.

• Identify the parameters that should be monitored in practical (implementable) programmes by using screening methodology from Task 2.1.

• Describe the expected evolution of the disposal system during the monitoring period, as it relates to the monitoring parameters identified.

The approach used will depend on the national programme, and may include consideration of safety cases during the operational phase, safety function indicators and/or FEPs.

It will be relevant to develop a link between EBS (Engineered Barrier System) monitoring results and the decision making processes during the operational phase of repository implementation.
Specifically, the work in Task 2.2 shall for different national programs elaborate on how results from the monitoring of the EBS might be utilised to support operational decision and provide support to stakeholders. This will feed into Task 2.3 to identify and develop methodologies and tools to for the decision making process.

2 System description

The Posiva EBS system consists of canister, buffer, backfill and closure, with the natural barrier, host rock, surrounding the repository openings. The system has been thoroughly described and its performance evaluated in TURVA-2012, Posiva's safety case for construction license application, which was submitted for Ministry of Economic Affairs and Employment (MEE) December 2012 (see Posiva 2012d). After evaluation, Posiva was granted construction license in 2015. Currently, the safety case is being updated for operating license application.

As the safety case is under update, references are mainly in this project from TURVA-2012, as updated material is not yet ready for use. However, the requirements have been under development, and this has been taken into account while executing the task at hand. Posiva has a long-term safety related requirements management system (Vaatimustenhallinta, VAHA), in which the requirements for the disposal system are in five levels as named below:
Level 1: Stakeholder requirements
Level 2: System requirements (including safety functions)
Level 3: Subsystem requirements (including performance targets and target properties)
Level 4: Design requirements
Level 5: Design specifications

Of the five VAHA levels, the first concerns international and national requirements arising from permits, laws and similar compulsory requirements, including YVL guides, which have been compiled and kept up to date by STUK (Radiation and Nuclear Safety Authority in Finland).

VAHA level 2 holds system requirements set by Posiva, the safety functions. Safety functions are to assure that disposal is done in safe manner considering long-term safety.

VAHA level 3, subsystem requirements, include performance targets for EBS's and for host rock. These both are set so that they produce safety functions mentioned in level 2.

VAHA level 4 includes the design requirements. These requirements are to guide design of EBS's and construction of underground openings. Many have numerical values and are already quite specific in what are required attributes from which component.

VAHA level 5, design specifications, specify with what design parameters the design requirements are met.

In 2016-2017 Posiva and SKB started co-operation attempting to unify their requirements, as disposal process and design (KBS-3V) are similar. This produced the first step in updating the requirements and is reported in Posiva SKB (2017). Until the testing of the MoDeRn2020 screening methodology for Modern2020, Task 2.2., the aforementioned requirements were updated a bit further and updated requirements on Level 3 (performance targets) were detached and versioned for this project in February 2017 (Appendix 2). These are not necessarily the final requirements that will be in Posiva's next safety case, but are a draft version, which should be noted by the reader. The review and update work of the requirements is ongoing at the moment of compilation of this report in 2017. It was, however, determined in Posiva's Modern2020 task group that it is more useful to go forward with incomplete but updated requirements, than it would have been to remain in old requirements from TURVA-2012 safety case, which are already outdated as such for some parts.

Posiva's disposal system for spent nuclear fuel consists of access tunnel and shafts leading to repository depth, technical rooms, halls and connection tunnels at depth, and then of parallel central tunnels, each set leading to deposition tunnel with deposition holes drilled in them. Construction of the disposal facility will take place also during operational time to minimise the open volume, and deposition tunnels are closed after spent fuel has been installed in them. Central tunnel sets will be closed, when adjoined deposition tunnels have been backfilled and closed with plugs. Low and intermediate level waste repository (LILW-R) for operational waste is designed to be constructed so that it diverges from the access tunnel, being at significantly shallower depth than the high-level waste repository. It is a separate system and excluded from this work. Encapsulation plant at ground level is connected to the SNF repository considered in this work with the canister shaft for canister transfer to underground storage and then to disposal. Encapsulation plant is also excluded from this work, as the repository EBS's are not in any connection to it. A schematic presentation of the components of the disposal system is presented in **Figure 1-26**.

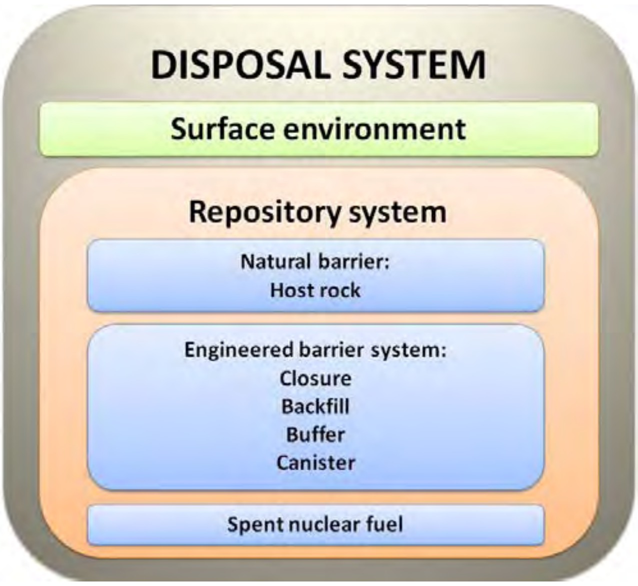

Figure 1-26. A schematic presentation of the components of the spent nuclear fuel disposal system (Posiva 2012d, Figure 2-4).

2.1 EBS/Host-rock system

Posiva's safety concept for the geologic disposal of spent nuclear fuel is based on the KBS-3 design of the geologic repository and the characteristics of the Olkiluoto site, which have been studied since 1980's and monitored more than 20 years. In the KBS-3V design (Figure 1-27), the spent nuclear fuel assemblies are placed into copper canisters with cast iron load-bearing inserts, and the canisters are emplaced vertically in individual deposition holes bored in the floor of the deposition tunnels excavated in Olkiluoto crystalline host rock more than -420 meters below surface. The canisters are surrounded by a swelling clay buffer material that separates them from the bedrock. The deposition tunnels, central tunnels, access tunnel and other underground openings are backfilled with natural materials and plugged with manmade structures ensuring the favourable conditions for host rock and for the other engineered barriers. Engineered barrier system (EBS) includes canister, buffer, backfill and deposition tunnel plug, and closure, with its different backfill and plug types. Closure is excluded from this work, and focus was directed to EBS components in deposition holes and tunnels.

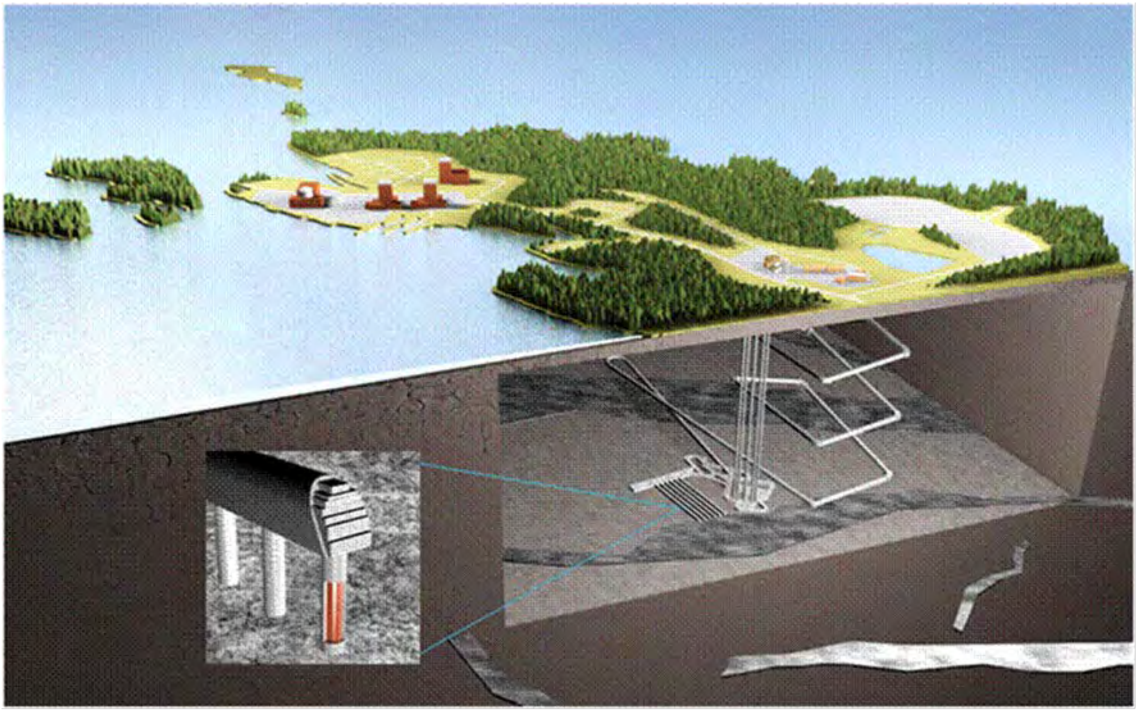

Figure 1-27. KBS-3V Concept (Posiva 2012d, Figure 2-1).

2.2 Expected behavior of EBS

According to safety concept, safety depends first and foremost on the long-term containment of radionuclides within the copper-iron canisters and their long-term isolation in the deep bedrock. Clay buffer protects the canisters from rock movements and potential detrimental substances, limits groundwater flow around the canisters and limits and retards radionuclide releases in the event of canister failure. Long-term containment within the canisters, in turn, depends primarily on the proven technical quality of the engineered barrier system and favourable near-field conditions for the canisters. The technical quality of the EBS is favoured by the use of components with well-characterised material properties and by the development of appropriate acceptance specifications and design criteria. Favourable and predictable bedrock and groundwater conditions are requirements for the natural barrier, i.e. the host rock (the safety functions for engineered and natural barriers are described in Posiva 2012b, 2012d and in Table 1-60). The design confirmation, site characterization, QA/QC procedures and monitoring are the tools, which are used to confirm the performance of the disposal system and fulfilment of the safety functions.

Table 1-60. Safety functions of the EBS and host rock (Posiva 2012d, Table 2-1). Safety functions will be reviewed and potentially updated for safety case for operating licence.

Barrier	Safety functions
Canister	Ensure a prolonged period of containment of the spent fuel. This safety function rests first and foremost on the mechanical strength of the canister's cast iron insert and the corrosion resistance of the copper surrounding it.
Buffer	Contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister. Protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides. Limit and retard radionuclide releases in the event of canister failure.
Deposition tunnel backfill	Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters. Limit and retard radionuclide releases in the possible event of canister failure. Contribute to the mechanical stability of the rock adjacent to the deposition tunnels.
Host rock	Isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface. Provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers. Limit the transport and retard the migration of harmful substances that could be released from the repository.
Closure	Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals. Contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings. Limit and retard inflow to and release of harmful substances from the repository.

The disposal facility is constructed with a step-wise production manner, in which deposition tunnels are not all constructed before the start of the disposal, but also during the operational phase. With this step-by-step approach and long duration of the operational phase, the EBS components are in different phases of early evolution during the operational phase, which is estimated to last for approximately 100 years. First deposition tunnels will be closed quite early, leaving time to monitor the deposition tunnel plug for quite a long time before the closure of the central tunnel.

Operation phase excavation and closure steps have an influence on groundwater flow and chemistry conditions. Excavating the volumes may change flow paths, which can potentially be restored after closing the volumes, or possibly altered again to differ from the open phase. The clay EBS components are expected to swell and homogenise with inflow. Early phase evolution depends on the geometry, density and consistency of the clay EBS components, but also much on the inflow rate. Deposition tunnel plugs are expected to endure for the operational phase, but they are not required to hold their strength throughout the long-term evolution of the system. They can deteriorate, with the requirement that part of the material (aggregate at minimum) remains in installed location as tunnel fill.

3 Monitoring objectives

EBS monitoring is the monitoring activities to follow up the behaviour of EBS components (canister, buffer, backfill, closure and their interaction with surrounding host rock) during and after installation. The monitoring can be done directly or indirectly. EBS monitoring is intended to be done only during operational phase. Posiva is not intending to directly monitor the EBS performance after installation or to monitor the site after closure at all, as the disposal system as a whole is designed to last for long term, hundreds of thousands of years and provide passive safety. An indirect approach to EBS monitoring during the operational phase is seen as a more applicable choice. Not all structures as such will endure, e.g., concrete structures as they were built, but the system after closure should be seen as an entity, instead of single components. The overall design and production produces integrity and long-term safety.

During operation, the direct monitoring of each EBS component is considered impossible without jeopardizing the long-term safety after it has been covered by another component. With this, the final visual examination of the top of the canister is when the buffer is set atop it. Also the interface between the buffer and backfill remains outside observation when the backfilling of the tunnel advances over the deposition hole. The backfill will also eventually be left outside direct monitoring after deposition tunnel plug is built in front of it. Knowledge from the behaviour of the components can be obtained beforehand and/or during operation in laboratory and in-situ tests. Quality assurance has a crucial role in confirming with the requirements and assuring that long-term safety is achieved.

Posiva's monitoring programme includes the following 5 sub-sections:

- Hydrogeochemistry
- Rock mechanics
- Surface environment
- Hydrology and hydrogeology
- EBS-monitoring (under development)

Hydrogeochemistry includes monitoring of the groundwater composition within the whole site, including deep bedrock and shallow soil ground waters. Hydrology and hydrogeology is concentrated on monitoring the hydrological and hydrogeological conditions of the site regarding processes such as groundwater flow, level, pressure and connections at the site. Both sub-sections also have the important task of monitoring repository construction and operation-related disturbances in the groundwater system of the site. The sub-section of surface environment is mainly concentrating on monitoring of the conventional environmental effects and disturbances of the final disposal activities related to e.g. water handling, excavations and rock piling activities. The sub-section of rock mechanics is responsible of monitoring the rock mechanical evolution of the site, such as phenomena related to rock stress distribution in the tunnels, rock temperature, bedrock uplift and seismic activity of the site. The microseismic monitoring network is also used for safeguards-purposes. The sub-section of EBS-monitoring is currently under development and will be implemented during the operational phase of the repository, it has the main task of verifying the planned functioning of the EBS, especially required by the government decree VNA736/2008, 9§ and the YVL-guide D.5. The monitoring programme for the operational phase shall be compiled before applying for the operational licence of the repository, including all sub-sections of the programme.

In addition, Posiva also has lots of other site characterization and research activities in action, such as the Rock Suitability Classification (RSC)- process for selecting suitable rock volumes for final disposal or Biosphere- and dose modelling project (BSA2020) for modelling doses to humans and animals in different theoretical disturbance or leakage scenarios related to long-term safety.

In the monitoring programme developed and implemented by Posiva, limits have also been set for some of the monitored parameters; these are labelled "action limits". The action limits have been derived from performance targets related to long-term safety, requirements related to specific licenses (e.g. construction licence, operational licence, environmental licence) or limits related to environmental effects of the final disposal activities and related excavation, construction and rock piling works. The term action limit depicts a limit set for parameter values between the bounds of natural variation at the site and the parameter values outside the spectrum in which the disposal system has been designed to function. The idea is that the action limit functions as a threshold, alarming when parameter values are developing towards unacceptable levels, allowing planning and implementation of possible actions to take place before unacceptable conditions could be reached.

If an action limit is exceeded, an evaluation will be done and a decision will be made whether or not the observation requires actual actions to be undertaken. In some cases, it can be that further actions other than monitoring of the situation are not required. Such case could theoretically be, for example if the observation is very far from the actual repository. In cases where it is decided by Posiva that technical solutions are to be undertaken, the possible technical solutions in question could theoretically vary from post-grouting of the tunnels to layout revisions in the underground repository. In the surface environment, possible actions can be related to e.g. processing or handling of effluent waters from the underground facilities or waters leaching from the rock heaps.

Regarding the monitoring of the repository site, the procedure is already in action in Posiva. On the other hand, regarding the monitoring of the EBS, Posiva does not have a monitoring programme in action at the moment. Thus, with the programme for the EBS-monitoring still being under development, action limits do not exist for the EBS-monitoring for now.

Regarding the process currently implemented in Posiva, in general it can be concluded that the range of actions arising from monitoring observations can range from additional monitoring actions to technical solutions, such as post-grouting etc. in cases where action limits are exceeded. If the parameter values are so drastically out of the acceptable range of variation that performance targets for long-term safety are exceeded, in some cases this might lead to labelling certain disposal holes or tunnel sections not suitable for final disposal through the rock suitability classification procedure (RSC). The RSC-procedure has been described by McEwen et al. (2012). The latest published monitoring programme for the repository site has been described in Posiva-report 2012-01 (Posiva, 2012).

Monitoring data may support the understanding of the expected behavior with respect to repository operations and long-term safety (after closure) by reassuring the function of design(s) and safety, or by implying a need to enlarge the modelling parameter field. With potential need to update the safety case, there is already a schedule for safety case update needs, as the update is done with regular intervals. In Posiva, monitoring programme produces data and results. Decisions on possible actions triggered by monitoring observations are done according to internal guidance and decision responsibilities defined in the company's management system, not by the monitoring programme itself.

4 Monitoring parameter identification

Approach for EBS monitoring need during operation phase was selected to be viewed from requirements point of view. VAHA level 3 requirements, specifically performance targets, were selected as the starting point, as they produce the safety functions (Appendix 2). Host rock is excluded from consideration, as it is not EBS but a natural barrier. However, in some EBS monitoring cases, it is possible that monitoring is recommended to be done via host rock properties (e.g., groundwater properties and samples). Closure is also excluded as this was specifically determined so by the guide for Task 2.2.

For each performance target, the screening methodology diagram produced in Modern2020 Task 2.1 (White et al. 2017) for determination of monitored processes and parameters, was facilitated using also a pre-done template by Posiva’s Modern2020 task group for this purpose, with the use of issue list in addition (Appendix 1). For each performance target, it is thus determined:

1. EBS (canister/buffer/backfill) – determines the EBS from which requirements the monitoring need arises
2. Performance target (from VAHA level 3, draft Feb 2017) – provides a goal or limit, and the need to monitor
3. Process – defines which processes affect the performance target
4. Is there relevance and value for post-closure safety? – In occasions the process can be relevant, but monitoring it brings no additional value, these questions are discussed in this phase
5. Parameter – Defines what parameters can be used to monitor the identified processes
6. Expected evolution (parameter, process) – What is expected to happen to the process/parameter, and will it happen during operational phase or in post-closure phase.
7. Monitoring strategy and technological options – Describes how monitoring could be done, if it can be done
8. Is the option technically feasible? – Yes or no answer, relates to monitoring strategy and technological options
9. Are there sufficient, feasible parameters for monitoring this process?[22] – Similar to question 8, can the parameter be monitored?
10. Is the parameter/process included in monitoring plan? – Presents a yes/no answer, possibly with detailing explanations
11. Uncertainties and how they are met – Lists what is uncertain about process development, parameter measuring, linking of parameter to process or other similar issues
12. From measured parameter to behaviour – How the results regarding monitored parameters are used after obtaining them.

Process results are presented in

Table 1-61 for canister, Table 1-62 for buffer and Table 1-63 for backfill. In draft version (February 2017) of VAHA, deposition tunnel plug is a backfill component.

In identification of processes the processes are described with FEP (Features, Events and Processes) names when applicable. FEPs are attained from Posiva (2012c) with minor edits to draft form in considering current design phase. As the FEPs are also under updating, the names may have small differences to Posiva (2012c).

Table 1-61. Monitoring parameter screening for canister.

EBS	Canister
Performance target	In the expected repository conditions the canister should remain intact. (L3-CAN-5)
FEP (process)	1. Reactivation/displacement (Rock shear) 2. Metal corrosion
Is there relevance and value for post-closure safety?	Yes. Release of radionuclides needs to be prevented.
Parameter	1. Rock shear - Seismicity monitoring (indirect) - Swelling pressure - Displacement 2. Corrosion - Groundwater chemistry (e.g., sulphides, oxygen), changes

[22] This question was tested at first, then excluded, see comments in Chapter 7.

	during operation and in relation to EBS component construction and EBS material consistencies. - Corrosion potential
Expected evolution (parameter, process)	1. Canister rupturing seismic events are not expected, RSC[23] before installation, buffer will swell as result of water inflow. 2. Groundwater chemistry is expected to remain quite stable. EBS components contain certain materials that can be diluted in time to groundwater, but their quantities are limited.
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Monitoring strategy and technological options	1. Seismicity is monitored on site. Buffer swelling pressure is discussed more in buffer table (Table 4-2). Deformation is considered in full-scale test: Measuring canister geometry before and after test. 2. Monitoring from adjacent tunnels, (potentially also from deep ground surface holes). Process itself is studied as part of performance assessment (MIND[24]). Corrosion potential measurements could affect the buffer performance. Though it can in theory be measured during tests, the time is relatively short to offer results in comparison to detrimental effect the monitoring itself could cause to test case.
Is the option technically feasible?	1. It is unclear can seismic events be tracked to potentially ruptured canister, emphasis is more on the selection of the suitable canister locations. Buffer swelling pressure can be monitored in in-situ / full-scale tests 2. Possible to start measuring points (groundwater chemistry) in repository tunnel system. Corrosion potential measurements during in-situ/large-scale tests could cause more harm than offer results. Technology exists, but the value or possibility to reach results is questionable.
Are there sufficient, feasible parameters to monitoring this process?	1. Yes, magnitude and location of seismic event 2. Yes, groundwater composition and gas composition (Posiva SKB 2017) 2. Yes/no, corrosion potential can in theory be measured
Is the parameter/process included in monitoring plan?	1. Yes (seismicity), Yes (swelling pressure), No (displacement) 2. Yes (groundwater composition), no (corrosion potential)
Uncertainties and how they are met	1. and 2. are both indirect observations. They are regional and not monitored in near field.
From measured parameter to behaviour	1. The monitoring confirms the favourable conditions of the site. 2. Safety case describes the process from experiments, tests and modelling. The monitoring confirms the favourable conditions of the site.

[23] RSC: Rock Suitability Classification
[24] MIND (H2020 Project)

EBS	Canister
Performance target	The thickness of the copper shell should remain > 0 mm. (L3-CAN-7)
Process	1. Reactivation/displacement (Rock shear) 2. Metal corrosion 3. Water uptake and swelling (development of swelling pressure), also hydrostatic pressure to be considered
Is there relevance and value for post-closure safety?	Yes. Release of radionuclides needs to be prevented.
Parameter	1. Rock shear - Seismicity monitoring (indirect) - Swelling pressure - Displacement 2. Corrosion - Groundwater chemistry (e.g., sulphides, oxygen), changes during operation and in relation to EBS component construction and EBS material consistencies. - Corrosion potential 3. Pressure (with sensors)
Expected evolution (parameter, process)	1. Canister rupturing seismic events are not expected, RSC[25] before installation, buffer will swell as result of water inflow. 2. Groundwater chemistry is expected to remain quite stable. EBS components contain certain materials that can be diluted in time to groundwater, but their quantities are limited. 3. Pressure develops as inflow into buffer continues. No effect on canister is expected
Monitoring strategy and technological options	1. Seismicity is monitored on site. Buffer swelling pressure is discussed more in buffer table (Table 4-2). Deformation is considered in full-scale test: Measuring canister geometry before and after test. 2. Monitoring from adjacent tunnels, (potentially also from deep ground surface holes). Process itself is studied as part of performance assessment (MIND). Corrosion potential measurements could affect the buffer performance. Thought it can in theory be measured during tests, the time is relatively short to offer results in comparison to detrimental effect the monitoring itself could cause to test case. 3. Pressure development can be monitored with sensors in in-situ / full-scale tests. Deformation is considered in full-scale test: Measuring canister geometry before and after test.
Is the option technically feasible?	1. It is unclear can seismic events be tracked to potentially ruptured canister, emphasis is more on the selection of the suitable canister locations. Buffer swelling pressure can be monitored in in-situ / full-scale tests 2. Possible to start measuring points (groundwater chemistry) in repository tunnel system. Corrosion potential measurements during in-situ/large-scale tests could cause more harm than offer results. Technology exists, but the value or possibility to reach results is questionable. 3. Pressure sensors can be utilized in full-scale / in-situ tests
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[25] RSC: Rock Suitability Classification

Are there sufficient, feasible parameters to monitoring this process?	1. Yes, magnitude and location of seismic event 2. Yes, groundwater composition and gas composition (Posiva SKB 2017) 3. Yes, pressure sensors in full-scale / in-situ tests, no in operation phase
Is the parameter/process included in monitoring plan?	1. Yes (seismicity), Yes (swelling pressure), No (displacement) 2. Yes (groundwater composition), no (corrosion potential) 3. No, operation phase, yes in full-scale or in-situ test
Uncertainties and how they are met	1. and 2. are both indirect observations. They are regional and not monitored in near field. 1. It is unclear can seismic events be tracked to potentially ruptured canister. 3. Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution. Representativeness of sensor data.
From measured parameter to behaviour	1. The monitoring confirms the favourable conditions of the site. 2. Safety case describes the process from experiments, tests and modelling. The monitoring confirms the favourable conditions of the site. 3. The full scale / in situ test monitoring can build confidence on the expected behaviour of the buffer.

EBS	Canister
Performance target	The canister should withstand an isostatic load ≤ 50 MPa. (L3-CAN-9)
Process	1. Glacial load 2. Water uptake and swelling (development of swelling pressure), hydrostatic pressure included
Is there relevance and value for post-closure safety?	Yes. Canister is designed to endure.
Parameter	1. Not possible to monitor 2. Pressure (with sensors)
Expected evolution (parameter, process)	1. Load increases during ice age and decreases with melting of the ice cover. 2. Pressure develops as inflow into buffer continues. No effect on canister is expected
Monitoring strategy and technological options	1. Not possible to monitor 2. Pressure development can be monitored with sensors in in-situ / full-scale tests.
Is the option technically feasible?	1. No 2. Pressure sensors can be utilized in full-scale / in-situ tests
Are there sufficient, feasible parameters to monitoring this process?	1. No 2. Yes, pressure sensors in full-scale / in-situ tests, no in operation phase
Is the parameter/process included in monitoring plan?	1. No 2. No, operation phase, yes in full-scale or in-situ test
Uncertainties and how they are met	Endurance of the canister is ensured with QA/QC during design, manufacturing, sealing and installation of the canister.
From measured parameter to behaviour	N/A

EBS	Canister
Performance target	The canister should withstand a shear over the deposition hole with movement ≤ 5 cm at a velocity of 1 m/s for a buffer with the maximum allowed shear strength. (L3-CAN-20)
Process	Rock shear
Is there relevance and value for post-closure safety?	Yes. Release of radionuclides needs to be prevented.
Parameter	- Rock displacement - Rock displacement velocity
Expected evolution (parameter, process)	Canister rupturing rock displacements are not expected, RSC before installation.
Monitoring strategy and technological options	- QA/QC through RSC - Seismicity is monitored with micro seismic network on site, but its relation to canister durability monitoring is indirect.
Is the option technically feasible?	Not directly. There is no direct monitoring measure or need for it, at canister location.
Are there sufficient, feasible parameters to monitor this process?	Yes, indirectly.
Is the parameter/process included in monitoring plan?	Yes, displacements in general are monitored from still open disposal facility walls.
Uncertainties and how they are met	Observations are indirect and regional and not monitored in near field.
From measured parameter to behaviour	Monitoring confirms the favourable conditions of the site.

EBS	Canister
Performance target	The canister should withstand asymmetric buffer swelling pressure loads of 3-10 MPa. (L3-CAN-21)
Process	Stress redistribution (Development of stress/strain of the canister)
Is there relevance and value for post-closure safety?	Yes. Release of radionuclides needs to be prevented.
Parameter	- Canister deformation: geometry changes - Pressure development
Expected evolution (parameter, process)	Canister is designed to endure mentioned loads without deformation.
Monitoring strategy and technological options	Full-scale test: inspections of geometry before and after test, pressure sensors
Is the option technically feasible?	Not during operation phase, but short term monitoring can be done with full-scale / in-situ test inspections. Monitoring cannot follow long-term evolution of the process.
Are there sufficient, feasible parameters to monitor this process?	No, only as described in consideration if option is technically feasible.[26]
Is the parameter/process included in monitoring plan?	Yes, full scale / in situ test. Not in operational phase.
Uncertainties and how they are met	Full scale / in situ test is short term in comparison to long-term safety.
From measured parameter to behaviour	Possible deviations in geometry would indicate deformation. Pressure monitoring in tests will verify endurance in monitored circumstances.

[26] This question was removed from the questionnaire, see comments in Chapter 7.

EBS	Canister
Performance target	The canister should not impair the safety functions of other barriers. (L3-CAN-11)
Process	1. Heat transfer 2. Buffer alteration 3. Radiolysis
Is there relevance and value for post-closure safety?	Yes, but this is design and dimensioning topic, and monitoring does not offer value for long-term safety. Temperature measurements can verify the expected evolution of temperature (modelling verification). Mineralogical investigations after full-scale / In-situ test can confirm canisters compatibility with buffer and QA/QC will be followed during operation phase to ensure correct performance and expected evolution.
Parameter	1. Temperature 2. And 3. Buffer composition 3. N/A, laboratory tests possible
Expected evolution (parameter, process)	1. Rock and EBS temperature is expected to rise during operational time. (Performance Assessment, Posiva 2012) 2. Minor alteration of buffers accessory mineralogy is possible, no change in buffer performance. 3. Radiolysis could have an effect on bentonite (water structure)
Monitoring strategy and technological options	1. Temperature - QA/QC in dimensioning - Rock temperature measurements - Full scale / in situ test, temperature measurements 2. Buffer composition - QA/QC of buffer mineralogy - Full scale / in situ test, material sampling before and after 3. Radiolysis - QA/QC, laboratory experiments
Is the option technically feasible?	1. Temperature: Yes 2. Alteration: Monitoring cannot follow long-term evolution of the process. 3. Radiolysis: No, potentially laboratory tests
Is the parameter/process included in monitoring plan?	Yes
Uncertainties and how they are met	Heat transfer is slow process. Anisotropic rock could possibly cause anisotropic distribution of heat. Copper-bentonite interaction is so slow that possible effects might not be monitored due to short monitoring time.
From measured parameter to behaviour	Rising temperature indicates heat transfer from canisters.

EBS	Canister
Performance targets considered not to need monitoring and rationale	
Performance target	The canister should initially be intact when leaving the encapsulation plant for disposal except for incidental deviations. (L3-CAN-4)
Rationale for exclusion	No process. N/A
Is there relevance and value for post-closure safety?	Yes. Release of radionuclides needs to be prevented. No monitoring.
Parameter	N/A, manufacturing related requirement. - Weld inspections - Canister material quality - Canister manufacturing QC
Expected evolution (parameter, process)	N/A, manufacturing related requirement.
Monitoring strategy and technological options	No monitoring. Canister QC/QA
Performance target	The canister shall dissipate the spent fuel decay heat. (L3-CAN-19)
Rationale for exclusion	Not monitored, design issue.
Is there relevance and value for post-closure safety?	Yes, but this is design topic, and monitoring does not offer value for long-term safety.
Performance target	The effective multiplication factor of the encapsulated fuel shall remain < 0.95 for a canister with geometry and materials verified at encapsulation and filled with water. (L3-CAN-14)
Rationale for exclusion	Not monitored, design issue
Is there relevance and value for post-closure safety?	Yes, but this is design topic, and monitoring does not offer value for long-term safety.
Performance target	The effective multiplication factor of the encapsulated fuel shall remain < 0.98 in other design basis scenarios. (L3-CAN-22)
Rationale for exclusion	Not monitored, design issue
Is there relevance and value for post-closure safety?	Yes, but this is design topic, and monitoring does not offer value for long-term safety.
Performance target	The design of the canister should enable the retrievability of the disposal canister from the repository. (L3-CAN-18)
Rationale for exclusion	Not monitored, design issue
Is there relevance and value for post-closure safety?	N/A

Table 1-62. Monitoring parameter screening for buffer.

EBS	Buffer
Performance target	The buffer displacement should be limited to maintain the target thicknesses. (L3-BUF-28)
Process	1. Buffer characteristics 2. Water uptake 3. Deposition hole inflows (RSC)
Is there relevance and value for post-closure safety?	This is relevant, but monitoring does not bring value as the process takes a long time. Value is gained from full scale / in situ /laboratory tests to performance model validation.
Parameter	1. Buffer characteristics - Buffer composition, density and water content 2. Water uptake - Geometry at start and in dismantling - Density at start and in dismantling (homogeneity, full scale /in situ test) - Water content at dismantling, degree of saturation (from samples, full scale /in situ test), 3. RSC ate the beginning **In operational phase:** Only start characteristics, RSC, QA/QC (no monitoring)
Expected evolution (parameter, process)	Water uptake depends on water source and inflow rate.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC
Is the option technically feasible?	Yes, in full scale or in situ test. Only QA/QC at operational phase
Is the parameter/process included in monitoring plan?	Not in the monitoring programme, but handled by QA/QC
Uncertainties and how they are met	Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution.
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the buffer.

EBS	Buffer
Performance target	Diffusion should be the dominant transport mechanism for solutes in buffer. This corresponds to a hydraulic conductivity <10^{-12} m/s. (L3-BUF-29)
Process	1. Water uptake and swelling (homogenisation) 2. Erosion
Is there relevance and value for post-closure safety?	This is relevant, but monitoring does not bring value as the process takes a long time.
Parameter	In full scale / in situ tests, for both 1 and 2: - Geometry at start and in dismantling - Density at start and in dismantling (homogeneity) **In operational phase:** Only start characteristics, QA/QC (no monitoring) and input from deposition hole RSC
Expected evolution (parameter, process)	System is assumed to perform as required in long-term, diffusion remains dominant transport mechanism.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC - After construction, the deposition holes are characterised. Further monitoring of already characterised holes will depend on how long it remains open before use.
Is the option technically feasible?	Yes, in full scale or in situ test. Only QA/QC at operational phase
Is the parameter/process included in monitoring plan?	Not in the monitoring programme, but handled by QA/QC
Uncertainties and how they are met	Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution.
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the buffer.

EBS	Buffer
Performance target	To maintain canister integrity, the isostatic load from the buffer swelling pressure should be <10 MPa in the lower part of the buffer. (L3-BUF-32)
Process	Water uptake and swelling
Is there relevance and value for post-closure safety?	This is relevant, but monitoring does not bring value as the process takes a long time.
Parameter	In full scale / in situ tests: - Geometry at start and in dismantling (both canister and buffer) - Density at start and in dismantling (homogeneity) - Swelling pressure (sensors) **In operational phase:** Only initial characteristics, QA/QC (no monitoring)
Expected evolution (parameter, process)	System is assumed to perform as required in long-term, pressure develops with time and remains under given limit.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC
Is the option technically feasible?	Yes, in full scale or in situ test. Only QA/QC at operational phase
Is the parameter/process included in monitoring plan?	Not in the monitoring programme, but handled by QA/QC. Swelling pressure monitoring in full scale / in situ tests will be decided at test monitoring plans.
Uncertainties and how they are met	Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution. Representativeness of sensor data.
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the buffer.

EBS	Buffer
Performance target	To maintain favourable chemical conditions, the contents of substances in the buffer potentially contributing to corrosion should be limited. (L3-BUF-33)
Process	1. Mineralogy and chemistry at initial state 2. Alteration 3. Leaching
Is there relevance and value for post-closure safety?	Relevant. Value is gained from full scale / in situ /laboratory tests to performance model validation. Limited amount of potentially corrosion contributing substances is so low that monitoring concerned with them is not relevant.
Parameter	For all (1-3): - Material chemistry and mineralogy (QA/QC) - Groundwater composition
Expected evolution (parameter, process)	QA/QC verifies the compliance with the requirements at initial state. In long-term, alteration and leaching can occur.
Monitoring strategy and technological options	- Mineralogy and chemical composition at the start and end of full scale / in situ test - QA/QC (also in operation phase) - Groundwater sampling (to determine what substances are dissolved in it, indirect monitoring)
Is the option technically feasible?	QA/QC at manufacturing and installation only.
Is the parameter/process included in monitoring plan?	No direct monitoring. Groundwater monitoring is on-going throughout operation phase.
Uncertainties and how they are met	Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution.
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the buffer.

EBS	Buffer
Performance target	The buffer should be stable in postulated diluted[27] hydrogeochemical conditions in Olkiluoto with groundwater having a total charge equivalent of cations determined in requirement L3-ROC-14 (L3-BUF-36)
Process	1. Groundwater dilution 2. Buffer characteristics
Is there relevance and value for post-closure safety?	Yes, for groundwater dilution there is both relevance and value. Monitoring buffer characteristics is only needed in assuring QC/QA of the material.
Parameter	1. Groundwater chemistry 2. Buffer composition
Expected evolution (parameter, process)	This dilution is not assumed to occur during operational phase, would require very dilute waters for extremely long time.
Monitoring strategy and technological options	1. During operational phase groundwater chemistry is monitored, but not due to this specific reason. 2. QA/QC
Is the option technically feasible?	1. Yes 2. Yes
Are there sufficient, feasible parameters to monitoring this process?	1. Yes 2. Yes
Is the parameter/process included in monitoring plan?	1. Yes 2. Yes
Uncertainties and how they are met	None identified during process.
From measured parameter to behaviour	Changes in salinity build confidence in groundwater characteristics and their stability or direction of changes. Buffer characterisation and QC/QA confirm the suitability of the material.

[27] Groundwater at the repository level shall initially have sufficiently high ionic strength to reduce the likelihood of chemical erosion of the buffer or backfill. Therefore, total charge equivalent of cations, Σq[Mq+]*, shall initially be higher than 4 mM. (Posiva 2012b)
* [Mq+] = molar concentration of cations , q = charge number of ion)

EBS	Buffer
Performance target	The buffer should have sufficiently fine pore structure to filter radio colloids. (L3-BUF-37)
Process	Water uptake and swelling (Density homogenisation)
Is there relevance and value for post-closure safety?	Yes, transport of radionuclides should be slowed.
Parameter	- Density (start and dismantling, samples) - Pore structure (start and dismantling, samples)
Expected evolution (parameter, process)	Homogenisation is expected to take a long time, and it is directly dependent on inflow rate. In theory, it is possible that buffer would first wet and then dry again (heat), which could cause fractures to buffer, but then again, when water enters the buffer it would re-swell and start to saturate again.
Monitoring strategy and technological options	Full scale / in situ test: Samples from start and dismantling, pore structures from different sample locations
Is the option technically feasible?	No monitoring in operational phase. Yes for density is test phase, for pore structure, due to sampling error potential, this is undecided.
Is the parameter/process included in monitoring plan?	No
Uncertainties and how they are met	Pore structure sampling is extremely difficult. Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution.
From measured parameter to behaviour	Measured change would build confidence in material characterisation methods and in reaching the expected evolution.

EBS	Buffer
Performance target	The lower part of the buffer should deform sufficiently under the load induced by a 5-cm rock shear displacement at a rate of 1 m/s to maintain canister integrity. (L3-BUF-39)
Process	Buffer deformation
Is there relevance and value for post-closure safety?	Relevant, but monitoring does not bring extra value.
Parameter	1. Density 2. Mineralogy
Expected evolution (parameter, process)	Properties affecting deformation are buffer characteristics, and monitored by following QA/QC. The evolution of characteristics is that of mineralogy (alteration), density and saturation.
Monitoring strategy and technological options	1. and 2. - Not monitored, but properties are verified. - QA/QC
Is the option technically feasible?	No, handled with QA/QC
Is the parameter/process included in monitoring plan?	No, handled with QA/QC
Uncertainties and how they are met	N/A
From measured parameter to behaviour	N/A

EBS	Buffer
Performance target	The buffer shall have swelling pressure less than the yield strength of copper canister and Olkiluoto hostrock. (L3-BUF-41)
Process	(1. Material selection) 2. Swelling pressure development
Is there relevance and value for post-closure safety?	Yes, but there is no added value from monitoring
Parameter	In full scale / in situ tests (2. Swelling pressure): - Geometry at start and in dismantling (both canister and buffer) - Density at start and in dismantling (homogeneity) - Swelling pressure (sensors) **In operational phase:** (1.) Only start characteristics, QA/QC (no monitoring)
Expected evolution (parameter, process)	System is assumed to perform as required in long-term, pressure develops with time and remains under given limit.
Is the option technically feasible?	Yes, in full scale or in situ test. Only QA/QC at operational phase
Is the parameter/process included in monitoring plan?	Not in the monitoring programme, but handled by QA/QC. Swelling pressure monitoring in full scale / in situ tests will be decided at test monitoring plans.
Uncertainties and how they are met	Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution. Representativeness of sensor data.
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the buffer.

EBS	Buffer
Performance targets considered not to need monitoring, and rationale	
Performance target	To maintain canister integrity, the buffer temperature should remain > -2.5 °C to avoid high swelling pressures induced by freezing. (L3-BUF-34)
Rationale for exclusion	N/A, this considers future ice age and is a layout issue.
Performance target	To resist mineral transformation, the buffer should withstand temperatures < 100 °C. (L3-BUF-35)
Rationale for exclusion	N/A, this considers fuel selection for canisters and layout design (spacing) and buffer material selection.
Performance target	The buffer material should be favourable for the retardation of radionuclides. (L3-BUF-38
Rationale for exclusion	Material selection issue, not monitoring.
Performance target	The buffer should deform under the loads generated by gases without damaging the canister or the host rock. (L3-BUF-40)
Rationale for exclusion	Material selection issue, not monitoring.

Table 1-63. Monitoring parameter screening for backfill.

EBS	Backfill
Performance target	The backfill shall have average hydraulic conductivity between two adjacent deposition holes <10^{-10} m/s in fully saturated state. (L3-BAC-22)
Process	1. Water uptake and swelling (homogenisation of density) 2. Water uptake and swelling (saturation)
Is there relevance and value for post-closure safety?	This is relevant, but monitoring does not bring value as the process takes a long time. Value is gained from full scale / in situ /laboratory tests to performance model validation.
Parameter	Full scale or in situ test: 1. Homogenisation of density - Installation and dismantling densities (measurements and calculated) (measures hydraulic conductivity) - Piping and erosion (visual, in dismantling) (measures hydraulic conductivity) - Measured backfill geometry (before and after) (design) - Pressure (in different parts of backfill) (sensors, during test) 2. Saturation - Water content and distribution (sensors and dismantling samples) - Relative humidity (sensors, during test) - Pressure (in different parts of backfill) (sensors, during test)
Expected evolution (parameter, process)	Saturation develops slowly after installation of the backfill and depends much on water inflow into tunnel. The hydraulic conductivity is dependent on the degree of homogenisation of the backfill and this is related to the development of saturation.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC (also in operational phase) - Monitoring of pressure development behind the deposition tunnel plug (with lead-through) is feasible also during operational phase, but at this phase it is considered not to give extra value and is thus not included in monitoring (parameter is parked).
Is the option technically feasible?	Full scale / in situ tests can be monitored in described manner.
Is the parameter/process included in monitoring plan?	Yes, in full scale / in situ test phase. QA/QC in operational phase.
Uncertainties and how they are met	Representativeness of sampling. Sensor setup, do we record data from correct locations? Interpretation of sensor data is challenging. Can monitoring cause disturbances to backfill behaviour? Full scale / in situ tests only offer information on very early phase evolution. If monitoring during operational phase is later added to monitoring programme, uncertainties arise from that the deposition tunnel is several hundreds of meters long and monitoring would be done only from behind the plug (very local data).
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the backfill.

EBS	Backfill
Performance target	The backfill shall have swelling pressure at all points in the deposition tunnel >0.1 MPa in fully saturated state. (L3-BAC-24)
Process	1. Water uptake and swelling (homogenisation of density) 2. Water uptake and swelling (saturation) 3. Pressure development
Is there relevance and value for post-closure safety?	This is relevant, but monitoring does not bring value as the process takes a long time. Value is gained from full scale / in situ /laboratory tests to performance model validation.
Parameter	Full scale or in situ test: 1. Homogenisation of density - Installation and dismantling densities (measurements and calculated) - Piping and erosion (visual, in dismantling) - Measured backfill geometry (before and after) 2. Water uptake (Saturation) - Water content and distribution (sensors and dismantling samples) - Relative humidity (sensors, during test) 3. Swelling pressure - Swelling pressure (in different parts of backfill) (sensors, during test)
Expected evolution (parameter, process)	Saturation develops slowly after installation of the backfill and depends much on water inflow into tunnel. Swelling pressure is dependent on the degree of homogenisation of the backfill and this is related to the development of saturation.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC (also in operational phase) - Monitoring of pressure development behind the deposition tunnel plug (with lead-through) is feasible, but at this phase it is considered not to give extra value and is thus not included in monitoring.
Is the option technically feasible?	Full scale / in situ tests can be monitored in described manner. QA/QC in operational phase.
Is the parameter/process included in monitoring plan?	Yes, in full scale / in situ test phase
Uncertainties and how they are met	Representativeness of sampling. Sensor setup, do we record data from correct locations? Interpretation of sensor data is challenging. Can monitoring cause disturbances to backfill behaviour? Full scale / in situ tests only offer information on very early phase evolution. Uncertainty in what part of monitored pressure is swelling pressure and which is hydrostatic pressure (calculation possible, relying on theoretical hydrostatic pressures). If monitoring during operational phase is later added to monitoring programme, uncertainties arise from that the deposition tunnel is several hundreds of meters long and monitoring would be done only from behind the plug (very local data).
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the backfill.

EBS	Backfill
Performance target	The backfill shall contribute to the mechanical stability of the deposition tunnels. (L3-BAC-17)
Process	1. Water uptake (and swelling) (2. Backfill properties)
Is there relevance and value for post-closure safety?	Value is gained from full scale / in situ /laboratory tests to performance model validation. Contact of backfill and rock can be seen in dismantling.
Parameter	1. Water uptake - Swelling pressure - Density - Swelling clay content - Backfill geometry 2. Backfill properties, design and QA/QC issue
Expected evolution (parameter, process)	Swelling pressure develops slowly after installation of the backfill and depends much on water inflow into tunnel.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC (for material properties also in operational phase) - Monitoring of pressure development behind the deposition tunnel plug (with lead-through) is feasible, but at this phase it is considered not to give extra value and is thus not included in monitoring.
Is the option technically feasible?	Full scale / in situ tests can be monitored in described manner. Only material and installation QA/QC in operational phase.
Is the parameter/process included in monitoring plan?	Yes, in full scale / in situ test phase
Uncertainties and how they are met	Representativeness of sampling. Sensor setup, do we record data from correct locations? Interpretation of sensor data is challenging. Can monitoring cause disturbances to backfill behaviour? Full scale / in situ tests only offer information on very early phase evolution. Uncertainty in what part of monitored pressure is swelling pressure and which is hydrostatic pressure (calculation possible, relying on theoretical hydrostatic pressures). If monitoring during operational phase is later added to monitoring programme, uncertainties arise from that the deposition tunnel is several hundreds of meters long and monitoring would be done only from behind the plug (very local data).
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the backfill.

EBS	Backfill
Performance target	The deformation of the backfill should be limited in order to maintain the sufficient dry density of the buffer. (L3-BAC-25)
Process	1. Water uptake (and swelling) 2. Erosion (3. Backfill properties)
Is there relevance and value for post-closure safety?	Value is gained from full scale / in situ /laboratory tests to performance model validation. Contact between buffer and backfill can be seen in dismantling full-scale /in situ test.
Parameter	1. Water uptake, and 2. Erosion - Swelling pressure - Density - Swelling clay content - Backfill geometry - Clay content in groundwater (chemical/mechanical erosion) 3. Backfill properties: design and QA/QC issue
Expected evolution (parameter, process)	Swelling pressure develops slowly after installation of the backfill and depends much on water inflow into tunnel. Minor erosion can be met with swelling pressure and quantity of backfill. Erosion is expected to remain low and bentonite has capacity to seal potential flow routes.
Monitoring strategy and technological options	- Monitoring feasible before and after full scale or in situ test, at installation and dismantling phases. - No monitoring during operational phase - QA/QC (of material and installation, also in operational phase) - Monitoring of pressure development behind the deposition tunnel plug (with lead-through) is feasible, but at this phase it is considered not to give extra value and is thus not included in monitoring. - Groundwater sampling could detect bentonite (suspension/colloids), but verification of source is inaccurate.
Is the option technically feasible?	Full scale / in situ tests can be monitored in described manner. QA/QC and groundwater sampling in operational phase. Chemical erosion cannot be monitored, as if it occurs, it will happen in long-term, after closure of the disposal facility. Mechanical erosion can be monitored if flow is into open tunnel space (or drillhole, which is sampled). Analysing and measuring any leakage water coming through the deposition tunnel plug or from plug-rock interface
Is the parameter/process included in monitoring plan?	Yes, in full scale / in situ test phase
Uncertainties and how they are met	Representativeness of sampling. Sensor setup, do we record data from correct locations? Interpretation of sensor data is challenging. Can monitoring cause disturbances to backfill behaviour? Full scale / in situ tests only offer information on very early phase evolution. Uncertainty in what part of monitored pressure is swelling pressure and which is hydrostatic pressure (calculation possible, relying on theoretical hydrostatic pressures). If monitoring during operational phase is later added to monitoring programme, uncertainties arise from that the deposition tunnel is several hundreds of meters long and monitoring would be done only from behind the plug (very local data).
From measured parameter to behaviour	The full scale / in situ test monitoring can build confidence on the expected behaviour of the backfill.

EBS	Backfill
Performance target	The backfill shall have limited potential to be a source of sulphide. (L3-BAC-26)
Process	Mineralogy is known and according to this requirement (QA/QC issue), the affecting processes are: - Alteration - Leaching - Groundwater monitoring in addition
Is there relevance and value for post-closure safety?	Relevant. Value is gained from full scale / in situ /laboratory tests to performance model validation.
Parameter	- Material chemistry and mineralogy (QA/QC) - Groundwater chemistry, sulphate and sulphide (sampling from sampling locations) (on site)
Expected evolution (parameter, process)	QA/QC verifies the compliance with the requirements at initial state. In long-term, alteration and leaching can occur.
Monitoring strategy and technological options	- Mineralogy and chemical composition at the start and end of full scale / in situ test - QA/QC (also in operation phase) - Operational phase groundwater monitoring programme
Is the option technically feasible?	Yes, but not directly in the near-field.
Is the parameter/process included in monitoring plan?	Yes
Uncertainties and how they are met	Representativeness of sampling. Full scale / in situ tests only offer information on very early phase evolution. Indirect observations.
From measured parameter to behaviour	Groundwater samples provide indirect data of early phase evolution as changes in chemistry. QA/QC is, however, the most important aspect in controlling the S content.

5 Monitoring system description and implementation

From parameter screening, a list of parameters presented in Table 1-64 was gained. Parameters are listed according to process, which means each process is listed once and parameters can be mentioned several times in the list. Table 1-64 includes also information on if the process is planned to be monitored during operation phase, studied though in-situ or full-scale test, or monitored only through quality assurance and control of materials and installation. Parked parameters are also included. A decision was made for the screening methodology testing, that no active direct monitoring of buffer or backfill will be done during operational phase in tunnels containing emplaced high-level waste, which leaves only a few parked parameters to be included in the list, as some parameters were deemed impossible from the start with this decision. FEP nomenclature was attempted to be followed, but for certain processes more detailed explanatory names were given for clarification. After comparison of different parameters form all identified processes, a summary of parameters was drafted to

Table 1-65.

Table 1-64. Screened parameters for canister, buffer and backfill.

Process	Parameter	Related EBS	Parked	QC/QA	Full-scale test/ demonstration	In situ test on site (single component)	Operation phase monitoring	Note
Seismic events, Reactivation/ displacement	Seismicity monitoring	Canister					x	Indirect
	Rock displacement	Canister		x			x	RSC
	Rock displacement velocity	Canister	x				x	
Metal corrosion	Groundwater chemistry (sulphides, oxygen, etc.)	Canister			(x)	(x)	x	
	Corrosion potential	Canister	x					
	Composition	(Canister) buffer and backfill		x	x	x		
Glaciation	Maximum long-term pressure load, design issue	Canister		x				
Stress redistribution	Canister geometry changes	Canister			x	x		
Heat transfer	Temperature*	Canister		x	x	x	x	Indirect
Alteration (mineral)	Buffer composition	(Canister)/ Buffer		x	x	x		
Water uptake and swelling (density homogenisation)	Geometry	Buffer		x	x	x		
		Backfill			x	x		
	Density (dry and bulk)	Buffer		x	x	x		
		Backfill		x	x	x		
	Water content, degree of saturation	Buffer		x	x	x		
	Swelling pressure	Buffer			x	x		
		Backfill			x	x		
	Mineralogy	Buffer		x				
		Backfill		x				
	Piping and erosion (visual, in dismantling)	Backfill			x	x		
	Pore structure	Buffer		x	(x)	(x)		Needs further consideration
Water uptake and swelling (saturation)	Water content and distribution	Backfill			x	x		
	Relative humidity	Backfill			x	x		
	Pressure (in different parts of backfill)	Backfill			x	x		
	Mineralogy	Backfill		x				
	Dry density	Backfill		x				
	Water content	Backfill		x				
	Relative humidity	Backfill			x	x		

Process	**Parameter**	**Related EBS**	**Parked**	**QC/QA**	**Full-scale test/ demonstration**	**In situ test on site (single component)**	**Operation phase monitoring**	**Note**
Water uptake and swelling (swelling pressure development)	Pressure (Swelling pressure)	Backfill			x	x		
	Pressure (plug lead through)	Backfill	x					Not in operational phase
Erosion	Density (at start and in dismantling)	Buffer			x	x		
		Backfill			x	x		
	Leakage water quantity and composition (through/past plug)	Backfill					x	
	Groundwater composition	Backfill			(x)	(x)	x	
	Swelling clay content	Backfill		x				
	Geometry	Backfill		x				
Leaching	Mineralogy	Buffer		x	x	x		
	Chemistry	Buffer/ ground-water		x	x	x	x	
Groundwater recharge and water exchange (dilution)	Groundwater chemistry	Buffer			(x)	(x)	x	
Deformation	Density	Buffer		x				
	Mineralogy	Buffer		x	x	x		
Aqueous solubility and speciation (leaching of S into groundwater)	Groundwater chemistry	Backfill			(x)	(x)	x	
	Chemistry	Backfill		x				
	Mineralogy	Backfill		x				

*Temperature is measured from tunnels. This is not directly related to specific requirement for canister and is very indirect.

Table 1-65. Parameters to be monitored to verify safety functions of canister, buffer and backfill.

Canister monitoring	
In operation phase:	QA/QC in design (material; physical, chemical and geometry), manufacturing and operation
In full-scale and/or in-situ test:	Canister geometry at installation and dismantling
Buffer monitoring:	
In operation phase:	QA/QC in design, manufacturing and operation
	- Initial state mineralogy
	- Initial state chemistry
	- Initial state geometry
	- Initial state density (dry and bulk)
	- Initial state water content
	- Initial state pore structure
In full-scale and/or in-situ test:	Mineralogy at installation and dismantling
	Chemistry at installation and dismantling
	Geometry at installation and dismantling
	Density (dry and bulk) at installation and dismantling
	Water content at installation and dismantling
	Pore structure at installation and dismantling
	Swelling pressure (sensors)
Backfill monitoring	
In operation phase:	QA/QC in design, manufacturing and operation
	- Initial state mineralogy
	- Initial state chemistry
	- Initial state geometry
	- Initial state density (dry and bulk)
	- Initial state water content
	- Visual observation of the deposition tunnel plug face
	- Analysing and measuring any leakage water coming through the deposition tunnel plug or from plug-rock interface
In full-scale and/or in-situ test:	Mineralogy at installation and dismantling
	Chemistry at installation and dismantling
	Geometry at installation and dismantling
	Density (dry and bulk) at installation and dismantling
	Water content at installation and dismantling
	Swelling pressure (sensors)
	Relative humidity (sensors)
	Piping and erosion (visual observation in dismantling)
Other monitored parameters with indirect relation to canister, buffer and backfill	
Throughout construction and operation:	Groundwater flow and chemistry
Additional monitored parameters with indirect relation to canister and buffer	
Throughout construction and operation:	Seismicity (incl. potential rock displacements)
	Temperature

In operational phase, several issues are handled through quality assurance and quality control. Material selection according to specifications and proper storage and installation are key elements in achieving safety functions as they are the only measurable attributes. In many cases, direct monitoring after installation is often not feasible without compromising the long-term safety of the system. Properties of clay components, such as mineralogy, swelling clay quantity, dry density, water content, and geometry at installation are important factors and affect several parameters. For canister, the quality control is the only measure for monitoring, all other monitoring is very indirect and, actually, concentrated on monitoring the bedrock or groundwater. Design has an important role both, for EBS and layout, and as such they are mentioned in several occasions in Chapter 4.

Full-scale and/or in-situ tests have a large role in confidence building, and as monitoring of most of the EBS's is challenging, the weight of verifying compliance to requirements is most often placed upon tests. Each test will have its own monitoring plan, and hence it is not here separated what could be monitored in which possibly upcoming test or demonstration. Laboratory tests are not mentioned in Chapter 4, but they too, have this same role. Only in tests and demonstrations done in advance can we more directly present the performance of the barriers.

Posiva has from the start of design for disposal facility emphasized that the system needs to be robust, and function without maintenance when completed. This has also led to EBS design in such manner that emphasis is in planning, designing, quality assurance and quality control, and in high performance production and installation chain, not forgetting the storage phases of materials. Posiva has also undertaken a modified Failure Mode and effects Analysis (FMEA) to determine potential deviations during operation phase with emphasis on effects on long-term safety (Karvonen 2017). With these, the actual monitoring will relate more to site characteristics. The deposition tunnel plug will be visually monitored when it is accessible, but its main function in long-term is only to fill its volume and not to harm other components. Therefore, the monitoring of the deposition tunnel plug, along with the other EBS components, at this moment, is foreseen to be quite light.

6 Monitoring results in the confidence building and decision making process

The role of the monitoring programme is to collect, provide, interpret and publish the data. Unprocessed monitoring results in Posiva are not reported as such to public. They are complex numerical values that need interpretation and explaining. With this, the results as such go to internal memorandums and from there they are interpreted and the interpreted results are then published as public annual sub-section- specific monitoring reports. The reports are published once a year in Posiva's working report- series. These reports are free for anyone to access. Raw data as such would not serve in confidence building, as the interconnections between processes and sources of potential distractions are very complicated and the results require interpretation before any conclusions can be made. However, also the non-published monitoring memorandums with the raw data can be provided to STUK on request, and these documents can be freely received from their office on request by anyone based on the Act on the Openness of Government Activities (621/1999) as well as other documents not especially defined classified based on law.

The generic management functions and related deciders in the decision making process related to actions arising from monitoring observations are briefly addressed in this chapter from Posiva's perspective. Posiva has established internal guidance for procedures related to evaluation and implementation of actions in cases where action limits of the monitoring programme are exceeded. In Posiva's approach, monitoring programme itself has an informative role, not making decisions on the actions. If an action limit is exceeded, the situation will be assessed by a specific group established for addressing special issues and questions related to the design, construction and research use of the final disposal facility. The group can also consult e.g. safety case if necessary. The group will then make a suggestion on actions or decide that actions are not needed regarding the case. The decision maker on the actual implementation of the actions will be determined based on the type, extent and cost of the suggested action, according to the decision-making responsibilities defined in Posiva's management system. In general, it can be stated that the most important thing related to management functions for decision making related to monitoring observations is that the organization has up-to-date guidance regarding the decision-making process, this enables efficient processing of the observations requiring actions.

As can been seen from tables in Chapter 4, the main outcome, from parameters to performance, is building confidence in models, design and performance of EBS's, host rock and the disposal system as a whole. It increases the knowledge about the site and processes taking place during construction. If action limits, discussed in Chapter 3, are reached the possible actions will be assessed and decided upon in the organization as described above and in Chapter 3.

7 Conclusions and recommendations

Process and parameter screening was implemented from requirement based (performance target) starting point by using the screening methodology chart presented in White et al. (2017). The list of issues to be addressed in Task 2.2 (APPENDIX 1) was also used in the process. Screening methodology from White et al. (2017) is presented in **Figure 1-28**. Some comments were raised during workshops concerned with the feasibility of the screening methodology. Main comments during the work were:

1. In some occasions, options to monitor certain processes were not only parked, they were removed completely from the start as technically not feasible or irrelevant.
2. TEC1 and PAR3, appeared to answer the same question, just from two different point. As the answer is similar, though, it was found that only one question about this phase was used. During workshops it formed to be: Are there technically feasible options for monitoring this parameter?
3. PRO6, even though watching from process viewpoint, felt again like repetition of TEC1 and PAR3.

Recommendation for the screening methodology would be to combine the steps from TEC1 to PRO6 more, or to better explain the difference between these steps already in step names, as during work it is not practical to always refer to the longer explanatory texts describing what each short sentence has in the background.

The screening method chart was well applicable to Posiva's project in parameter identification, and especially the first steps were useful and assisted in establishing broader thought on what actually is the evolution of processes, which might have been overlooked easily. The evolution section in Posiva's work could have been more elaborated, even, but it was kept short on purpose as there already exist long reports of this topic, e.g., Posiva (2013).

During work, it was noted that not all monitoring needs come from the long-term safety. Construction of EBS can also require monitoring. An example of this is temperature of concrete, which needs to be monitored after casting, to verify the strength development. In accomplishing review from performance targets point of view, technical needs do not arise from it, however, they should be part of the QA/QC. This work was not elaborated to include technical construction related monitoring needs, as they as such do not directly reply to EBS monitoring needs, thought such monitoring does provide verification of endurance and function of installed barriers.

The work clearly brought up the importance of full scale and in-situ testing, together with material characterization and laboratory testing. It is imperative to know the materials and their performance, as the design of the disposal system is such that direct monitoring after installation cannot be done. Only indirect monitoring options remain at the operational phase.

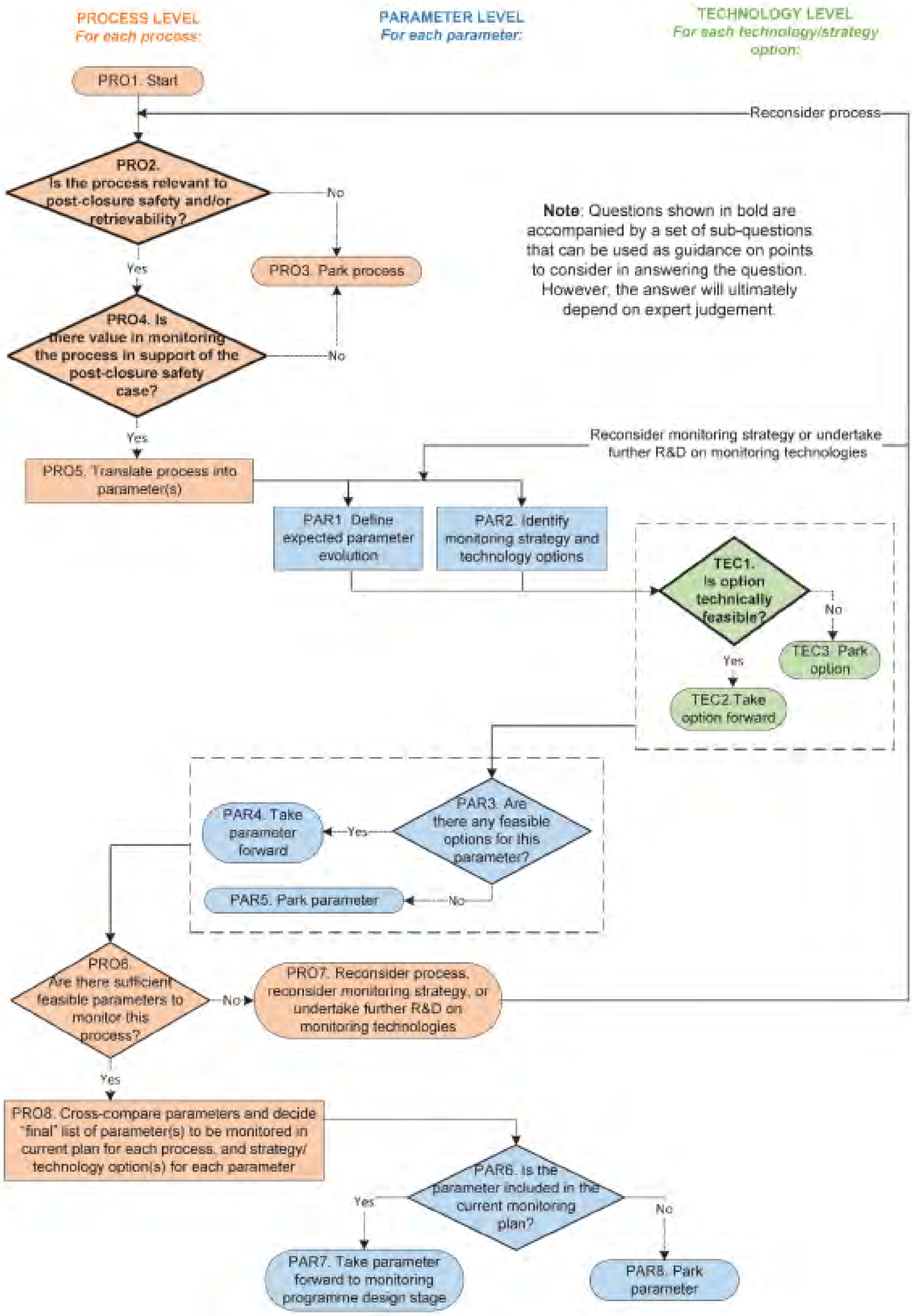

Figure 1-28. Screening process from Task 2.1.

8 Summary

The work in Task 2.2 included process and parameter screening with screening methodology provided by Task 2.1. Screening was initiated from performance targets defined by Posiva for EBS components. The performance targets used in this work are draft versions, and may differ from final versions, which will be provided for safety case for operating license for the disposal facility. In addition, a guide on how to perform Task 2.2, with given table of contents and description of what is wished to be included, was utilised in the work.

The work was successful in identifying processes and parameters for operation phase EBS monitoring. The screening methodology was usable, but recommendations for improvement were also identified. LILW-R and closure were excluded from the work. At the start, a decision was done also to exclude any monitoring inside the EBS in operational phase. With this decision, majority of the monitoring will occur in the demonstration tests and confirmation of material performance and compatibilities, and through design and quality assurance and quality control. In some cases, monitoring even in full-scale or in-situ tests was identified not necessary, as the tests will only reveal early phase evolution occurrences and the sensors and lead-throughs could have a detrimental effect on the system components, potentially harming their performance in the tests. Even though groundwater and host rock monitoring was not assigned for this work to be considered, certain EBS processes can potentially be monitored, indirectly, with groundwater monitoring. The only operational phase monitoring activities identified in this project were the monitoring of seismic activity, potential rock displacements (connected to seismic activity monitoring), groundwater composition and flow, and monitoring of the deposition tunnel plug face on central tunnel side visually, measuring potential water leakages from it and defining the leakage water composition. Temperature is also monitored in the disposal facility throughout the operational phase, with or without relation to EBS monitoring. The general monitoring of the site (groundwater conditions, rock mechanical conditions etc.), however provide important information on verifying that the boundary conditions of the site remain within the range of conditions where the EBS has been designed to perform as planned.

Posiva has designed the disposal system to provide passive safety, without the need to directly monitor the performance of the EBS. This was well detected in this work, as no major needs to monitor were identified. The safety is best attained with pre-defined material parameters and quality, and with understanding of the system as an entity.

This work and the resulting monitoring parameters and processes have been defined purely for the purpose of testing the screening methodology, developed in MoDeRn2020 Task 2.1 and the work, or its results do not represent Posiva's actual operational monitoring programme plans.

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Appendix 1 – Issues to address by Test cases

Issues	Comments
1_System description	
g) What is the adopted approach for the system description: safety case, safety functions, FEP´s, proxies ?	
h) Describe the EBS and host-rock processes	The purpose is to give an overview and a context , for deep details it is better to provide a reference.
i) Explain the set of parameters that are involved in the EBS/host-rock processes	This should cover a complete set which corresponds to what could be measured (=preliminary parameter list), being the population from which a sample of relevant parameters is drawn which shall be monitored.
2_Parameters	
u) Explain the implementation of the methodology/workflow for the parameter screening process, i e how to arrive at the parameters to actually monitor.	This is an adaptation to nation- and site specific of the generic screening methodology given by Task 2.1.
v) Explain what parameters are actually going to be monitored (i. e. screened parameter list) and why.	The chosen parameters should be relevant and measureable and their monitoring not impact detrimentally on the safety of the system.
w) Describe the expected system behaviour/evolution of processes and measured EBS monitoring parameters. (holistic)	With system behaviour is meant the spatial-temporal development of an aggregate of monitored parameters of the coupled rock-EBS system.
x) What are the performance measures for the expected behaviour?	With performance measure is meant a qualitative method or quantitative measure or a combination of both to compare monitoring results with an a-priori modelled behaviour. E.g. temperature evolution - comparison/correlation between the temperature time series for given points in space and or snap shots of many points in space at different time.
y) Explain the methodology of going from measured parameters to actual behaviour to comparison with expected system behaviour.	The intention is to have a transparent description of the stepwise process and underlying consideration/motivations of going from single measured parameters to interpreted system behaviour based on an aggregate of monitored parameters and to compare this with expectations based on the a-priori modelled results.
z) Describe a range of possible actions in response to measured "deviations"	Here it is necessary to explain the "baseline" i.e. expected behaviour and relate monitored parameters to it, then a discussion of feasible/possible bounds which are deemed "acceptable". Outside of this bound are what may be envisaged as "deviations" which could be addressed by certain actions as a direct response.
aa) Explain the methodology and application of Q/C and Q/A procedures for the implementation and operation of the EBS monitoring	If quality control measures relevant for the implementation of the EBS monitoring system then these should be described and explained
bb) What are the uncertainties in the implementation and operation of the EBS monitoring and how are they handled: parameters, redundancy, system behaviour, (decision making),….?	These relate e.g. to reliability of monitored data over long periods of time, what are they and how are they mitigated? Is parameter redundancy one way? Other uncertainties are interaction of regulators and citizen stakeholder with monitoring results – what is their interpretation and desire for action - how is this addressed?
cc) Suggestions for improvement/revisions to the parameter screening process and the Screening template in Appendix B.	The undertaken parameter screening process provides valuable experience which shall be utilised for improvement.
dd) Explain how you assess whether the monitoring system might impact on the long-term safety of the EBS. What are your considerations and deliberations?	This issue is implicit through the Screening methodology but shall be explicitly addressed.

3_Added value	
g) What are the motivations for undertaking EBS monitoring?	
h) Explain how EBS monitoring may support confidence building and decision making process	
i) Explain how EBS monitoring may contribute towards the interaction with citizen stakeholders in support of confidence building	
4_Decision support	
g) Explain which decisions may be supported by monitoring results, if any.	
h) Explain how monitoring data may support the understanding of the expected behaviour with respect to repository operations and long-term safety (post closure).	
i) Describe the management functions (generic) required for the decisions making process and the involved deciders.	

Appendix 2 – Posiva VAHA L3 performance targets for canister, buffer and backfill (draft, February 2017)

CANISTER		
VAHA ID	**Requirement, full text**	**In parameter screening or N/A**
L3-CAN-3	2 Containment	-
L3-CAN-4	The canister should initially be intact when leaving the encapsulation plant for disposal except for incidental deviations.	N/A
L3-CAN-5	In the expected repository conditions the canister should remain intact.	Yes
L3-CAN-6	3 Chemical resistance	-
L3-CAN-7	The thickness of the copper shell should remain > 0 mm.	Yes
L3-CAN-8	4 Mechanical resistance	
L3-CAN-9	The canister should withstand an isostatic load ≤ 50 MPa.	Yes
L3-CAN-20	The canister should withstand a shear over the deposition hole with movement ≤ 5 cm at a velocity of 1 m/s for a buffer with the maximum allowed shear strength.	Yes
L3-CAN-21	The canister should withstand asymmetric buffer swelling pressure loads of 3-10 MPa.	Yes
L3-CAN-10	5 Compatibility with the EBS and host-rock performance	-
L3-CAN-11	The canister should not impair the safety functions of other barriers .	Yes
L3-CAN-19	The canister should transfer the spent fuel decay heat.	N/A
L3-CAN-13	6 Subcriticality	-
L3-CAN-14	The effective multiplication factor of the encapsulated fuel shall remain < 0.95 for a canister with geometry and materials verified at encapsulation and filled with water.	N/A
L3-CAN-22	The effective multiplication factor of the encapsulated fuel shall remain < 0.98 in other design basis scenarios.	N/A
L3-CAN-17	8 Retrievability	-
L3-CAN-18	The design of the canister should enable the retrievability of the disposal canister from the repository.	N/A
BUFFER		
VAHA ID	**Requirement, full text**	**In parameter screening or N/A**
L3-BUF-28	The buffer displacement should be limited to maintain the target thicknesses.	Yes
L3-BUF-29	Diffusion should be the dominant transport mechanism for solutes in the buffer. This corresponds to a hydraulic conductivity < 10^{-12} m/s.	Yes
L3-BUF-32	To maintain canister integrity, the isostatic load from the buffer swelling pressure should be < 10 MPa in the lower part of the buffer.	Yes

Table continues to the next page.		
Table continues from the previous page.		
L3-BUF-33	To maintain favourable chemical conditions, the contents of substances in the buffer potentially contributing to corrosion should be limited.	Yes
L3-BUF-34	To maintain canister integrity, the buffer temperature should remain > -2.5 °C to avoid high swelling pressures induced by freezing.	N/A
L3-BUF-35	To resist mineral transformation, the buffer should withstand temperatures < 100 °C.	N/A
L3-BUF-36	The buffer should be stable in postulated dilute hydrogeochemical conditions in Olkiluoto with groundwater having a total charge equivalent of cations determined in requirement L3-ROC-14.	Yes
L3-BUF-37	The buffer should have sufficiently fine pore structure to filter radiocolloids.	Yes
L3-BUF-38	The buffer material should be favourable for the retardation of radionuclides.	N/A
L3-BUF-39	The lower part of the buffer should deform sufficiently under the load induced by a 5 cm rock shear displacement at a rate of 1 m/s to maintain canister integrity.	Yes
L3-BUF-40	The buffer should deform under the loads generated by gases without damaging the canister or the host rock.	N/A
L3-BUF-41	The buffer should have swelling pressure less than the yield strength of copper canister and Olkiluoto hostrock.	Yes
BACKFILL		
VAHA ID	**Requirement, full text**	**In parameter screening or N/A**
L3-BAC-22	The backfill should have an average hydraulic conductivity between two adjacent deposition holes < 10^{-10} m/s in the fully saturated state.	Yes
L3-BAC-24	The backfill should have a swelling pressure at all points in the deposition tunnel > 0.1 MPa in the fully saturated state.	Yes
L3-BAC-17	The backfill should contribute to the mechanical stability of the deposition tunnels.	Yes
L3-BAC-25	The deformation of the backfill should be limited in order to maintain a sufficient dry density of the buffer.	Yes
L3-BAC-26	The backfill should have limited potential to be a source of sulfide.	Yes

Appendix H: Test case report SKB (SR-Site)

Contents

Executive summary

The objective with Task 2.2 is to test the methodologies for screening monitoring parameters identified and developed in Task 2.1. Specifically to describe objectives for monitoring of the barrier system to identify the parameters that should be monitored and to describe the expected evolution of the disposal system during the monitoring period, as it relates to the monitoring parameters identified. Participation in the project as well as the Task provides a focus and ground for common understanding of the issue while informing and honouring the national contexts.

Screening was undertaken with safety functions rather than processes as the starting point for which a) relevance to safety have already been established and b) relations and interdependencies of processes are already considered since the functions are developed with the performance assessment exercise (SR-Site). In order to contain the screening in time while at the same time honouring the objective of testing the screening methodology, it was decided to limit the screening to only 4 parameters (safety function indicators) from different barrier components. These parameters were hydraulic conductivity and swelling pressure for the backfill, charge concentrations of cations for the buffer and copper thickness for the canister.

For each process/parameter (safety function/ safety function indicator) the screening worksflow was followed and outcome documented in an excel sheet template.

The screening methodology was found useful to identify parameters (safety function indicators) suitable for monitoring during the operational phase of the repository in a systematic, structured, traceable and repeatable way.

The EBS-function is governed by a large number of processes/parameters which are often coupled and interdependent making an assessment of the first and most basic question (PRO2) “if the process is relevant for post-closure safety”, quite difficult to answer in some cases. The reason being that screening a singular process at a time to decide on post-closure relevance might be insufficient. Hence, the adoption of safety functions, instead of parameters, as starting point for the parameter screening was found more robust and workable.

The following alterations to the screening methodology are suggested,

- The expected behaviour of the option for the parameter (PAR3) ought to be described if the option parameter is adopted – this is missing in the present workflow.

- Screening workflow ought also allow to start with a more compounded function than a singular process, where relevance for safety is already established.

- The workflow of the screening methodology need to bring forward and make more visible the step of checking whether the proposed technology can be applied without significantly affecting the passive safety of the repository system (TEC1). It is of such importance that it ought to be highlighted in the workflow and be addressed directly and bluntly.

- The technical feasibility question (TEC1) is understood as the feasibility at the time of installation. Durability and reliability of data output over such long time periods from gauges need to be proven before taking the decision on whether the parameter should be taken forward to the monitoring programme design stage (PAR7). Somehow this ought to be a check in the workflow.

- The critical question "Can the proposed technology be applied without significantly affecting the passive safety of the repository system?" is part of TEC1 but can not be answered at TEC1 level, needs to be addressed after PAR7.

1 Introduction

The focus of the Modern2020 Project is monitoring during the operational period in support of demonstration of post-closure safety. Aspects of monitoring after final closure are for consideration by the WMO. It is an implicit principle of the Screening Process that any monitoring after full closure of a repository would be a continuation of monitoring prior to full closure. Therefore, the process that is developed here is equally applicable to all phases of monitoring. Closure entails that deposition is completed and galleries backfilled. Once monitoring is put in place during the operational period it is up to the WMO and its regulatory framework to decide on discontinuation.

Monitoring programmes based on these safety cases are at different levels of development. Preliminary parameter lists exist for the Cigéo and Olkiluoto repositories. For the other programmes, preliminary parameter lists will be developed within Task 2.2.

The general objective of Task 2.2 is to test the methodologies for screening monitoring parameters identified and developed in Task 2.1. Specific objectives are:

- Describe specific objectives for monitoring of the barrier system in different national programmes, based on generic objectives for monitoring identified in MoDeRn.
- Identify the parameters that should be monitored in practical (implementable) programmes by using screening methodology from Task 2.1.
- Describe the expected evolution of the disposal system during the monitoring period, as it relates to the monitoring parameters identified.

The approach used will depend on the national programme, and may include consideration of safety cases during the operational phase, safety function indicators and/or FEPs.

It will be relevant to develop a link between EBS (Engineered Barrier System) monitoring results and the decision making processes during the operational phase of repository implementation. Specifically, the work in Task 2.2 shall for different national programs elaborate on how results from the monitoring of the EBS might be utilised to support operational decision and provide support to stakeholders. This will feed into Task 2.3 to identify and develop methodologies and tools to for the decision making process.

2 System description

2.1 EBS/Host-rock system

Overview of the system

The repository system is based on the KBS-3 method, in which copper canisters with a load-bearing cast iron insert containing spent nuclear fuel are surrounded by bentonite clay preventing groundwater flow, deposited at approximately 500 m depth in groundwater saturated, granitic rock, see Figure 2-1.

The facility design with rock caverns, tunnels, deposition positions etc. is based on the design originally presented in the KBS-3 report /SKBF/ KBS 1983/ which has since been developed in more detail. The deposition tunnels are linked by main tunnels for transport and communication. One ramp and several shafts connect the surface facility to the underground repository. The ramp is used for heavy and bulky transports and the shafts are used for utility systems, ventilation and for transport of excavated rock, backfill and staff. The different parts of the final repository are outlined in Figure 2-2.

Around 54,000 spent fuel assemblies corresponding to around 12,000 tonnes (heavy metal – initial weight) of spent nuclear fuel are forecast to arise from the Swedish nuclear power programme (see the **Spent fuel report TR-10-46**), corresponding to roughly 6,000 canisters in the repository. These figures are
based on assumed reactor operational times of 50–60 years. The SR-Site assessment is, therefore, based on a repository with 6,000 canisters, corresponding to around 12,000 tonnes of fuel.

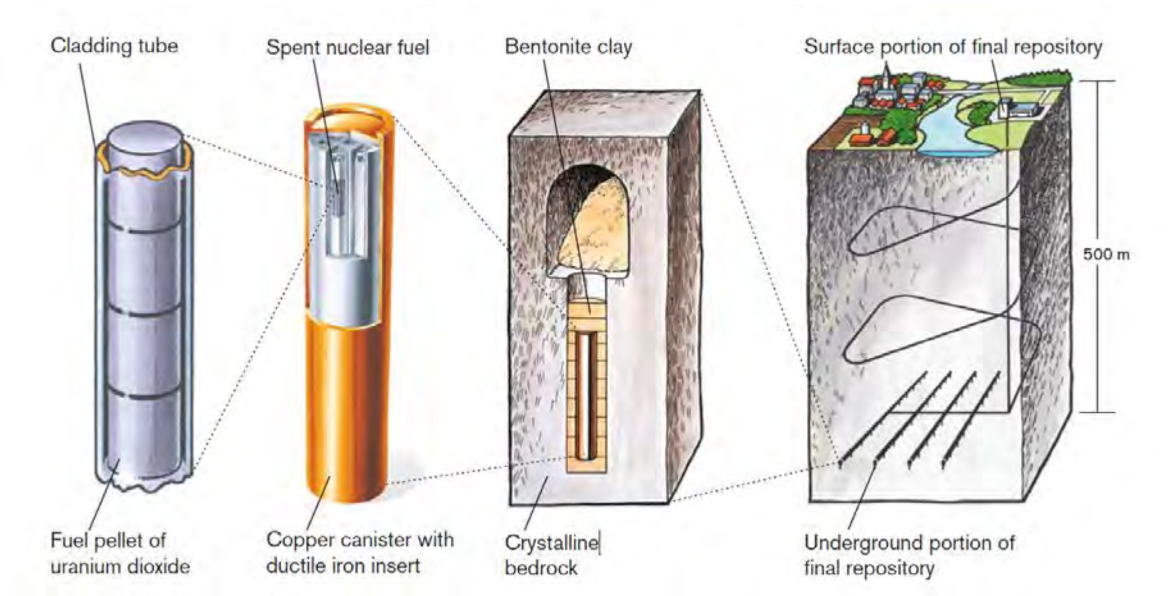

Figure 2-1. *The KBS-3 concept for storage of spent nuclear fuel.*

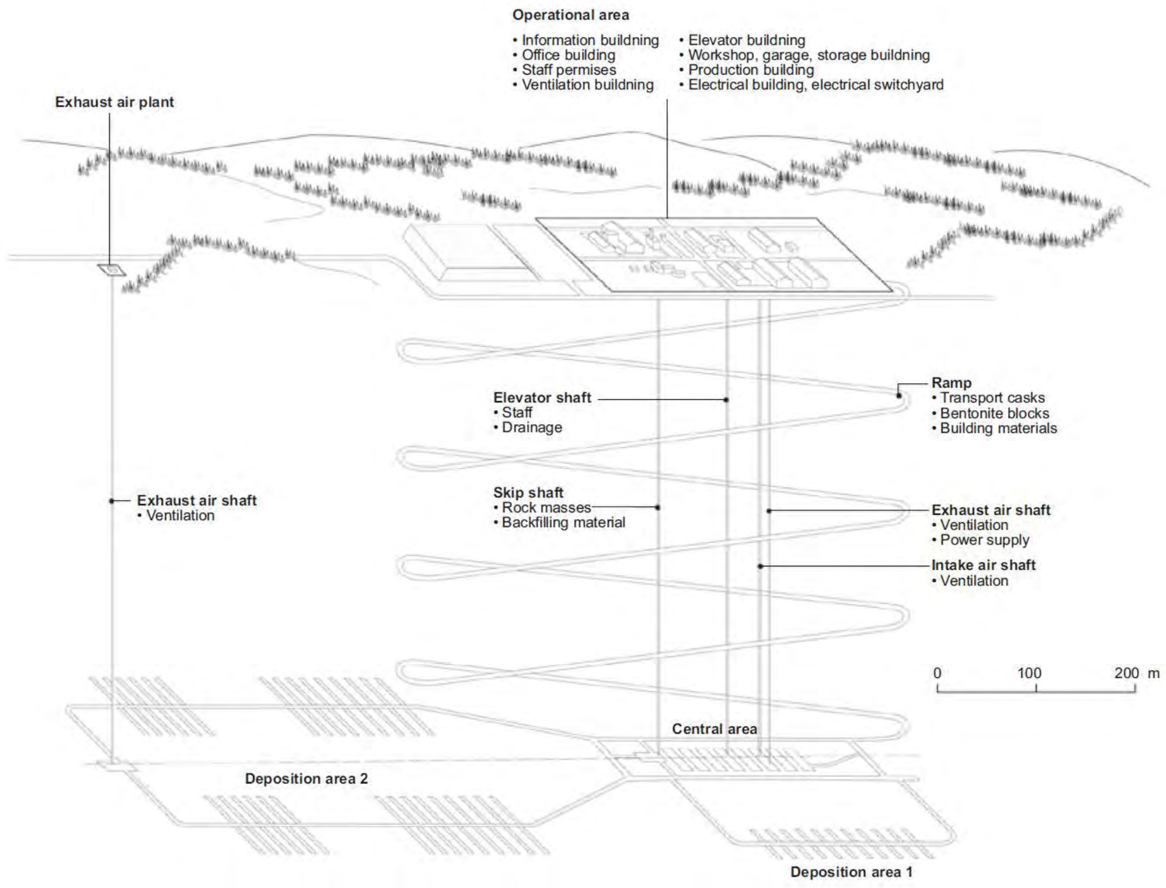

__Figure 2-2.__ General repository layout showing the location of the underground functional areas (Access, Central and Deposition areas) and the surface facilities.

8.1.1 EBS related system components

For the purpose of the safety assessment, the repository system is divided into several system components and each component is characterised by a number of specified time-dependent physical parameters (= variables in SKB terminology). Besides the canister, the main system components related to the EBS are the buffer, the backfill and the tunnel plug. SKB are not planning to monitor the canister, buffer or backfill barriers directly. The flow through the plug will be monitored and hence its function is described in greater detail than the rest of the EBS.

- **Buffer:** In the deposition hole, the copper canister is surrounded by a buffer of clay. The buffer is installed as bentonite blocks and pellets. The blocks are placed below and above the canister and the bentonite rings surround the canister.

- **Backfill** : When the holes in a deposition tunnel have been filled with canisters and buffer the tunnel will be backfilled. Before backfilling, all tunnel installations including concrete on the floor of the tunnel will be removed. In SR-Site, the deposition tunnels as well as the transport tunnels and the lower part of the ramp and shaft, extending from 200 m down to the repository is assumed to be filled with backfill material and will be considered as "backfill".

- **Tunnel plug**: The plug is in itself not a barrier but it is a necessary component to confine the backfill in the deposition tunnel and thereby maintain its barrier function. The main requirements of the plug are as follow,
  – The plug shall seal the deposition tunnel and keep the backfill in place during the operational phase until the deposition and transport tunnels have been backfilled and water saturated, and have regained their hydrostatic water pressure.

- The plug shall resist the hydrostatic water pressure at repository level and the swelling pressure from the backfill and the bentonite seal.
- The plug shall limit water flow from the deposition tunnel past the plug to such an extent that no harmful backfill erosion takes place from the deposition tunnel.
- The deposition tunnel plug must be sufficiently gas tight during the operational phase to prevent convection of air outside the tunnel into the deposition tunnel where the oxygen in the air that might corrode the canister.
- The plug shall not significantly impair the barrier function of the other barriers.
- The movement of the plug due to pressure shall be within sufficiently small to avoid a drop in backfill density in the vicinity of the plug.

When repository operations are completed the remaining tunnels, caverns, shafts and ramp will be sealed. The function of the sealing is to prevent the formation of preferred groundwater flow paths and to make unintended intrusion in the repository substantially more difficult.

When the central tunnel is filled and closed, it will provide a counter pressure for the backfill swelling and expansion. This counter pressure will be fully developed after the saturation of the connecting tunnel. The plug has then fulfilled its function to keep the backfill in place.

8.1.2 EBS related system processes

Within a specific system component, a number of processes act over time to alter the state of the system, i.e. changing the parameters. Examples from the buffer are heat transport, water uptake, swelling, chemical decomposition and ion exchange.

The coupling between the processes is expressed by the network of connected processes and parameters and the system of coupled processes needs to be managed in the safety assessment. Couplings between system components are, if required, handled via the time-dependent boundary conditions at the component interfaces.

Most processes and influences on barrier properties are only relevant in some of the several time frames that need to be considered in the safety assessment.

The identification of relevant processes has been a continuing effort over many years, based on R&D results, findings in earlier safety assessments etc. In the SR 97 assessment, an identification of the set of processes to be managed in the safety assessment was made /Pers et al. 1999/ and this set was the starting point for process identification in SKB's safety assessment, SR-Can and SR-Site.

There are a large number of processes involved in the EBS relating to the respective component, most of which are however of common type, including thermal, hydraulic, mechanical, chemical and radionuclide transport process. There are about 76 processes for the mentioned components as compiled in to Appendix 2.

Each process is driven by a number of parameters which vary in time making them in principle amenable for monitoring over time. The total number of parameters available would be in the range of approximately 600-800.

For example, the hydraulic processes of piping/erosion of the buffer is controlled by 12 parameters with dependencies according to Table 2-1.

Table 2-1. *Direct dependencies between the process "Piping/erosion" and the defined buffer parameters and a short note on the handling in SR-Site.*

Parameter	**Parameter influence on process**		**Process influence on parameter**	
	Influence present? (Yes/No) Description	**Handling of influence (How/Why not)**	**Influence present? (Yes/No) Description**	**Handling of influence (How/Why not)**
Buffer geometry	Yes, the distance between the bentonite blocks and the rock surface strongly influences the susceptibility to piping, since it affects the time to reach a high swelling pressure	The geometry of the buffer is simplified – only a mass balance is used	Yes, through lost buffer material	Amount of lost buffer is calculated
Pore geometry	Yes, by influence of void size distribution in the pellet gap and indirectly through the stress state	Included in the mass balance estimations	No, but indirect through stress state	
Radiation intensity	No		No	
Temperature	No		No	
Water content	Yes, a change in water content changes the swelling pressure, which influences the piping risk. It also influences the hydraulic conductivity, which influences the swelling rate	Piping will only occur before the buffer is fully saturated and homogenised	Yes. Piping may increase the saturation rate and thus affect the water ratio and degree of saturation since it may distribute the water in a more homogeneous manner via a net of pipes inside the pellets. Erosion will change the final water content	Amount of lost buffer is calculated
Gas content	Yes, the degree of saturation and the porewater pressure in the backfill influences the risk of piping and the erosion rate	Piping will only occur before the buffer is fully saturated and homogenised	No	
Hydroparameters (pressure and flows)	Yes, basic parameters	The hydraulic gradient, the water flow and the duration are included in the estimate of piping and erosion	Yes	The pipes are assumed to seal when the hydraulic gradients are restored. An "after piping" hydraulic conductivity based on the loss of mass is estimated
Stress state	Yes, determines if piping occurs	Included in the consequence estimation	Yes	An "after piping" swelling pressure distribution is estimated
Bentonite composition	Yes, the bentonite and montmorillonite composition affects important parameters	Included in the consequence estimation made indirectly through stress state	No	

Parameter	Parameter influence on process		Process influence on parameter	
	Influence present? (Yes/No) Description	Handling of influence (How/Why not)	Influence present? (Yes/No) Description	Handling of influence (How/Why not)
Montmorillonite composition	Yes, the bentonite and montmorillonite composition affects important parameters	Included in the consequence estimation made indirectly through stress state	No	
Porewater composition	Yes, the salinity of the water affects many parameters that govern susceptibility to piping and erosion, i.e. the swelling pressure, the swelling rate (through hydraulic conductivity) and the erodability	Included in the consequence estimation since the porewater composition will affect the amount of eroded buffer. However, a conservative upper limit is used in SR-Site	No	
Structural and stray materials	No		No	

2.2 Expected behaviour of EBS

Transients in the system are induced when constructing the underground facility and when depositing hot and radioactive nuclear waste. These transients relate to the alterations of state of the basic parameters of stress (pressure), flow and heat. The expected behaviour is therefore related to these entities in the different system components over time. The expected behaviour is acquired through laboratory and field experiments, conceptual modelling and numerical simulations.

In order to test the screening methodology four different cases were chosen. The cases were chosen to illustrate different resulting monitoring strategies or strategy elements, i.e. monitoring in situ monitoring of repository components or monitoring of batch test.

For this exercise we will limit ourselves to four cases and perform the screening of four parameters (Table 2.2) but will only describe the expected behaviour for Case 1, the hydraulic process of piping/erosion which is relevant from installation and the early development/evolution of the repository. It´s expected behaviour is described in chapter 2.3.

Table 2-2. *Test cases taken through the parameter screening process.*

Barrier component	Safety function	Safety function indicator (Parameter)	Safety function indicator criteria (TR-11-01) = Performance target (Posiva-SKB Report 01)	Detrimental process	Evaluated parameter for monitoring
Case 1 Buffer	limit advective mass transfer	Hydraulic conductivity	Hydraulic conductivity $< 10^{-12}$ m/s	Erosion of buffer	Flow past deposition tunnel plug
Case 2 Buffer	limit advective mass transfer	Swelling pressure	Swelling pressure 3-10 MPa	A number of contributing processes	Swelling pressure: Direct measurement
Case 3 Backfill Buffer	Retain sufficient mass over life cycle	Stable in contact with water with a certain total charge equivalent of cations	Stable in contact with ground water with total charge equivalent of cations $\Sigma q[Mq+] > 8 \times 10^{-3}$ mol/L .	Chemical erosion	Electrical conductivity of groundwater
Case 4 Canister	Withstand corrosion	Copper thickness	Copper thickness > 0	Corrosion	Estimation of canister average thickness via direct measurement of weight-loss. In-situ batch experiments with copper coupons as proxy for canister.

2.3 Expected behaviour of piping/erosion of the buffer, backfill and plug

8.1.3 Buffer

Water inflow into the deposition hole will take place mainly through fractures and will contribute to wetting of the buffer. However, if the inflow is localised to fractures that carry more water than the swelling bentonite can absorb, there will be a water pressure in the fracture acting on the buffer. Since the swelling bentonite is initially a gel, which increases its density with time as the water goes deeper into the bentonite; the gel may be too soft to stop the water inflow. The results may be piping in the bentonite, formation of a channel and a continuing water flow and erosion of soft bentonite gel. There will be competition between the swelling rate of the bentonite and the flow and erosion rate of the buffer.

Piping will take place and the pipes remain open if the following three conditions are fulfilled:

1. The water pressure *pwf* in the fracture, when water flow is prevented, must be higher than the sum of the counteracting confining pressure from the clay and the shear resistance of the clay.

2. The hydraulic conductivity of the clay must be so low that water flow into the clay is sufficiently retarded to keep the water pressure at *pwf* .

3. There is a downstream location available for the flowing water and the removal of eroded materials in order for the pipe to stay open.

Erosion will take place if the drag force on a clay particle from water movement is higher than the sum of the frictional and attractive forces between the particle and the clay structure.

Piping only occurs before complete water saturation and homogenisation since then the swelling pressure of the buffer material is very high. Erosion can occur both as a consequence of channels caused by piping and, over the long-term, at the interface between the clay and the fractures in the rock. Since the water flow rate in the latter case is very low, erosion will only be important for colloids leaving the clay gel that has penetrated into the fractures, see further Section 3.5.11, TR-10-47.

The consequence of piping will be a channel and outflow of water to dry or unfilled parts of the repository. Since the clay swells the channel will reduce in size with time but, on the other hand, erosion will counteract and abrade bentonite particles and thus increase the size of the channel. There is thus a competition between swelling clay and eroding clay. If the inflow is low and the increase in water pressure slow the pipe may seal before water pressure equilibrium has been reached.

After complete water saturation and homogenisation of the buffer and backfill and re-establishment of the hydrostatic water pressure the water pressure will be separated from the swelling pressure according to the effective stress theory. The pipes or openings caused by the erosion will thus be sealed and a swelling pressure established if the density and resulting swelling pressure are high enough to overcome internal friction. Later on, there is very little risk of piping since piping requires a strong and fast increase in water pressure gradient locally in the rock at the contact with the buffer or backfill.

8.1.4 Backfill

Water inflow into the deposition tunnel will take place mainly through fractures and will contribute to the wetting of the backfill. However, if the inflow is localised to fractures that carry more water than the backfill can absorb, there will be a build-up of water pressure in the fracture and therefore an increase in the hydraulic gradient across the backfill. The backfill close to the rock surface initially consists of pellets with low density. As a result the backfill will probably not be able to stop the water inflow due to the high water pressure that will be achieved in the fracture. The results will be piping, formation of a channel and a continuing water flow, water filling of the space between the pellets and erosion. The processes are described in Section 3.3.4 (buffer) TR-10-47. The knowledge of this process and its consequences for the backfill seems to be sufficient today (/Sandén and Börgesson 2010, Sandén et al. 2008/) but research is ongoing, see also Börgesson et al. 2015.

The plug and the sealing of leakages in the plug that may occur with time will reduce the flow rate and move the hydraulic gradient from the backfill to the plug, which will allow the backfill to self-heal. The flow channels will be closed when the blocks have been sufficiently wetted to cause expansion and consolidation of the pellets, thereby yielding a sufficient resistance to erosion.

8.1.5 Plug

The process of erosion is described in the Buffer section above. Since erosion is mainly a concern for the bentonite seal in the plug, the same description is valid here.
After full saturation and reestablishment of hydrostatic water pressure in the entire repository, the plug is not required to have any sealing function. Since the bentonite seal is saturated under very low hydraulic gradient no erosion of this is foreseen. Any consequences of erosion of the plug itself are thus not important.
The plug and bentonite seal are instead required to stop eroding water from the tunnel to pass the plug during the saturation phase. The bentonite seal is expected to prevent the leakage. If water leaks through the rock and past the bentonite seal or if the bentonite seal malfunctions, the function of the plug is not fulfilled. However, erosion may help to seal these fractures since the eroding material will get stuck and clog the fractures as shown in tests.

3 Monitoring objectives

3.1 Background

SKB has performed a large number of experiments concerning the function of barriers at the Äspö Hard rock Laboratory. These experiments have also included a large component of monitoring for long periods of time, e.g. the Prototype Repository experiment. A general conclusion that may be drawn from these and similar experiences, is that the direct measurements from gauges installed in the buffer and canister may be difficult to interpret and may jeopardise the function of the barrier. On the other hand, important information on the development of the barriers may be obtained by measuring the composition of the groundwater surrounding the repository in conjunction with specific long-term field experiments that are excavated and evaluated after a certain period of time.

Additionally there other type of monitoring than of the EBS which SKB is undertaking, environmental for EIA purposes and geosphere for characterisation and understanding the biosphere, hydrosphere and lithosphere. In practice this is one and the same monitoring system which is described in R-07-34 for the on-going monitoring at Forsmark. A time sequencing of monitoring and its objectives for SKB´s operations up to closure of the repository is shown schematically in Figure 3-1.

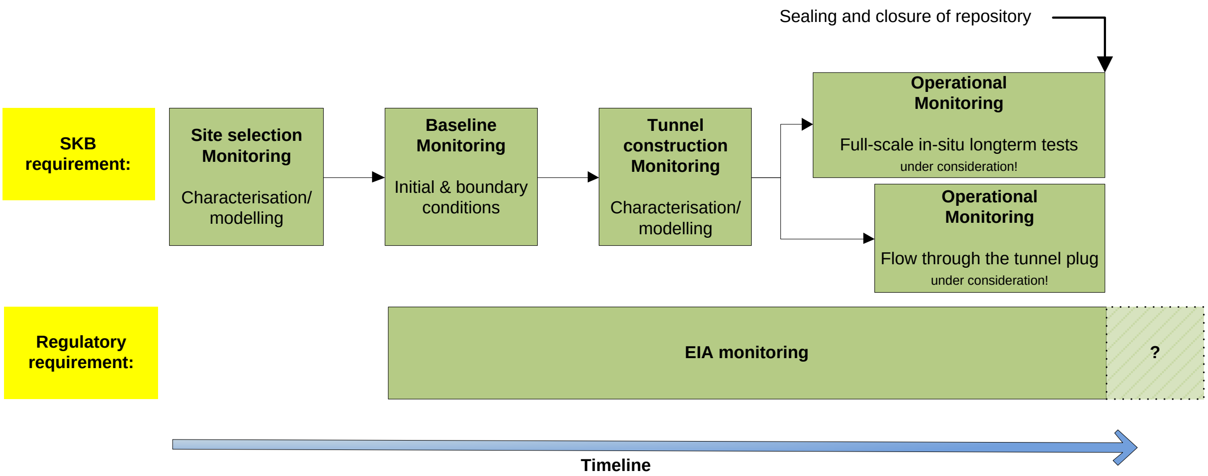

Figure 3-1. *Schematic sequencing of different type of monitoring and their objectives.*

8.2 Objectives with EBS-monitoring

The function of the repository shall be monitored, even after emplacement of the canister. It is an important issue of trust, although the added knowledge will only cover a very limited period of time of repository development.

The primary purpose of the EBS-monitoring is not to identify faults, mistakes or deviations in the manufacturing and installation procedure/process. These important tasks are handled through the quality control programme.

3.2 Development of suitable EBS-monitoring methodology.

SKB intend to develop the methodology for monitoring of the repository. The participation in MoDeRn and Modern2020 is in line with this ambition. The goal is to develop methodology that may be utilised for monitoring the development of the technical (engineered) barriers under repository conditions during many years, or even for decades.

The monitoring must be undertaken at sites with conditions that correspond to the actual repository volume and other potential repository volumes, as far as possible. Disturbances of the monitored object must be minimised while at the same time ensure that the monitoring system does not harm the fulfillment of other objectives for the tests.

The greatest challenges with monitoring of long-term experiments are longevity and durability of the gauges which shall be able to measure small changes over very long periods of time, that the installation of cables and lead-through for data transfer and power supply do not disturb the development of the monitored system. Under consideration are wireless technology and methods that to not rely on integrated gauges in the monitored object/system. The present view is however, that monitoring is performed with wired technology.

Even if reliable technology may be developed there is a need to develop a strategy on where in the system to install the measurement gauges. A starting point of view for this planning is that siting in the active deposition volumes should be avoided for safety reasons. Should such siting take place anyway it ought to be confined to a limited number of sites.

Other possibilities for EBS-monitoring should be considered such as long-term experiments of different extent and character focusing on the most important aspects of the technical barriers at different representative sites in the repository. Such experiment might provide very relevant information on the development of the technical barriers at repository site without jeopardising the safety. Some of these experiment may be excavated and evaluated to provide input to the updating of the safety assessment (SAR). However, all such experiment should be terminated upon closure of the repository and provide support as well as confidence to the decision to close and seal the repository.

3.3 Constraints and possibilities

There are physical constraints on what may be measured directly regarding the development of the barriers. This concerns e.g. the problem of uniquely being able to interpret the signals from the different measurement devices and that measurement devices may be affected by an ageing process. Another constraint is that the measurement devices shall not deteriorate the barrier functions.

There are other possibilities for monitoring that give more relevant information about the evolution and development of the barrier at the repository, without jeopardising safety. One possibility is to install longterm tests/experiments of different extent and character, focusing on the most important aspects of the technical barriers in rock situated at different representative locations of the repository. Some of these tests may be discontinued and evaluated during the operational period of the repository in order to provide input to the updating of the governing safety assessment (SAR). Prior to sealing the repository , all such tests should be discontinued and evaluated in order to provide input and more confidence for the decision to seal and close the repository.

4 Monitoring parameter identification

The workflow to identify potentially suitable parameters for monitoring is described below. It comprise three steps Firstly giving the basis for arriving at a set of all parameters that could be monitored followed by describing the basis for arriving at a set of parameters with major impact on post-closure safety and finally identification of parameters that could be monitored by applying the Modern2020 screening methodology (Appendix 1).

4.1 Workflow for identification of all parameters

The basic pre-requisite for the identification of potential EBS-parameters to monitor stems from regulatory requirements (SSM and IAEA) and SKB-requirements identified through safety assessments performed by SKB. The design of SKB´s KBS-3 repository is the result of an iterative design and development process summarised in the Figure 4-1 and explained in the following chapters. This process identifies all processes and parameters needed to describe the system as explained in the System description above (Chapter 2).

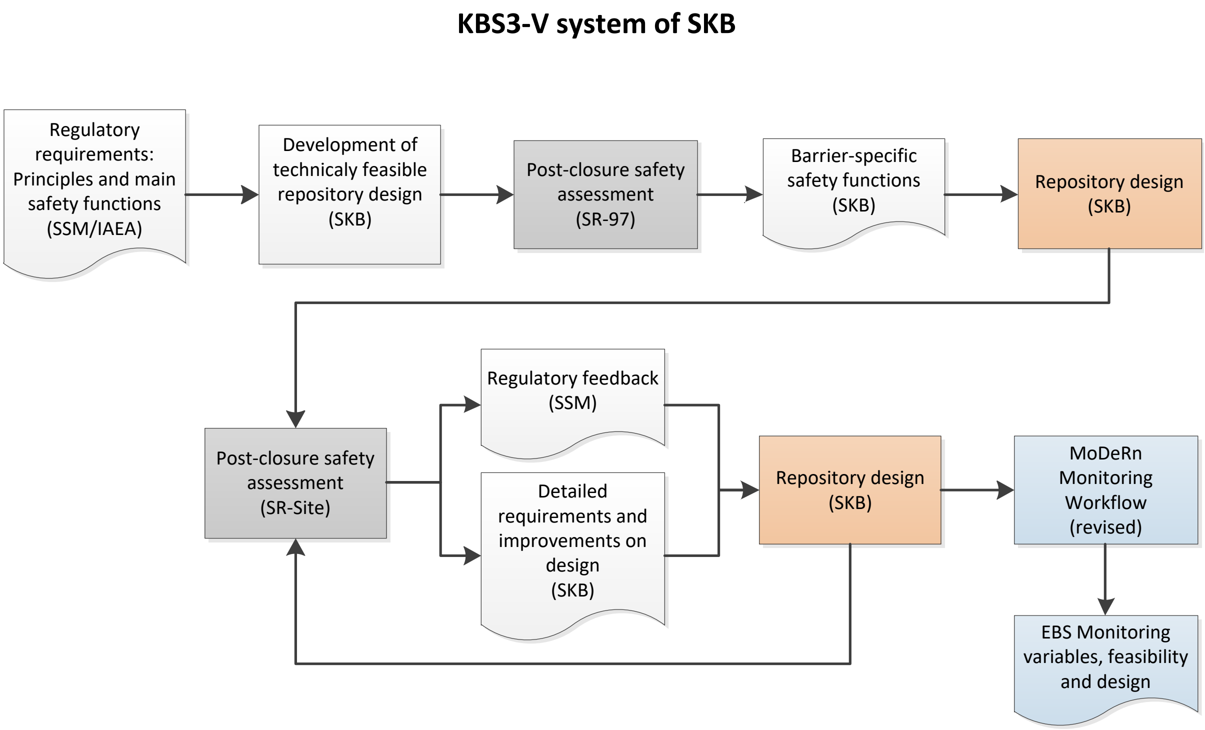

Figure 4-1. *Summary of steps required in order to arrive at a set of all parameters that could be monitored and at safety functions which is as pre-requisite to the MoDeRn workflow (based on SKB-Posiva Report 01).*

8.2.1 Regulatory basis

The requirements for a KBS‑3 repository originates firstly from the principle that future generations should not be exposed to radiation doses larger than those currently accepted for nuclear facilities or activities, and secondly from the multi-barrier principle. According to the multi-barrier principle the post-closure radiation safety of a final repository shall be based on a system of passive barriers that act in different ways, either directly or indirectly by protecting other barriers in the barrier system, so as to:

• isolate the repository from the surface environment,

• contain the radionuclides,

• retain the radionuclides and retard their dispersion into the environment.

In line with the IAEA glossary and safety standards isolation from the surface environment, the containment of radionuclides, to retain radionuclides and retard their dispersion into the environment and to protect and preserve the safety functions of the barrier system can be referred to as main safety functions of final repositories (IAEA 2007, 2012).

The design shall be robust i.e. durable with respect of the conditions expected during the long-term evolution and insensitive to variations that are expected to occur in the production or in the final repository. The production shall be reliable and insensitive to disturbances, and the design as well as the production shall be quality assured. The design is also based on high-level Swedish regulations through SSMFS2008:37 and SSMFS2008:21 addressing the risk criterion for exposure and performance of safety assessment respectively, see TR-11-01 chapter 1.4.1 and 1.4.2.

8.2.2 SKB requirements

The design cannot be determined directly from the radiation protection and safety principles and the main safety functions of final repositories mentioned above. Instead, **the principles and main safety functions form the basis for the development of technically feasible repository designs.** The ability of the designs to maintain safety are then analysed in post-closure safety assessments. The safety assessments provides more detailed requirements for the design as well as feedback on how the assessed designs may be improved to promote post-closure safety.

The current design requirements for the post-closure safety of a KBS-3-repository are specified in the SKB license application. SKB has presented requirements referred to as *design premises* relating to post-closure safety (SKB 2009), and demonstrated, in the post-closure safety assessment SR-Site (SKB 2011), that an as-built repository design that conforms to these design premises will maintain post-closure safety. The updating of the requirements and the development of the design, methods, processes and technical systems to produce and quality assure a KBS-3 repository have proceeded on the basis of the results of the safety assessments and the regulatory feedback received thus far. Coupled to this process there is a requirement management system.

4.2 Safety function based screening process

A detailed and quantitative understanding and evaluation of repository safety requires a more elaborated description of how the main safety functions of containment and retardation are maintained by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to containment and retardation can be identified. In this context, a *safety function* is defined qualitatively as a role through which a repository component contributes to safety. *(TR-11-01 p248-249)*

In a KBS-3 repository, the main safety functions of isolation, containment, retention, retardation and protection of other barriers are maintained by barrier-specific safety functions assigned to the canister, buffer, backfill, closure and the rock with its underground openings (Posiva SKB Report 01). These barrier-specific safety functions specify how each part of the barrier system contributes to the safety of the repository as a whole by specifying performance targets and design characteristics. A total of 13 barrier-specific safety functions have been identified for the EBS, these are summarised in Appendix 3 while a full description is given in Posiva SKB Report 01.

Safety function indicators
In order to quantitatively evaluate safety, it is desirable to relate or express the safety functions to measurable or calculable quantities, often in the form of barrier conditions. *(TR-11-01 p248-249)*

Safety function indicator criteria (= performance targets (Posiva SKB Report 01))
In order to determine whether a safety function is maintained or not, it is desirable to have quantitative criteria against which the safety function indicators can be evaluated over the time period covered by the safety assessment*(TR-11-01 p248-249)*

For example, some barrier-specific safety functions with related indicators and their criteria for the EBS-system are according to Table 4-1.

Table 4-1. *Some examples of barrier-specific safety functions with related indicators and their criteria.*

Barrier component	Safety function	Safety function indicator	Safety function indicator criteria (TR-11-01) = Performance target (SKB-Posiva report 01)
Canister	withstand corrosion	copper thickness	copper thickness > 0
Buffer	limit advective mass transfer	Hydraulic conductivity	Hydraulic conductivity < 10^{-12} m/s
Buffer	limit advective mass transfer	Swelling pressure	Swelling pressure > 1MPa
Backfill	retain sufficient mass over life cycle	Stable in contact with water with a *certain* total charge equivalent of cations	Stable in contact with water with total charge equivalent of cations $\Sigma q[M^{q+}] > 8 \times 10^{-3}$ mol/L . (This may be converted to an equivalent elctrical conductivity)
Plug		Restrict flow of water past the deposition tunnel mouth	

The safety functions are closely related to the processes identified in chapter 2 and the associated performance targets are related to parameters, as specified in Appendix 3. From this we identify a rather reduced set of parameters that control the safety functions then translate this parameter into parameter or proxy thereof that is amenable to monitoring, Table 4-2.

Table 4-2. *Set of type of parameters for the EBS system (canister/buffer/backfill/plug) relevant for post-closure safety that could be monitored.*

Parameter that control the safety function	Parameter that could be monitored
Hydraulic conductivity	Pressure in the buffer and backfill could be used as proxy since the relationship between swelling pressure and hydraulic conductivity can be established for a given bentonite material
Swelling pressure	Pressure in the buffer and backfill
Isostatic pressure	Rock stresses, Total pressure
Shear displacement	Rock stresses
Total charge equivalent of cations	Electrical conductivity of water
Copper thickness	Average corrosion depth measured by weight-loss
Dry density (buffer)	?
Temperature (buffer)	Temperature

Hence, whereas the Modern2020 screening methodology is process and parameter driven, SKB´s main driver is the safety function and related criteria (performance targets, design characteristics and technical design requirements) which, however, bear a direct correspondence with processes and parameters.

4.3 Application of the Modern2020 Screening Methodology

The screening methodology outlined in Appendix 1 is process/parameter driven, it serves the purpose to identify parameters suitable for monitoring during the operational phase of the repository in a structured, traceable and repeatable way. The basic steps involved in the workflow of this methodology may be summarised are as follows,

a) For each processes of the EBS assess the relevance of the process for post-closure safety and the value of monitoring it.
b) Next translate the process into parameters (or proxy for it) and define their expected evolution.
c) Then is to assess if the monitoring of the parameter is technically feasible.
d) Last step is to check and ensure that the monitoring and monitoring system does not constitute a risk for jeopardising the long-term safety case

However, as explained in chapter 4.2, for SKB´s case the Safety function is utilised as the starting point for the screening, it may be viewed as proxy for Process. In so doing we have established its relevance for post-closure safety and retrievability and answered PRO2 already at the outset.

We will restrict this exercise to three safety functions, namely

- "Limited advective mass transfer"
  addressing Piping/erosion process involving two safety function indicator criteria (parameters): Hydraulic conductivity and Swelling pressure of buffer

- "Retain sufficient mass over life cycle"
  addressing Transport of species process (Chemical erosion, diluted water) involving one safety function indicator criteria: Charge concentrations of cations

- "Withstand canister corrosion"
  addressing Corrosion of copper canister process involving one safety function indicator criteria: Copper thickness of canister

These were run through the Modern2020 screening methodology (Appendix 1) and its outcome documented in Appendix 4. They comprise four safety function indicators being potentially eligible as parameters for monitoring with conclusions according to Table 4-3.

Table 4-3. *Monitoring parameters, parameter options and plans*

Monitoring parameter	Parameter option and monitoring plan
Hydraulic conductivity of the buffer for piping/erosion process	*In the calculations of buffer erosion in the post closure safety assessment for different inflow conditions to deposition tunnel and deposition holes a limited flow past the plug was assumed. For some cases a tight plug reduces the buffer erosion in certain deposition holes. Hence a tight plug increases the robustness of the repository. The flow past the plug can however not be directly coupled to the safety functions of the buffer or backfill.* *Impact on passive safety:* As there are no installations in the buffer/backfill there can not be any impact of the monitoring system on the monitoring.
Swelling pressure of the buffer	Pressure gauges in the buffer and/or back-fill, wired or wireless. Technology with proven durability for such long-term measurements is not available *Impact on passive safety:* Long-term durability and reliability of installations need to be proven. There is no way to ensure that the installations do not jeopardise the long-term safety case.
Electrical conductivity of water around the backfill and buffer for chemical erosion process	Monitoring of groundwater chemistry through sampling at repository level is already performed. This is done in the framework of the host-rock monitoring programme. *Impact on passive safety:* This strategy entails no monitoring of the active repository and does not risk to jeopardise it.
Copper thickness of the canister	In-situ batch-experiments with copper coupons as proxy for canister for weight-loss analysis, retrieved at different time-scales. There is no monitoring plan but is considered in the planning. *Impact on passive safety:* This strategy entails no monitoring of the active repository and does not risk to jeopardise it.

The detailed outcome of the screening process, including considerations and judgements, is described in Appendix 4.

4.4 Comments and discussion to the Modern20202 screening methodology

The screening methodology was found useful to identify parameters (safety function indicators) suitable for monitoring during the operational phase of the repository in a structured, traceable and repeatable way. For SKB´s case a manageable number of parameters (12) are included in the safety functions for the EBS.

The EBS-function is assessed by a large number of processes and parameters (and FEP´s). These are furthermore largely coupled and interdependent. This makes an assessment of the first and most basic question (PRO2) “if the process is relevant for post-closure safety”, quite difficult to answer in some cases. The reason is that screening a singular process at a time to decide on post-closure relevance might be insufficient. Alternatively one can argue that due to the interdependencies, all processes are relevant and one would have to go through all processes and parameters, a daunting task indeed. From this it is judged that the process/parameter relevance for post-closure safety could be made prior to the screening. In order to make such judgement there is the prior need of the full support from safety assessment/repository design iterations, see Figure 4-1. Hence, the adoption of safety functions, instead of processes, as starting point for the parameter screening was found more robust and workable.

5 Monitoring system - description and implementation

Presently there is no EBS monitoring system designed. The planning includes monitoring of the flow through the plug with available technology during the period from completion of the plug until start of deposition of radioactive waste in that deposition tunnel. Data on flow through the plug and head in the surrounding host-rock would be collected digitally with a frequency of a tentatively few times a day with event triggered logging.

The other monitoring which is considered is through batch experiments on corrosion of copper coupons recovered regularly during the operational phase. This would be performed in pilot facility in repository rock at repository depth.

6 Monitoring results in the confidence building and decision making process

Given that the operational phase of the repository is rather long it would provide time series of duration on the selected parameters that are not otherwise available. The results would constitute the longest available duration of experimental nature which would complement existing experimental data support and ideally results might be utilised for checking against expected behaviour. However, re-saturation processes are so slow that even with this time perspective of the operational period for the repository (60-100years) it might be difficult to obtain usable results on the barrier function of the buffer and back-fill.

The design of the EBS does not require any monitoring data for its construction or operation. Any monitoring data results during the operational period that does not fall within reasonable bounds of expected behaviour would need to be assessed in entirety aiming at explaining such discrepancy.

7 Conclusions and recommendations

The expected behaviour of the option for the parameter (PAR3) ought to be described if the option parameter is adopted.

Screening ought to start with a more compounded function than a singular process for reasons described in chapter 4.4 e.g. the safety function.

The workflow of the screening methodology need to bring forward and make more visible the step of checking whether the proposed technology can be applied without significantly affecting the passive safety of the repository system (TEC1). It is of such importance that it ought to be highlighted in the workflow and be addressed directly.

Another aspect which should be considered in this workflow concerns the integrity of data output from such long-term monitoring system. The technical feasibility question (TEC1) is understood as the feasibility at the time of installation. Durability and reliability of data output over such long time periods from gauges need to be proven before taking the decision on whether the parameter should be taken forward to the monitoring programme design stage (PAR7).

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Summary of Methodology and Supporting Diagrams

The Modern2020 Screening Methodology (Figure 1) 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. The Methodology is supported by a diagram showing its iterative implementation (Figure 2) and a revised version of the MoDeRn Monitoring Workflow (Figure 3), 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 (Appendix 1b).

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 2. Figure 2 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 safety case or significant developments in technology.

The relationship of the Modern2020 Screening Methodology to the MoDeRn Monitoring Workflow is illustrated in Figure 3. In this figure, the MoDeRn Monitoring Workflow has been slightly updated to reflect the terminology used in the Modern2020 Screening Methodology, but is fundamentally unchanged from the version published in the MoDeRn Synthesis 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 below.

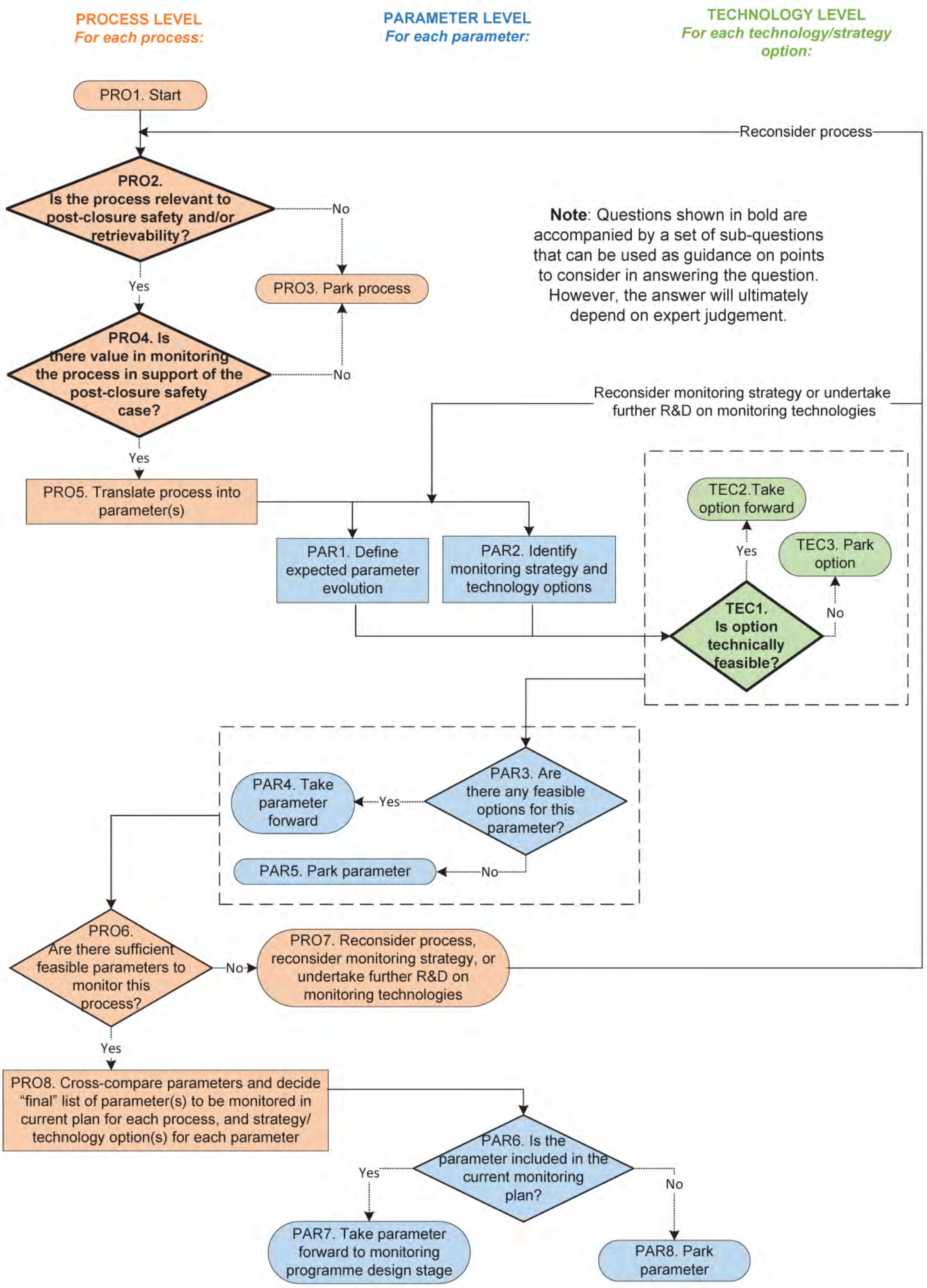

Figure 1: The Modern2020 Screening Methodology.

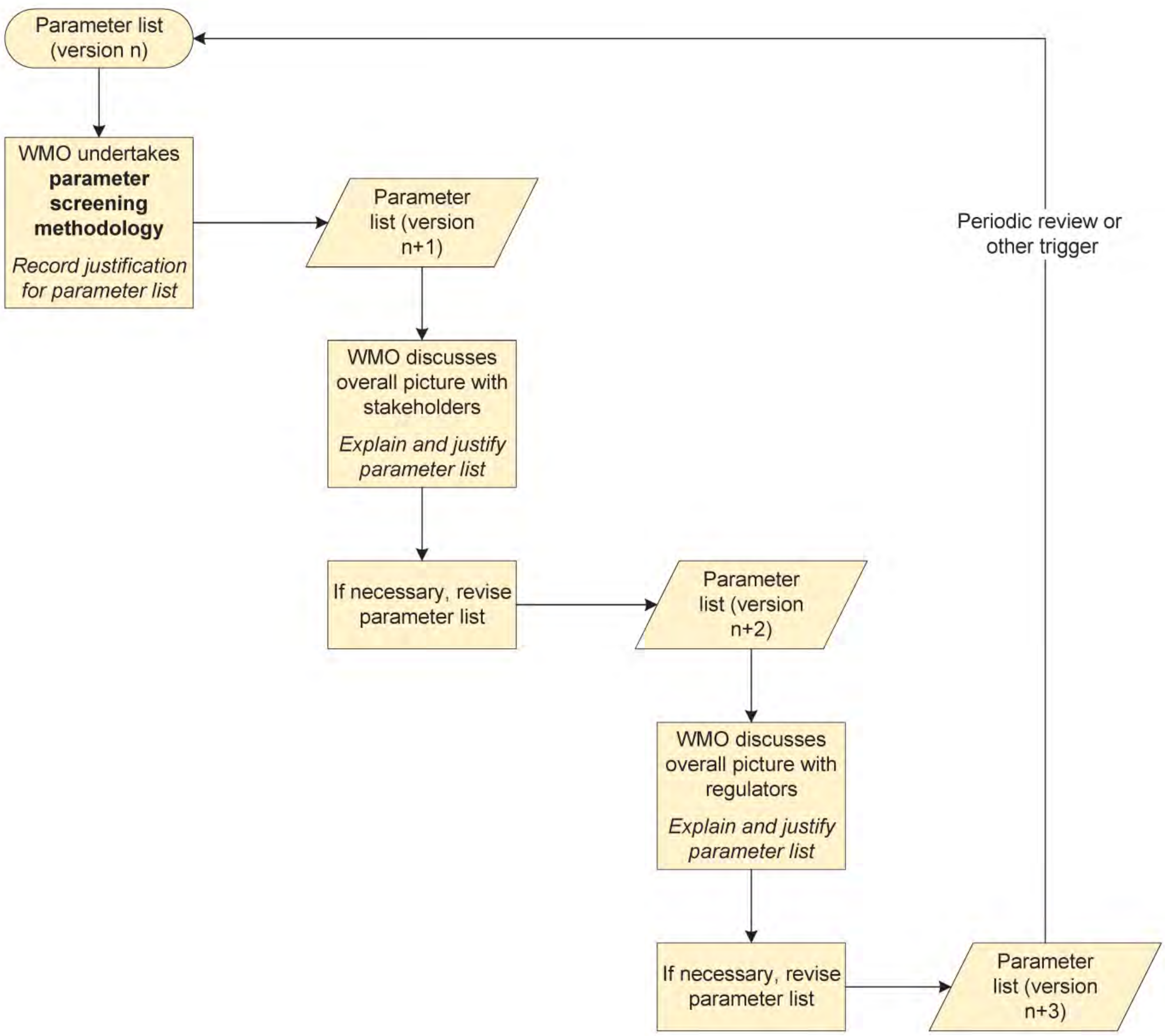

Figure 2: Illustration of the possible iterative implementation of the Modern2020 Screening Methodology.

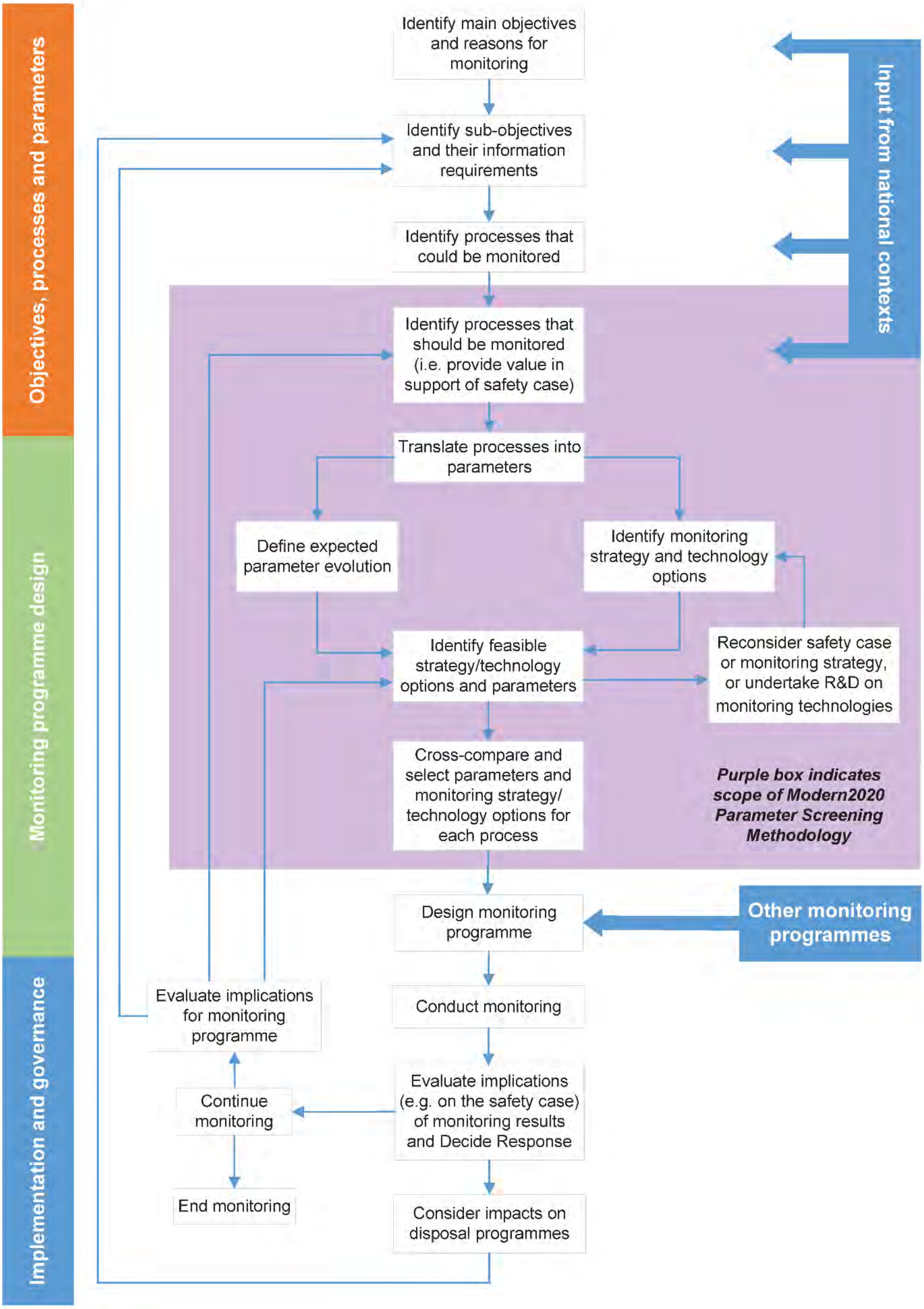

Figure 3: Revised MoDeRn Monitoring Workflow, illustrating the relationship of the Workflow to the Modern2020 Screening Methodology.

PRO1. Start

The Modern2020 Screening Methodology fits into the MoDeRn Monitoring Workflow between the steps "Identify 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 monitoring, e.g. derived from a features, events and processes (FEP) list. 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)

Recent Nuclear Energy Agency (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)

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 safety case. Some WMOs may consider that the benefit of monitoring such processes is limited compared to the detriments, 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.

Such judgements are necessarily subjective and 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 and previous experience.

PAR1. Define expected parameter evolution

Once parameter(s) associated with the process under consideration have been identified, it is necessary to define the expected evolution of each parameter over the planned monitoring period. This is needed in order to evaluate whether the potential options for monitoring it are suitable, e.g. to understand the scale of potential changes over the monitoring period. Note that "expected evolution" will in most cases comprise a range of values bounding all likely evolutions.

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 components will be monitored) and a technology. 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)

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. Although this assessment will provide a level of comparison between different options, it is not the aim here to undertake a full cost-benefit analysis (this would be considered at the detailed design stage). The primary aim is to determine which options are technically feasible.

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.

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 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.

Appendix 1b: Supplementary Guidance Questions

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 (for example, materials science, procedure development, full-scale experiments, natural analogues and fundamental scientific understanding)?
- Could monitoring provide additional confidence that the repository system has been implemented as designed (as demonstrated through, for example, 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 safety case?
- Could monitoring the process be helpful in accident situations?

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

- Can the proposed technology meet sensitivity, accuracy and frequency requirements for the parameter over the monitoring period?
- Can the proposed technology meet reliability and durability requirements for 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?

Appendix 2. Processes in the EBS

Processes on the cast iron insert and copper canister	Associated parameters (report#, table#)	Processes in the buffer	Associated parameters (report#, table#)	Processes in the tunnel backfill	Associated parameters (report#, table#)	Processes in the tunnel plugs	Associated parameters (report#, table#)
Radiation-related processes		**Radiation-related processes**		**Thermal processes**		**Thermal processes**	
- Radiation attenuation/heat generation	TR-10-46, T	- Radiation attenuation/heat generation	TR-10-47, T3-1	- Heat transport	TR-10-47, T4-1	- Heat transport	TR-10-47, T5-1
Thermal processes		**Thermal processes**		- Freezing	TR-10-47, T4-2	- Freezing	no significance
- Heat transport	TR-10-46	- Heat transport	TR-10-47, T3-2	**Hydraulic processes**		**Hydraulic processes**	
Hydraulic processes		- Freezing	TR-10-47, T3-3	- Water uptake and transport under unsaturated conditions	TR-10-47, T4-3	- Water uptake and transport under unsaturated conditions	TR-10-47, T5-2
Mechanical processes		**Hydraulic processes**		- Water transport under saturated conditions	TR-10-47, T4-4	- Water transport under saturated conditions	TR-10-47, T5-3
- Deformation of cast iron insert	T-10-46, T3-3	- Water transport under unsaturated conditions	TR-10-47, T3-4	- Gas transport/dissolution	TR-10-47, T4-5	- Gas transport/dissolution	TR-10-47, T5-2
- Deformation of copper canister from external pressur	TR-10-46	- Water transport under saturated conditions	TR-10-47, T3-5	- Piping/erosion	TR-10-47, T4-6	- Piping/erosion	TR-10-47, T5-4
- Thermal expansion	TR-10-46	- Gas transport/dissolution	TR-10-47, T3-6	**Mechanical processes**		**Mechanical processes**	
- Deformation from internal corrosion products	TR-10-46	- Piping/Erosion	TR-10-47, T3-7	- Swelling/mass redistribution	TR-10-47, T4-7	- Swelling/mass redistribution	TR-10-47, T5-5
- Radiation effects	TR-10-46	**Mechanical processes**		- Liquefaction	n/a anymore	**Chemical processes**	
Chemical processes		- Swelling/mass redistribution	TR-10-47, T3-8	**Chemical Processes**		- Advection	TR-10-47, T5-6
- Corrosion of cast iron insert	TR-10-46	- Liquefaction	n/a anymore	- Advective transport of species	TR-10-47, T4-8	- Diffusive transport of species	TR-10-47, T3-10
- Galvanic corrosion	TR-10-46	**Chemical processes**		- Diffusive transport of species	TR-10-47, T4-9	- Sorption (including exchange of major ions)	TR-10-47, T3-12
- Stress corrosion cracking of cast iron insert	TR-10-46	- Advective transport of species	TR-10-47, T3-9	- Sorption (including exchange of major ions)	TR-10-47, T4-10	- Alteration of concrete	TR-10-47, T5-7
- Corrosion of copper canister	TR-10-46	- Diffusive transport of species	TR-10-47, T3-10	- Alterations of backfill impurities	TR-10-47, T4-11	- Aqueous speciation and reactions	TR-10-47, T3-14
- Stress corrosion cracking of the copper canister	TR-10-46	- Colloid transport	TR-10-47, T3-11	- Aqueous speciation and reactions	TR-10-47, T3-14	- Osmosis	no significance
- Earth currents – stray current corrosion	TR-10-46	- Sorption (including ion-exchange of major ions)	TR-10-47, T3-12	- Osmosis	TR-10-47, T4-12	- Montmorillonite transformation	TR-10-47, T3-16
- Deposition of salts on the canister surface	TR-10-46	- Alterations of impurities	TR-10-47, T3-13	- Montmorillonite transformation	TR-10-47, T4-13	- Montmorillonite colloid release	TR-10-47, T3-18
Radionuclide transport		- Aqueous speciation and reactions	TR-10-47, T3-14	- Backfill colloid release	TR-10-47, T4-14	- Microbial processes	TR-10-47, T5-8
		- Osmosis	TR-10-47, T3-15	- Radiation-induced transformations	TR-10-47, T3-21	**Radionuclide transport processes**	
		- Montmorillonite transformation	TR-10-47, T3-16	- Microbial processes	TR-10-47, T4-15	- Speciation of radionuclides	TR-10-47, T5-1
		- Iron – bentonite interaction	TR-10-47, T3-17	**Radionuclide transport processes**		- Transport of radionuclides in the water phase	TR-10-47, T3-26
		- Montmorillonite colloid release	TR-10-47, T3-18	- Speciation of radionuclides	TR-10-47, T3-25	- Transport of radionuclides in a gas phase	TR-10-47, T3-27
		- Radiation-induced transformations	TR-10-47, T3-21	- Transport of radionuclides in the water phase	TR-10-47, T3-26		
		- Radiolysis of porewater	TR-10-47, T3-22				
		- Microbial processes	TR-10-47, T3-23				
		- Cementation	TR-10-47, T3-24				
		Radionuclide transport processes					
		- Speciation of radionuclides	TR-10-47, T3-25				
		- Transport of radionuclides in the water phase	TR-10-47, T3-26				
		- Transport of radionuclides in a gas phase	TR-10-47, T3-27				

Appendix 3. Safety functions and their indicators for the EBS

Safety functions of the canister	Safety function indicator	Safety functions of the buffer	Safety function indicator	Safety functions of the backfill	Safety function indicator	Safety functions of the tunnel plugs	Safety function indicator
Withstand corrosion	copper thickness	Limit advective transfer	Hydraulic conductivity. Swelling pressure.	Keep the buffer in place	Swelling pressure		
Withstand mechanical loads	Isostatic pressure. Shear displacement.	Limit microbial activity	Swelling pressure	Limit advective mass transfer	Hydraulic conductivity. Swelling pressure.		
Maintain sub-criticality		Filter colloids	Dry density				
		Protect the canister from detrimental mechanical loads – rock shear load	Rock shear displacement				
		Protect the canister from detrimental mechanical loads – pressure load	Swelling pressure. Temperature.				
		Resist transformation	Temperature				
		Keep the canister in position	Swelling pressure				
		Retain sufficient mass over life cycle	Total charge equivalent of cations				

Appendix 4. Modern2020-SKB Screening cases

The exercise comprise 4 cases, as follows

Case 1. Safety function / indicator :	Limited advective transfer / Hydraulic conductivity.
Case 2. Safety function / indicator :	Limited advective transfer / Swelling pressure.
Case 3. Safety function / indicator :	Retain sufficient mass over life cycle / Charge concentration of cations.
Case 4. Safety function / indicator :	Canister corrosion / Copper thickness

These cases were submitted to the screening methodology process of Appendix 1 and are presented below.

Case 1. Safety function / indicator : Limited advective transfer / Hydraulic conductivity

Level	Screening issues	Safety function: Limited advective transfer (Piping/erosion in the buffer process)
PRO1	*Start*	
PRO2	*Is the process process relevant to post-closure safety and /or retrievability ?*	yes
PRO3	*Park process*	no
PRO4	*Is there value in monitroing the process in support of the post-closure safety case?*	yes, during the early development of the repository.
PRO5	*Translate process into parameters*	Amount of erroded material - or flow through the deposition hole as proxy for amount of eroded material. Through safety function "limited advective transfer" the parameters - hydraulic conductivity and - swelling pressure
Loop-START Safety Function Indicator		**Safety function indicator: Hydraulic conductivity**
PAR1	*Define expected parameter evolution*	No or limited piping - see chapter 2.3
PAR2	*Identify monitoring strategies and technology options*	There are no technologies to measure hte piping/erosion directly. The strategy would be to find a proxy for it , if possible
TEC1	*Is option technically feasible?*	Not technicaly feasible to measure piping/erosion directly at deposition hole. No monitoring technology available to monitor the change in conductivity. The conductivity is measured at inception, constituting an initial condition) and quality assured.
TEC2	*Take option forward*	yes
TEC3	*Park option*	
PAR 3	*Are there any feasible options for this parameter?*	Yes! As direct measurement of piping/erosion might be very difficult or impossible to undertake the strategy would be to monitor flow through the plug as a proxy for the effect of that process. For given boundary condition (Head) , flow through the plug is related to flow through

		unsaturated deposition holes and could thus be an indication of piping erosion. .
missing	*Define expected evolution of option for this parameter*	expected evolution for flow through plug has not been modelled.
PAR4	*Take parameter forward*	yes
PAR5	*Park parameter*	
PRO6	*Are there sufficient feasible parameters to monitor this process?*	yes, flow through the plug as one possible indicator. Can not be answered until all parameters have gone through the loop.
PRO7	*Reconsider process, monitoring strategy or more R&D on monitoring technologies for all parameters of the process*	no
Loop-END Safety Function Indicator		
PRO8	*Cross compare parameters and decide final list of parameters to be monitored*	It is sufficient with monitoring of flow through the plug.
PAR6	*Is the parameter included in the current monitoring plan?*	The monitoring programme of the repository is stil being developed. The parameter will be considered,
PAR7	*Take parameter forward to monitoring programme design stage*	yes, monitor flow through the plug
PAR8	*Park parameter*	no
Part of TEC1 **BUT** can not be answered at TEC1 level, needs to be adressed after PAR7	*Can the proposed technology be applied without significantly affecting the passive safety of the repository system?*	As there are no installation in the buffer/backfill there can not be any impact of the monitoring system on the monitoring

Case 2. Safety function / indicator: Limited advective transfer / Swelling pressure

Level	Screening issues	Safety function: Limited advective transfer (Piping/erosion in the buffer process)
PRO1	*Start*	
PRO2	*Is the process process relevant to post-closure safety and /or retrievability ?*	yes
PRO3	*Park process*	no
PRO4	*Is there value in monitroing the process in support of the post-closure safety case?*	yes, during the early development of the repository.
PRO5	*Translate process into parameters*	Amount of erroded material - or flow through the deposition hole as proxy for amount of eroded material. Through safety function "limited advective transfer" the parameters - hydraulic conductivity and - swelling pressure
Loop-START Safety Function Indicator		**Safety function indicator: Swelling pressure**
PAR1	*Define expected parameter evolution*	No or limited piping - see chapter 2.3
PAR2	*Identify monitoring strategies and technology options*	Pressure gauges in the buffer and/or backfill, wired or wireless.
TEC1	*Is option technically feasible?*	Technology with proven durability for such longterm measurements is not availble
TEC2	*Take option forward*	no
TEC3	*Park option*	Yes, development of durable and longterm reliable technology is necesserary first.
PAR 3	*Are there any feasible options for this parameter?*	Monitoring flow trough the plug is a proxy for loss of buffer material, which affects the swelling pressure - se previous column
missing	*Define expected evolution of option for this parameter*	
PAR4	*Take parameter forward*	No
PAR5	*Park parameter*	
PRO6	*Are there sufficient feasible parameters to monitor this process?*	No
PRO7	*Reconsider process, monitoring strategy or more R&D on monitoring technologies for all parameters of the process*	NO! It is sufficient with monitoring of flow through the plug.

Loop-END Safety Function Indicator		
PRO8	*Cross compare parameters and decide final list of parameters to be monitored*	It is sufficient with monitoring of flow through the plug.
PAR6	*Is the parameter included in the current monitoring plan?*	no
PAR7	*Take parameter forward to monitoring programme design stage*	no
PAR8	*Park parameter*	yes
Part of TEC1 **BUT** can not be answered at TEC1 level, needs to be adressed after PAR7	*Can the proposed technology be applied without significantly affecting the passive safety of the repository system?*	Longterm durability and reliability of installations need to be proven. There is no way to ensure that the installations do not jeopardise the longterm safety case.

Case 3. Safety function / indicator : Retain sufficient mass over life cycle / Charge concentration of cations

Level	Screening issues	Safety function: Retain sufficient mass over life cycle (Chemical erosion)
PRO1	*Start*	
PRO2	*Is the process process relevant to post-closure safety and /or retrievability ?*	yes
PRO3	*Park process*	no
PRO4	*Is there value in monitoring the process in support of the post-closure safety case?*	Not really! Because the process is very slow and only active after swelling of the buffer. To take place it then requires dilute waters.
PRO5	*Translate process into parameters*	Going from saline to dilute waters surrounding the buffer involves a transport of species which alters the electrical conductivity of the water. The relevant parameter to monitor would therefore be the electrical cionsuctivity of the water. All this is contained in the safety function "Retain sufficient mass over life cycle". Colloidal formation of bentonite reduces its mass and hence density. This affects the hydraulic conductivity and swelling pressure of the bentonite.
Loop-START Safety Function Indicator		**Safety function indicator:** **Charge concentration of cations**
PAR1	*Define expected parameter evolution*	10.2.5 i TR-11-01:) Ionic strength; $\Sigma q[M^{q+}] > 4$ mM charge equivalent. (The 4mM limit has later been changed to 8 mM, Posiva SKB Report 01) For the whole temperate period following repository closure, the cation charge concentrations at repository depth at Forsmark will, in general, remain higher than 0.008 mol/L. However, a fraction of a percent of the deposition holes may experience dilute conditions during the first ten thousand years.
PAR2	*Identify monitoring strategies and technology options*	Monitoring of groundwater chemistry through sampling at repository level is already performed . This is done in the framework of the host-rock monitoring programme.
TEC1	*Is option technically feasible?*	Yes, see PAR2
TEC2	*Take option forward*	Yes, see PAR2
TEC3	*Park option*	No

Level	Screening issues	Safety function: Retain sufficient mass over life cycle (Chemical erosion)
PAR 3	*Are there any feasible options for this parameter?*	No
missing	*Define expected evolution of option for this parameter*	
PAR4	*Take parameter forward*	Yes, see PAR2
PAR5	*Park parameter*	no
PRO6	*Are there sufficient feasible parameters to monitor this process?*	Yes, see PAR2
PRO7	*Reconsider process, monitoring strategy or more R&D on monitoring technologies for all parameters of the process*	no
Loop-END Safety Function Indicator		
PRO8	*Cross compare parameters and decide final list of parameters to be monitored*	n/a
PAR6	*Is the parameter included in the current monitoring plan?*	Yes, it is already part of the far-field host-rock monitoring of groundwaters.
PAR7	*Take parameter forward to monitoring programme design stage*	yes
PAR8	*Park parameter*	no
Part of TEC1 **BUT** can not be answered at TEC1 level, needs to be adressed after PAR7	*Can the proposed technology be applied without significantly affecting the passive safety of the repository system?*	This strategy entails no monitoring of the active repository and does not risk to jeopardise it.

Case 4. Safety function / indicator : Canister corrosion / Copper thickness

Level	Screening issues	Safety function: Canister corrosion
PRO1	*Start*	
PRO2	*Is the process relevant to post-closure safety and /or retrievability ?*	yes
PRO3	*Park process*	no
PRO4	*Is there value in monitroing the process in support of the post-closure safety case?*	There is some value in such monitoring, even if corrosion during repository operation is due to various transient processes, of limited impact. Understanding the early stages of corrossion may provide some additional detailed and site specific understanding.
PRO5	*Translate process into parameters*	In-situ monitoring of corrosion rates are prone to many errors and uncertainties and therefore not feasible to monitor directly. Batch "experiments" where samples are retrieved and evaluated regularly is an alternative approach. A series of parameters such as corrosion depth, corrosion products, .. can be examined or assessed from the retrieved samples.
Loop-START Safety Function Indicator		**Safety function indicator: Copper thickness**
PAR1	*Define expected parameter evolution*	The total amount of copper corrosion during the excavation and operational phases and the first 1,000 year period can be estimated to be less than 1 mm. The largest contribution to this estimate comes from the initially entrapped oxygen." See further in TR-11-01 chapter 10.3.13 (SR Site).
PAR2	*Identify monitoring strategies and technology options*	In-situ batch-experiments with copper coupons as proxy for canister.
TEC1	*Is option technically feasible?*	Yes, many such experiments have been performed e.g. at Äspö HRL
TEC2	*Take option forward*	yes
TEC3	*Park option*	no
PAR 3	*Are there any feasible options for this parameter?*	No other option than th above mentioned batch-experiment seem practical.
missing	*Define expected evolution of option for this parameter*	
PAR4	*Take parameter forward*	yes
PAR5	*Park parameter*	no
PRO6	*Are there sufficient feasible parameters to monitor this process?*	yes

Level	Screening issues	Safety function: Canister corrosion
PRO7	*Reconsider process, monitoring strategy or more R&D on monitoring technologies for all parameters of the process*	no need.
Loop-END Safety Function Indicator		
PRO8	*Cross compare parameters and decide final list of parameters to be monitored*	n/a
PAR6	*Is the parameter included in the current monitoring plan?*	The monitoring programme of the repository is stil being developed. The parameter will be considered,
PAR7	*Take parameter forward to monitoring programme design stage*	se answer PAR6
PAR8	*Park parameter*	
Part of TEC1 **BUT** can not be answered at TEC1 level, needs to be adressed after PAR7	*Can the proposed technology be applied without significantly affecting the passive safety of the repository system?*	This strategy entails no monitoring of the active repository and does not risk to jeopardise it.

Appendix I: Reference Project 2011 Test Case (SURAO)

Contents

Executive summary

The focus of the Modern2020 Project is monitoring during the operational period in support of demonstration of post-closure safety. Aspects of monitoring after final closure are for consideration by the WMO. The operation of all Czech repositories, including the monitoring of the closed repositories repository, is managed by SÚRAO in compliance with the relevant licences granted by the regulatory body. SURAO is also responsible for preparation of a deep geological repository intended for disposal of spent fuel and high and intermediate level waste. The safety of the future deep geological repository must be proved prior to construction. The systematic development of a deep geological repository programme in the Czech Republic began following the termination of a contract which provided for the transportation without charge of spent nuclear fuel to the former Soviet Union in 1989. A comprehensive review of available geological data on the selected localities was conducted and currently nine of the sites were recommended for further research. All sites are located in crystalline massive because no other suitable rock environment is available in the Czech Republic in sufficient dimensions. The reference project for a deep geological repository at a hypothetical site within the Czech Republic was developed already in 1999 and updated in 2011 to take into account a horizontal emplacement variant according to the Swedish KBS-3 concept.

The Czech Republic is in an early stage of DGR development focussing to find the most suitable sites for a DGR. Initiation of a monitoring program in this early stage of DGR development can underpin a repository safety strategy. It can provide an important baseline for parameters needed to monitor in construction and operational stages of the DGR development. Early developed monitoring program generally can provide better understanding of needs needed to confirm safety of the DGR. It can also provide sufficient time to development of monitoring methods.

The screening of the parameters that should be used for monitoring was based on the analyses of the relationship of safety functions of Czech DGR concept and parameters needed to show compliance with them.

The proposed M2020 screening methodology for parameter screening process turned out to be useful to realise all the aspects important to select parameters to be monitored in an implementable and logical repository monitoring programme and to select the parameters for monitoring that will be suitable for long term measurements.

The conducted test case helped to get a deeper understanding of parameters that will be important and useful to monitor in operational period of the repository lifetime and also helped to realise necessity to start as early as possible to prepare a postclosure safety related monitoring programme.

1 Introduction

The focus of the Modern2020 Project is monitoring during the operational period in support of demonstration of post-closure safety. Aspects of monitoring after final closure are for consideration by the WMO. It is an implicit principle of the Screening Process that any monitoring after full closure of a repository would be a continuation of monitoring prior to full closure. Therefore, the process that is developed here is equally applicable to all phases of monitoring. Closure entails that deposition is completed and galleries are backfilled. Once monitoring is put in place during the operational period it is up to the WMO and its regulatory framework to decide on discontinuation.

Monitoring programmes based on these safety cases are at different levels of development. Preliminary parameter lists exist for the Cigéo and Olkiluoto repositories. For the other programmes, preliminary parameter lists will to some extent be developed within Task 2.2.

The general objective of Task 2.2 is to test the methodologies for screening monitoring parameters identified and developed in Task 2.1. Specific objectives are:

- Describe specific objectives for monitoring of the barrier system in different national programmes, based on generic objectives for monitoring identified in MoDeRn.
- Identify the parameters that should be monitored in practical (implementable) programmes by using screening methodology from Task 2.1.
- Describe the expected evolution of the disposal system during the monitoring period, as it relates to the monitoring parameters identified.

The approach used will depend on the national programme, and may include consideration of safety cases during the operational phase, safety function indicators and/or FEPs.

It will be relevant to develop a link between EBS (Engineered Barrier System) monitoring results and the decision making processes during the operational phase of repository implementation. Specifically, the work in Task 2.2 shall for different national programs elaborate on how results from the monitoring of the EBS might be utilised to support operational decision and provide support to stakeholders. This will feed into Task 2.3 to identify and develop methodologies and tools to for the decision making process.

2 System description

The Czech DGR concept assumes that spent fuel assemblies from Czech nuclear power plants will be enclosed in steel-based canisters placed in vertical or horizontal boreholes at a depth of ~ 500m below the surface in a crystalline rock. The space between the canister and the host crystalline rock will be filled with compacted bentonite which will make up the final engineered barrier. The reference canister design contained in the Czech DGR concept is composed of two shells, an outer shell of carbon steel which will corrode very slowly under anaerobic conditions and a second inner shell of stainless steel which will corrode at an almost negligible general corrosion rate and exhibit a low tendency to local corrosion under anaerobic conditions in a low chloride concentration of groundwater of Czech potential sites.
Intermediate-level waste (ILW) with long-lived radionuclides, such as reactor core parts, that cannot be disposed of in the near-surface repositories available in the Czech Republic is intended to be disposed of in a future deep geological repository in caverns filled by cement or cement/bentonite mixtures. The ILW repository will be located at the same site as that for spent fuel assemblies; however the exact location of the ILW repository in respect to the spent fuel repository has not been selected yet.

2.1 EBS/Host-rock system

The safety important components of the engineered barrier system for the spent fuel repository in the Czech reference concept are:

- Two-shell (carbon steel – stainless steel) waste packages (canister)
- Ca, Mg compacted bentonite surrounding canisters (buffer)
- Mixture of bentonite and host rock backfilling all free volumes (backfill)
- Host rock affected by excavation works (openings)
- Other components (plugs, grouting, construction materials)

The components of the engineered barrier system can meet their safety functions only under specific conditions determined by characteristics of a surrounding host rock environment. The characteristics of the host rock environment important for the evaluation of its compatibility with

EBS system were divided into external and internal factors in the agreement with international recommendations[28].

External factors cover primarily:

- Earthquakes
- Faults potentially capable of moving due to seismo-tectonic changes
- Vertical movements of the Earth's crust
- Post-volcanic phenomena (gas emanations, hot water leaks, etc.)
- Climatic changes and their impact on the groundwater regime and geomorphological development at the site
- Anthropogenic activities

The internal factors cover:

- Thermal processes caused by the heat generated by waste
- Hydrogeological processes (changed possibly by construction of a repository)
- Mechanical changes due to excavation works (spalling)
- Geochemical processes in the rock relevant with respect to degradation engineered barriers
- Microbiological processes of the host and engineered barriers affecting also degradation rate of engineered barriers
- Impact of gas generated mainly by anaerobic corrosion of metal components

2.2 Expected behavior of EBS

The expected behaviour of engineered barrier system components (Table 1) was formulated in relation to safety functions allocated on the EBS components. It helps identify parameters needed to verify safety functions and also to verify assumptions concerning host rock environment or host rock – EBS interactions accepted in performance assessments of EBS components before the operational period.

Table 1: Safety functions and requirements of EBS components and expected behaviour in a crystalline rock

Component	Safety function/Requirement	Expected behaviour at the operational phase suitable for monitoring
Canister	Ensure integrity of the canisters with spent nuclear fuel so that radionuclides are confined in them as long as possible	It is expected that canisters will contain radionuclides until their failure due to corrosion and isostatic and shear stress expected in the host rock during period of at least 100 000 years.
	Limit the adverse effect of gases or other corrosion products arising primarily from degradation of the spent nuclear fuel canisters by anaerobic corrosion	It is expected that steel canisters will anaerobically corrode under generation of hydrogen.

[28] The NEA International Database, Version 2.1, November 2006

Component	Safety function/Requirement	Expected behaviour at the operational phase suitable for monitoring
Buffer	Isolate the disposal canisters so as to prevent any water transport to the canisters and/or radionuclide transport from the canisters by any mechanism other than diffusion decrease of radionuclides concentration to negligible level	It is expected that compacted bentonite will gradually saturate under formation of swelling pressure at least 2 MPa. Saturation will be affected by temperature and water composition. It is expected that the properties of bentonite will not change significantly for period of 1 million of years
	Prevent the transport of aggressive substances (oxygen, chlorides, sulphides, etc.) from the surrounding rock to the disposal canister r	It is expected only very limited transport of corrosive agents (e.g. O_2, Cl^-, NO_3^-, HS^-) to the canisters. It is expected that oxygen will quickly disappear in the vicinity of disposal boreholes.
	Prevent the erosion of bentonite from disposal boreholes	It is expected that only in a very limited number or in none of the boreholes bentonite will erode so that the weight of bentonite in a borehole would have decreased under unacceptable values.
	Prevent microbial corrosion of the disposal canisters	It is expected a very limited microbial activity in bentonite and surroundings
	Prevent mechanical damage of the canisters caused by rock movement; prevent canister sinking in the waste emplacement boreholes	It is expected that canister will not sink if bentonite swelling pressure will be higher than 2 MPa
	Remove heat from the disposal canisters so as to prevent any unacceptable impacts on the functional properties of the buffer material and/or other barriers	It is expected that that due to acceptable thermal conductivity of buffer, backfill and host rock, the temperature approaching 95 °C will not be exceeded
	Remove gases arising from the wastes so as to prevent disturbance of the functional properties of the other barriers and creation of advective transport routes for radionuclide leak	It is expected that gases generated by corrosion of canister will proceed by diffusion through bentonite and will not deteriorate bentonite properties
Backfill	Seal any free areas to prevent formation of preferential routes for radionuclide migration	It is expected that all free areas will be backfilled
	Protect buffer against erosion	It is expected that density of backfill will be high enough to prevent buffer erosion.
Openings	Prevent/control the formation of preferential routes due to rock damage/disturbance by the drilling operations and by heat from waste packages	It is expected disposal boreholes at selected sites of host rock will have no fractures of high transmissivity that could form preferential paths for release of radionuclides and no spalling or formation preferential path due to stress conditions in the host rock will occur at disposal boreholes. It is also expected that no additional preferential paths (fractures) will be generated for examples due to heat spread from heat generated waste.
Other repository components (plugs, grouting)	Ensure that other design components will not unfavourably affect EBS environment	It is expected that other EBS components will not affect unfavourably safety functions of other barriers, it means that the values of parameters of the environment will not exceed the values assumed in safety cases.

3 Monitoring objectives

Before construction and operation of a repository the conditions of a host rock in the depth of repository on safety functions of engineered barriers are estimated on the basis of laboratory or in situ experiments conducted under conditions that can more or less approach the real conditions in a repository, but there are not the same as real conditions in a repository. Monitoring of the parameters during its construction and operation can therefore justify assumptions accepted in performance and safety assessments conducted before construction and operation of the repository. The information acquiring from monitoring during construction and operation of a repository can be used for preparation of periodical safety assessments carried out during the repository operation and confirming the assumptions accepted before the repository operation and for a safety case needed to get the license for the repository closure. Monitoring during construction and operation of the repository is therefore a very important tool for validation of safety assessment results.

The information from monitoring can be also utilized for adaptation of technologies used for construction of the underground structures (e.g. excavation technologies), layout of the repository or improving properties of engineered barriers.

4 Monitoring parameter identification

4.1 Screening methodology

Due to the early, conceptual stage of the Czech programme of DGR development (operational phase of the repository is planned since 2065) no detailed screening process for determination of the parameters has been applied. The screening process was focused primarily on the identification of possible monitoring parameters on the basis of analyses of their relationship to safety functions and performance and safety assessment assumptions.

The identification of possible parameters for monitoring was also based on discussions with Czech researchers from research organizations and universities involved in Czech R&D programme, particularly those participating on research activities in underground laboratories located in Bedrichov water tunnel, Josef gallery and Bukov URL. R&D activities in Bedrichov water tunnel have been focused on development and testing of the following possible monitoring parameters:

- Geophysical measurements
  - Resistivity tomography (used for the estimation of water content)
  - Seismic profiles (used for the estimation of mechanical properties)
- Movements of activity of brittle fractures (optical triaxial measurements)
- Seismic measurements
- Water inflow
- Water chemistry pH, Eh, conductivity, water composition)
- Water, air, rock temperature

A lot of knowledge concerning identification of possible parameters for monitoring have been also acquired by Czech researchers from the DOPAS project where the function of plug built in Josef Gallery has been monitored (leak of water, temperature, water content, pore pressure).

4.2 Relation between T2.1 screening methodology and SURAO approach

SURAO approach was based primarily on identification of relationships of safety functions and relevant parameters needed to verify the compliance of EBS components with the safety function requirements or assumptions accepted in performance assessments. In the following Table 2, the parameters that could serve for verifying safety functions requirements or safety function assumptions, have been identified. All the parameters were given without judging of the possibility of their use in long term monitoring in the operational period. It is expected that they will be tested in underground laboratory conditions and then the most suitable parameters and ways of their implementation will be selected.

Table 2: Safety functions and parameters

Component	Safety function	Parameters significant to safety function
Canister	Ensure integrity of the canisters with spent nuclear fuel so that radionuclides are confined in them as long as possible	Isostatic pressure, shear stress, temperature, radiation dose Water content pH, Eh, conductivity, water composition Brittle fracture movement
	Limit the adverse effect of gases or other corrosion products arising primarily from degradation of the spent nuclear fuel canisters by anaerobic corrosion	Hydrogen concentration, corrosion product concentration
Buffer	Isolate the disposal canisters so as to prevent any water transport to the canisters and/or radionuclide transport from the canisters by any mechanism other than diffusion decrease of radionuclides concentration to negligible level	Density of saturated bentonite, swelling pressure, saturation level and change of bentonite properties Water content, pH, Eh, conductivity, water composition
	Prevent the transport of aggressive species (oxygen, chlorides, sulphides, nitrates, etc.) from the surrounding rock to the disposal canister	Oxygen and other aggressive species concentration at bentonite/host rock interface
	Prevent the transport of radionuclides as colloids from the disposal canister and limit the formation of colloids from the buffer materials resulting in bentonite erosion and increased radionuclide mobility	Concentration of colloids in a repository, primarily bentonite colloids
	Prevent microbial corrosion of the disposal canisters	Microbial activity
	Prevent mechanical damage of the canisters caused by rock movement; prevent canister sinking in the waste emplacement boreholes	Canister sinking in boreholes, Bentonite swelling pressure
	Remove heat from the disposal canisters so as to prevent any unacceptable impacts on the functional properties of the buffer material and/or other barriers	Temperature distribution
	Remove gases arising from the wastes so as to prevent disturbance of the functional properties of the other barriers and creation of advective transport routes for radionuclide leak	Gas and other corrosion products concentration

Component	Safety function	Parameters significant to safety function
Backfill	Seal any free areas to prevent formation of preferential routes for radionuclide migration	Backfill density and homogeneity and changes
	Protect buffer against erosion	Backfill density
Openings	Prevent/control the formation of preferential routes due to rock damage/disturbance by the drilling operations or by heat from waste packages	Fracture density around disposal boreholes and their transmissivity, Convergence, contact stress
Other repository components (plugs, grouting)	Ensure that no other design components has any impact on the safety functions of the other repository barriers	Leakage of backfill, change of chemical parameters (pH, Eh, aggressive species (e.g. nitrates), Strength of anchor, anchor slippage

Some of the parameters, such as swelling pressure, density of buffer and backfill, or concentration of gas released from EBS corrosion can be used directly for verifying compliance of the components with safety function requirements, but most of the parameters serve for verifying assumptions accepted in performance assessments, for example composition of water, Eh, pH, temperature or stress evolution.

It is expected that the operational period of a repository will be about 100 years, it can be therefore expected that long term monitoring of some parameters, such as temperature, could be utilized to the optimization of the layout of a repository, e.g. to ease the requirements on the distance between disposal boreholes, or properties of engineered barriers.

4.3 Interest of regulatory body and other stakeholders

The regulatory requirements have not been formulated for post-closure period. It can be expected that they will be formulated in later phases of a DGR development. For other stakeholders the period of more than 50 years before starting a routine operation of a repository is also too far to be interested in detailed monitoring of parameters in the operation period. Their interest concerning monitoring is focused mainly on monitoring of environmental parameters related to the construction and operation of the repository.

5 Monitoring system description and implementation

Monitoring system and implementation is tested in the water supply tunnel at Bedrichov (several meters under surface), intended for evaluation of phenomena in rock analogue to repository concept host rock and for testing of procedures to be used in candidate sites and Josefy gallery.

The measurement comprises spatial-temporal evolution of temperatures, groundwater inflow rates to the tunnel, temporal and spatial variability of chemistry, water residence time by means of natural tracers, natural seismicity, and triaxial displacements on fractures, and geophysical measurement of seismic and electrical resistivity tomography. Additionally, laboratory measurements complementing the field work – permeability and migration parameters are conducted. The monitoring parameters such as bentonite pore pressure or content are tested in Josef gallery.

The results from Bedrichov water tunnel and Josef gallery will be used for implementation of a similar monitoring program in the generic underground laboratory at Bukov situated 550m below surface near one of the potential sites, then in a confirmation underground laboratory at a selected site and then in the selected site.

6 Monitoring results in the confidence building and decision making process

Monitoring will support the confidence building in safety of a repository by verifying the results of performance and safety assessments prepared before the operational period. The early preparation of monitoring program and discussion of the program with stakeholders, and particularly with public from potential sites can be used in building continuous confidence in geological disposal development process. Checking the monitoring results is one of the most important tools for the regulatory body to follow the compliance with regulatory body requirements and serve for making decisions concerning updating of licenses for the operation and closure of repositories.

7 Conclusions and recommendations

The Czech Republic is in the siting stage of DGR development, expecting commissioning of a DGR in 2065. Initiation of a monitoring program in this early stage of DGR development can underpin a repository safety strategy. It can provide an important baseline for parameters needed in further stages of DGR development. Without the availability of continuous set data from early stage of site characterization it would be very difficult to discuss some future changes in the repository. Early developed monitoring program generally can provide better understanding of needs needed in future stages of DGR development. It must be also taken into account that monitoring methods require time for development to implement them in needed time.

The screening methodology proposed in Modern2020 project is a useful tool for realizing all the aspect of development of monitoring program. Particularly, it enabled to understand and implement the way for identification and screening of parameters for monitoring

The proposed screening methodology has not been fully applied in SURAO test case, because of early phase of DGR development in the Czech Republic. Some of the steps of proposed methodology, such as inclusion of regulatory requirements or stakeholder request in relation to monitoring of postclosure behavior of EBS could not be therefore used.

It was also difficult to evaluate “nice to have “parameters according to proposed evaluation scheme. But this knowledge can be used in later phases of DGR development. Technical feasibility assessment of monitoring have already started, but nevertheless, the stage is too premature to make some evaluations.