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### Integration of demonstrator activities in performance assessment: analysis of processes and indicators

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### **ABSTRACT:**

This report summarizes the work performed by NRG as part of the 4-years European FP7-project DOPAS (Full scale Demonstration of Plugs and Seals), with the objective to investigate how demonstrator monitoring activities can be coupled more closely to PA calculations, and to develop and test approaches that allow the integration of technical demonstrator's results into a safety case. NRG aimed to investigate a strategy for integration of monitoring results by identifying indicators that are directly or indirectly measurable in demonstrators, and allows assessing the complete system behaviour.

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Integration of demonstrator activities in performance assessment: analysis of processes and indicators

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# Contents

<b>Summary</b>		<b>1</b>
<b>1</b>	<b>Introduction</b>	<b>3</b>
1.1	Purpose and structure of this report	3
1.2	General considerations	6
1.3	Safety functions	7
1.4	Scenarios and scenario analysis	9
1.5	Safety and Performance indicators	13
1.5.1	<i>Safety indicator</i>	14
1.5.2	<i>Performance indicator</i>	15
1.5.3	<i>Safety function indicator</i>	15
1.5.4	<i>Performance indicator related to safety functions</i>	17
1.6	Monitoring of indicators	18
1.6.1	<i>Availability of technology</i>	18
1.6.2	<i>Requirements on monitoring</i>	20
<b>2</b>	<b>Establishment of a generic PA demonstrator case</b>	<b>21</b>
2.1	Functional abstraction of plugs and seals	21
2.1.1	<i>Generic functional abstraction of plugs and seals during the period of full containment</i>	22
2.1.2	<i>Generic functional abstraction of plugs and seals after failure of container</i>	24
2.1.3	<i>Key processes for migration modelling</i>	26
2.1.4	<i>Link between key processes in PA and underlying process models</i>	28
2.2	Definition of indicators	31
2.2.1	<i>Hydraulic conductivity</i>	31
2.2.2	<i>Péclet number</i>	31
2.2.3	<i>Travel-time based indicator</i>	34
2.2.4	<i>Integrated amount of brine inflow</i>	36
2.3	Analysis of the relevance of indicators, processes and parameter for the long-term safety	38
2.4	Synthesis: indicator analysis workflow	42
<b>3</b>	<b>Example PA demonstrator case: ELSA shaft sealing</b>	<b>45</b>
3.1	Functional abstraction of the shaft seal	46
3.2	Key processes for migration modelling	48
3.2.1	<i>Convergence behaviour</i>	48
3.2.2	<i>Compaction</i>	50
3.2.3	<i>Porosity and permeability</i>	54
3.3	Model representation	55
3.4	Definition of indicators	56
3.4.1	<i>Péclet number</i>	56
3.4.2	<i>Travel-time based indicator</i>	56
3.4.3	<i>Integrated amount of brine inflow</i>	57
3.5	Results of the simulations	57
3.6	Analysis of the relevance of indicators, processes and parameters for the long-term safety	61
3.7	Monitoring of indicators	63
<b>4</b>	<b>Analysis of the DOPAS demonstrators</b>	<b>65</b>
4.1	Key processes for long-term safety	66



4.2	Relevance of monitored parameters for the long-term safety	70
4.2.1	<i>Temperature</i>	71
4.2.2	<i>Pressure</i>	72
4.2.3	<i>Relative humidity</i>	75
4.2.4	<i>Displacement</i>	76
4.2.5	<i>Leakage</i>	76
4.3	Monitoring results	77
<b>5</b>	<b>Synthesis &amp; conclusions</b>	<b>83</b>
<b>Appendix A: Case Studies</b>		<b>87</b>
A.1	Deposition tunnel end plug of the Swedish disposal concept in granite: <i>DOMPLU</i>	87
A.1.1	<i>Disposal design, Safety Functions, FEP's &amp; Scenario's</i>	87
A.1.2	<i>Indicators &amp; Criteria</i>	90
A.1.3	<i>Demonstrator &amp; Monitoring system</i>	92
A.1.4	<i>Relevance of monitored processes for the long-term safety</i>	98
A.2	Shaft seal of the German disposal concept in rock salt: <i>ELSA</i>	100
A.2.1	<i>Disposal design, Safety Functions, FEP's &amp; Scenario's</i>	100
A.2.2	<i>Indicators &amp; Criteria</i>	104
A.2.3	<i>Demonstrator &amp; Monitoring system</i>	105
A.2.4	<i>Relevance of monitored processes for the long-term safety</i>	106
A.3	Drift and ILW disposal vault seal of the French disposal concept in clay: <i>FSS</i>	108
A.3.1	<i>Disposal design, Safety Functions, FEP's &amp; Scenario's</i>	108
A.3.2	<i>Indicators &amp; Criteria</i>	113
A.3.3	<i>Demonstrator &amp; Monitoring system</i>	114
A.4	Pressure and sealing plug of the Czech disposal concept in granite: <i>EPSP</i>	119
A.4.1	<i>Disposal design, Safety Functions, FEP's &amp; Scenario's</i>	119
A.4.2	<i>Indicators &amp; Criteria</i>	121
A.4.3	<i>Demonstrator &amp; Monitoring system</i>	122
A.5	Deposition tunnel end plug of the Finish disposal concept in granite: <i>POPLU</i>	124
A.5.1	<i>Disposal design, Safety Functions, FEP's &amp; Scenario's</i>	124
A.5.2	<i>Indicators &amp; Criteria</i>	128
A.5.3	<i>Demonstrator &amp; Monitoring system</i>	129
A.5.4	<i>Relevance of monitored processes for the long-term safety</i>	132
<b>References</b>		<b>133</b>
<b>List of tables</b>		<b>139</b>
<b>List of figures</b>		<b>140</b>

## Summary

This report summarizes the work performed by NRG as part of the 4-years European FP7-project *DOPAS* (Full scale Demonstration of Plugs and Seals), a technology development project for testing plugging and sealing systems for geological disposal facilities for radioactive waste. The project is built around a set of full-scale underground demonstrations, laboratory experiments, and performance assessment studies focussing on plugs and seals for disposal concepts in three different host rocks:

- Crystalline rocks: tunnel plugs for Czech, Finnish and Swedish repository concepts,
- Argillaceous rocks: tunnel plugs for French and Swiss repository concepts;
- Salt rock: shaft seal of the German repository concept.

The objective of NRG's contribution to WP5 of the *DOPAS* project is to investigate how demonstrator monitoring activities can be coupled more closely to PA calculations, and develop and test approaches that allow the integration of technical demonstrator's results into a safety case. Presently the results of PA calculations are communicated in a safety case by so-called *Safety and Performance Indicators*. NRG aimed to investigate a strategy for integration of monitoring results by identifying meaningful indicators that have two characteristics:

- the indicator is directly or indirectly measurable in demonstrators, and
- the indicator allows assessing the complete system behaviour.

For the preparation of the report, the five demonstrators that form the core of the *DOPAS* project where studied:

- *DOMPLU* (Dome Plug, SKB),
- *ELSA* (Schachtverschlüsse für Endlager für hochradioaktive Abfälle, GRS & DBE Technology),
- *FSS* (Full Scale Seal, Andra),
- *EPSP* (Experimental Pressure and Sealing Plug, SURAO), and
- *POPLU* (POsiva PLUg, Posiva).

On basis of a screening of the five demonstrators, shortly summarized in the Appendix, system abstractions are performed to establish a generic demonstrator case, key processes for the purpose of PA calculations are discussed, and potential indicators for the long-term safety are evaluated. A PA representation of a demonstrator test case is presented, based on the *ELSA* shaft seal concept for a disposal concept in rock salt, and several indicators are evaluated. Finally, a synthesis and description of the overall approach are given, and general conclusions are provided.

A stepwise approach is proposed to identify suitable indicators and evaluate their monitorability:

- In a first step, the general properties of the disposal concept, and the related safety functions, FEPs, considered scenarios, and - if available - existing indicators and criteria related to the barrier of interest have to be analysed.
- In a second step, key features and processes, and the system-specific underlying processes and parameters have to be established.
- In a third step, potential indicators and the related parameters are evaluated.
- In a fourth step, the relative contributions of diffusive and advective processes to the overall mass transport of radionuclides are estimated. Furthermore, the relevance of the barrier of interest for the overall safety is deduced by relevance based indicators.
- In the last step, the technical feasibility to monitor the parameters of interest has to be investigated.

SKB's concept of *safety function indicators*, including quantitative *criteria*, provides a good starting point for identifying indicators, but these indicators do not provide information on the safety in case criteria are not met. This makes it difficult to substantiate the consequences for the long-term safety. Nevertheless, the identification of *safety functions* for repository components is of vital importance for the development of a monitoring programme.

A second principal limitation noted for the DOPAS demonstrators was the operation time: relevant processes, e.g. the resaturation of swelling clay, are rather slow and full resaturation of the barrier often exceeds the operational life time of the demonstrator. The slow evolution of the identified processes may hamper the practical determination of parameters regarded relevant for these processes: monitoring of processes may provide significant evidence for a safe evolution only over time intervals that cannot be realized due to technical limitations.

The *safety function indicators* and *performance indicators related to safety functions* are useful in identifying monitorable indicators, either because these provide statements on safety, or allow to quantify the contribution of each safety function or EBS-(sub)component to the long-term safety.

The principal parameter identified as relevant for the long-term safety is the *hydraulic conductivity*. The hydraulic conductivity can be related to swelling pressure and density in case of a swelling clay material, or to the salt compaction and backfill pressure in case of salt grit. Other relevant key features and processes identified are the pressure gradient over the barrier, sorption, and solubility of radionuclides, with the latter two usually determined in independent batch experiments. Diffusion related processes are assumed to be of less relevance for monitoring, because for most concepts and host rocks, diffusion cannot be avoided.

Identification of *monitorable parameters* relevant for PA should therefore focus on *hydraulic aspects*, related to permeability, pressure, porosity, compaction, convergence, etc. Because most of the related parameters cannot be monitored either in demonstrators nor *in-situ*, they must be determined through indirect measurements or based on laboratory experiments. The derivation of these parameters involves process assumptions as a rule. For disposal systems in rock salt, the presence of brine is an important factor, which is monitorable by e.g. measurement of the electrical conductivity.



# 1 Introduction

This report presents the work performed by NRG as part of the 4-years European FP7-project *DOPAS* (Full scale Demonstration of Plugs and Seals). *DOPAS* is a technology development project for testing plugging and sealing systems for geological disposal facilities for radioactive waste. Fourteen nuclear waste management organisations and research institutes from eight European countries participate in *DOPAS*. The project is built around a set of full-scale underground demonstrations, laboratory experiments, and performance assessment studies focussing on plugs and seals for disposal concepts in three different host rocks:

- Crystalline rocks: tunnel plugs for Czech, Finnish and Swedish repository concepts,
- Argillaceous rocks: tunnel plugs for French and Swiss repository concepts;
- Salt rock: shaft seal of the German repository concept.

The overall objective of *DOPAS* is to improve the adequacy and consistency regarding industrial feasibility of plugs and seals, the measurement of their characteristics, the control of their behaviour over time under repository conditions, and their hydraulic performance with respect to the safety objectives. The *DOPAS* project is divided into seven work packages:

- WP1 - *Project Management and Coordination*
- WP2 - *Definition of requirements and design basis of the plugs and seals to be demonstrated*
- WP3 - *Design and technical construction feasibility of the plugs and seals*
- WP4 - *Appraisal of plug and seal systems' function*
- WP5 - *Performance assessment of the plugs and seals systems*
- WP6 - *Integrating analysis including cross-review of each other's work*
- WP7 - *Dissemination*

## 1.1 Purpose and structure of this report

This report is part of *DOPAS*'s WP5 - *Performance assessment of plugs and seals system* and describes the outcome of NRG's work on Task 5.9 on "*Integration of results of demonstrators in total repository system's PA by special performance indicators*".

The general aim of WP5 is to understand the implications of the plugs and seal performance on the overall safety on the long term. An important element of this work is to develop justification of model simplifications for long-term safety assessment simulations. The main objective of WP5 is to improve the state-of-the-art in process modelling and its abstraction in integrated performance assessment (PA). More specifically the objectives were defined as follows:

- process modelling of the experiments performed in WP3 to gain process understanding;
- identify the main processes that are relevant and thus to be considered for predicting the short and long-term behaviour of the plug and sealing systems;
- identify remaining uncertainties and their influence on PA;
- development and justification of conceptual models of plugs and seals for the different disposal concepts and geological environments;
- simulation of processes and their evolution within individual sealing components;
- further develop and apply the PA methodology and (conservative) PA models for analysing the system behaviour.

The objective of NRG's contribution to WP5 of the DOPAS project is to investigate how demonstrator monitoring activities can be coupled more closely to PA calculations, and develop and test approaches that allow the integration of technical demonstrator's results into a safety case. Presently the results of PA calculations are communicated in a safety case by so-called *Safety and Performance Indicators* (see e.g. the EU-FP6 *PAMINA* project [Bailey *et al.*, 2011]). NRG aims to develop a strategy for integration of monitoring results by identifying meaningful indicators that have two characteristics:

- the indicator is directly or indirectly measurable in demonstrators, and
- the indicator allows assessing the complete system behaviour.

In order to do so, five activities were performed by NRG:

1. Identification of (new) indicators that can potentially be measured and analysis of its technical feasibility.
2. Qualification of the potential weight (or relevance) of the indicator on the (seal's) performance status by discussing its potential impact on the overall safety.
3. Establishment of a generic demonstrator case, and development and application of a suitable PA model representation to derive potential evolutions of the selected indicators in time.
4. Analysis and discussion of the results of the actual demonstrators/experiments performed in DOPAS - as far as available - in the light of the indicator methodology.
5. Development and description of an overall methodology, in particular the extensions needed to include demonstrators in existing methodologies.

The results of NRG's activities are summarized in this report, comprising of six chapters and an Appendix:

- The remainder of this chapter reviews shortly general concepts and methods of the safety case and PA that are of use.
- In Chapter 2, systems abstractions are performed to establish a generic demonstrator case. Key processes for the purpose of PA calculations are derived, and potential indicators for the long-term safety are evaluated. That chapter concludes with a description for an overall approach for indicator identification.

- In Chapter 3, the system abstractions developed in Chapter 2 are applied to a demonstrator test case, based on the *ELSA* shaft seal concept for a disposal concept in rock salt. Key processes are discussed, and several indicators are evaluated.
- In Chapter 4, lessons learned from the analysis of the five demonstrator activities performed within DOPAS are summarized.
- In Chapter 5, methods for indicator identification are discussed and general conclusions are provided.
- In the Appendix, an overview of relevant features of the five DOPAS demonstrators with respect to indicator identification and assessment of the long-term safety is given. The Appendix is based on information on the demonstrator activities provided (early) in the DOPAS project, and is mainly used as internal reference. For an up-to-date reference on the DOPAS demonstrator activities we refer to the final reports of the Work Packages 2 to 4, provided by the responsible organisations ([www.posiva.fi/dopas/deliverables](http://www.posiva.fi/dopas/deliverables)).

The results of the current work served as basis for the NRG contribution to the public DOPAS WP5 Deliverable D5.10 “*Final report on conceptual and integrated modelling activities*”.

## 1.2 General considerations

Plugs and seals as part of the engineered barrier system (EBS) have essential roles in the design of radioactive waste disposal facilities. The design basis of plugs and seals, and related criteria and requirements has been extensively reviewed in [DOPAS, 2016a]. Design requirements include:

- Requirements on hydraulic performance,
- Requirements on mechanical performance,
- Requirements on chemical performance,
- Requirements on gas migration,
- Requirements on the host rock,
- Requirements on operational issues.

Safety and performance assessments have been identified as important steps in the iterative process for developing the design basis [DOPAS, 2016a], but they go beyond *design criteria*: design criteria relate to the initial state of the repository, whereas the assessment period covers hundreds of thousands to millions of years.

To assess the EBS performance over such a long term, *safety functions* are attributed to components of the EBS or the host rock that can be evaluated by performance assessment (PA) calculations. Performance assessment is related to the assessment of the performance of a system or subsystem and its implications for protection and safety, and can be applied to parts of a facility. Unlike in a safety assessment, it does not necessarily require the assessment of radiological impacts [IAEA, 2007]. The definition of suitable *indicators* facilitates the analysis, understanding and communication of the outcomes of PA calculations. Indicators are structural elements of performance and safety assessments as part of the safety case methodology, and can have a relevant role in supporting system understanding and providing evidence for safety, and thus are expected to contribute to the overall objective of confidence building. The use of *safety function indicators* (SFI), a specific type of indicator, allows to link design criteria with the contribution of an EBS component to the long-term safety. In the view of SKB [NEA, 2007]:

*“design criteria should be established so that, ideally, taking into account evolution and deterioration of system components, all SFI criteria are fulfilled throughout the full assessment period.”*

The *demonstration* of the proper performance of relevant EBS components, *in-situ* and on real scale, either in Underground Research Laboratories (URLs) in the host rock of interest or in the waste disposal facility itself (e.g. as part of a pilot facility [Wildi *et al.*, 2000]) can provide valuable evidence for safety. Part of such a demonstration is the *monitoring* of the evolution of relevant features or process parameters in time. Monitoring is generally seen as beneficial for confidence building, and monitoring of demonstrators can do so in advance of the actual disposal of waste, facilitating the implementation process.

NRG’s interest in demonstrators comes also from the fact - as will be elaborated later - that demonstrator monitoring may overcome some limitations of repository monitoring: one important

outcome of the EU-FP7 project *MoDeRn* on the role of monitoring in geological disposal is that the technical options available for *in-situ* monitoring can present a limiting factor, and thus may represent a relevant constraint with respect to the kind of deviating evolutions or events that can be identified by monitoring activities, and the contribution it may provide to decision-making [MoDeRn, 2011, 2013a, 2013b, 2013c]. Long-term monitoring under harsh environmental conditions prevailing in a geological disposal facility is currently technically challenging, and the ability to exclude technical failures as cause of deviating monitoring results might be essential for the usability of monitoring results. Monitoring of demonstrators thus could provide valuable, additional evidence for safety, because the technical requirements on monitoring technology are less stringent and potential failures of monitoring equipment can be easier traced and excluded. This is expected to result in more parameters that can potentially be measured, and higher precisions and accuracies that can be achieved, finally leading to better and potentially more significant results.

Based on the above considerations, understanding of demonstrator and monitoring activities are also of interest for countries that are still early in the implementation process of a disposal facility, or have explicitly chosen for a policy of long interim storage of the radioactive waste, like the Netherlands. Hence NRG's interest to understand and elaborate options to use (monitoring data from) demonstrator activities for the purpose of safety analysis.

### 1.3 Safety functions

The concept of *safety functions* as part of the defence-in-depth methodology used in nuclear power plants was adapted by the Swedish radioactive waste management programme in 1995 and applied to radioactive waste disposal [Marivoet *et al.*, 2008]. A *safety function* defines the role of a repository component in terms of its contributions to the overall safety of the disposal system, and complements the multi-barriers principle. The concept of safety functions is expected to make the role of various components of a disposal concept more transparent [NEA 2007]. While slight differences in definition between different countries were noted in [Marivoet *et al.*, 2008], for the purpose of this report the definition of [SKB, 2006a] is followed:

*“A safety function is a role through which a repository component contributes to safety.”*

[IAEA, 2011] defines requirements with respect to safety functions as part of the multi-barrier concept:

*“The host environment shall be selected, the engineered barriers of the disposal facility shall be designed and the facility shall be operated to ensure that safety is provided by means of multiple safety functions. Containment and isolation of the waste shall be provided by means of a number of physical barriers of the disposal system. The performance of these physical barriers shall be achieved by means of diverse physical and chemical processes together with various operational controls. The capability of the individual barriers and controls together with that of the overall disposal system to*

*perform as assumed in the safety case shall be demonstrated. The overall performance of the disposal system shall not be unduly dependent on a single safety function.”*

Many national geological disposal programs define safety functions for each component of the multi-barrier system. These functions vary for different concepts, times and geological environments. A list of safety functions that is generic with respect to these variables is provided in [Chapman *et al.*, 2011, Table 2]. Three *key functions* of a multi-barrier disposal concept were identified:

- the *isolation* of the wastes by safely removing them from direct interaction with human beings and environment;
- the *containment* of the radionuclides by preventing for as long as required of the release of contaminants from the waste container;
- the *retardation* of the radionuclides associated with the waste by retaining them within various parts of the multi-barrier system until their potential hazard decreases considerable by decay.

The key function *isolation* relies on the reduction of the probability of inadvertent human intrusion and provision of stable conditions for the disposed waste and the disposal system. This function can be provided amongst others by access control during the operational phases, or by the subsurface layer on top of the disposal that makes the disposal difficult to access in the post-closure phase and that provides sufficient protection to geological processes as erosion or subsidence on the long-term. Since these function has no relation with demonstrators analysed in the present study it will not considered further analysis in the present report.

The key function *containment* is based on the complete containment of the waste within canisters over the entire required period, and will be discussed further in Chapter 2.

The key function *retardation* relies on a multitude of safety functions of the multi-barrier system, and its evaluation forms the core of PA. Retardation is related to three functions:

- limitation of contaminant releases from the waste forms;
- limitation of the water flow through the disposal system;
- retardation of contaminant migration.

SKB combined the function of isolation and containment and distinguish in their disposal concept between *primary* and *secondary safety functions* [SKB, 2006a]:

- The *primary safety function* of the barriers is to *isolate* the radioactive waste.
- Should isolation be breached, the *secondary safety function* of the barriers is to *retard a potential release* from the repository.

## 1.4 Scenarios and scenario analysis

*Scenarios* represent specific descriptions of a potential evolution of the repository system from a given initial state. They are used to identify and define assessment cases and are based on a compilation of safety relevant features, events and processes (FEPs) that are part of the safety case methodology [IAEA, 2012].

Typically, five different types of scenarios can be distinguished [Röhlig *et al.*, 2012, p.10]<sup>1</sup>:

1. a *normal evolution scenario*, the central scenario aimed at representing the expected evolution of the repository;
2. *plausible alternative scenarios* representing less likely but still plausible repository evolutions;
3. *extreme natural events* that are very unlikely;
4. possible *future human actions*, which may significantly impair the performance of the disposal system;
5. *'what-if' scenarios*, conceptual scenarios in which implausible or physically impossible assumptions are adopted in order test the repository's robustness.

Scenarios can be developed by a 'top-down' or 'bottom-up' approach by either identifying first the crucial safety functions and then focussing on what combination of processes and conditions could impair one or more safety functions, or assessing a range of external events or conditions that may trigger changes in the disposal system and may affect its performance. An example of a 'bottom-up' approach is depicted in Figure 1-1.

Regardless of the method used for developing the scenarios, all FEPs that could significantly influence the performance of the disposal system should be addressed in the assessment. It should be shown that all potentially significant transport pathways have been considered and that possible evolutions of the system have been taken into account. It should be explained and justified which scenarios are regarded as representing the normal or expected evolution of the system, and which scenarios address FEPs having a low or particularly uncertain probability of occurrence. To the extent possible, an indication of the likelihood of the scenarios considered should be provided for risk assessment.

<sup>1</sup> note that not all types of scenarios are necessarily part of a safety case or license application

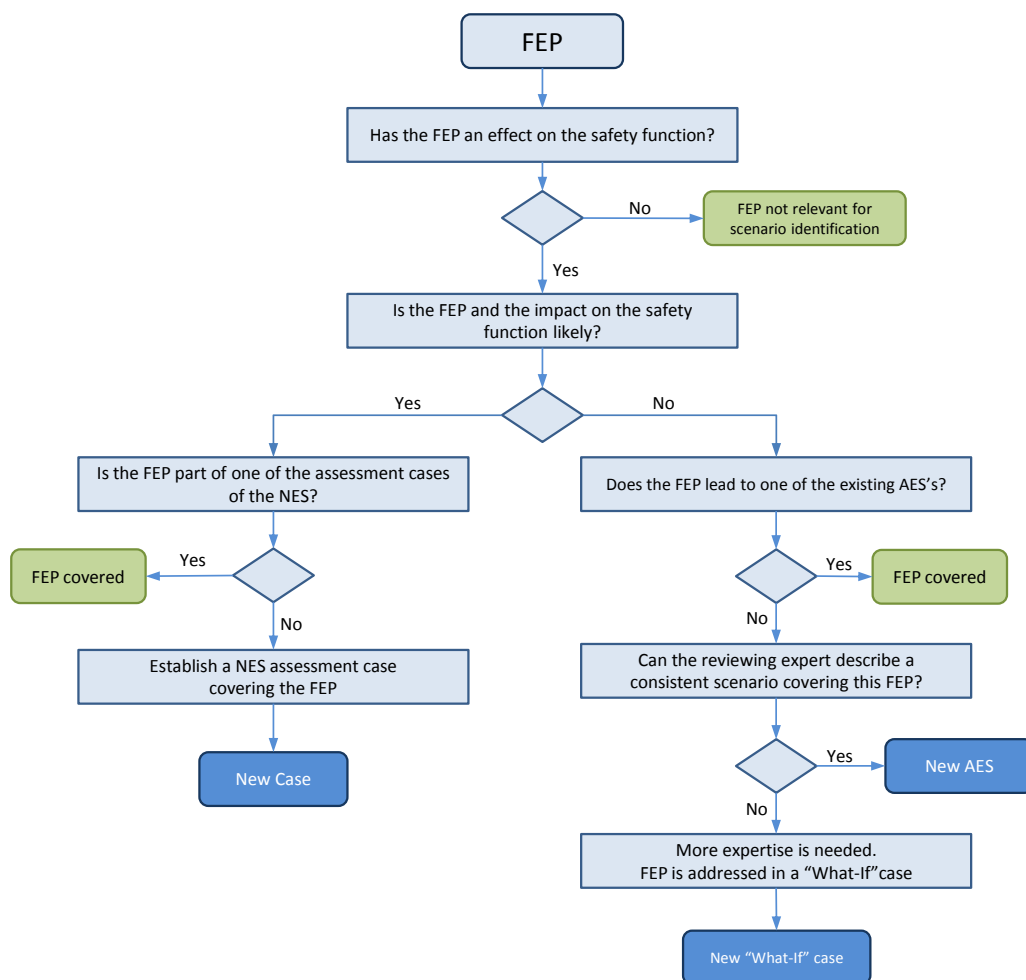


Figure 1-1: Example of FEP screening process [Grupa *et al.*, 2016]

Of particular interest in the context of this report is the fact that the set-up of a demonstrator is linked to boundary conditions that represent one or more, but not all scenarios considered in a safety case. As consequence, a demonstrator cannot cover all scenarios of a safety case, and often it not covers the most challenging one, i.e. the scenarios where the demonstrated barrier has a large contribution to the overall safety. This limits the usability of the demonstrator monitoring results for PA purposes in two manners:

- The physico-chemical conditions present under normal evolution conditions are not expected to lead to any relevant impairment of the safety function of a barrier, because these are covered by the design. A demonstrator performed under normal evolution conditions thus may not allow drawing conclusions on the behaviour of the barriers short-term safety function under altered, more critical conditions.
- Because of the multi-barrier principle, it is likely that assessments of the normal evolution scenario will lead to no relevantly increased risks even in case of a total failure of a single barrier examined in a demonstrator. Assessing the normal evolution scenario by PA thus may provide only limited information on the role of the barrier for the long-term safety.



Monitoring might lead to the necessity to re-evaluate the considered scenarios: for each parameter of interest, the expected temporal evolution of the parameter value can be computed. If this is performed for all scenarios considered in a safety case, this results in a group of parameter evolutions (and their inherent numerical uncertainties) that altogether cover all “expected” potential evolutions of that particular parameter (grey lines in Figure 1-2). When progressing from theoretical process studies to real scale demonstrators, parameter values or evolutions might be observed by monitoring that are not covered by any of the considered scenarios (blue diamonds and red dotted lines in Figure 1-2). Such outcomes can be denoted as “unexpected” or “deviating” results (Modern, 2013c), and correspond to either “real” system behaviour or to a technical failure of the monitoring infrastructure. However, if technical failure can be excluded, such observations represent an additional ‘scenario’.

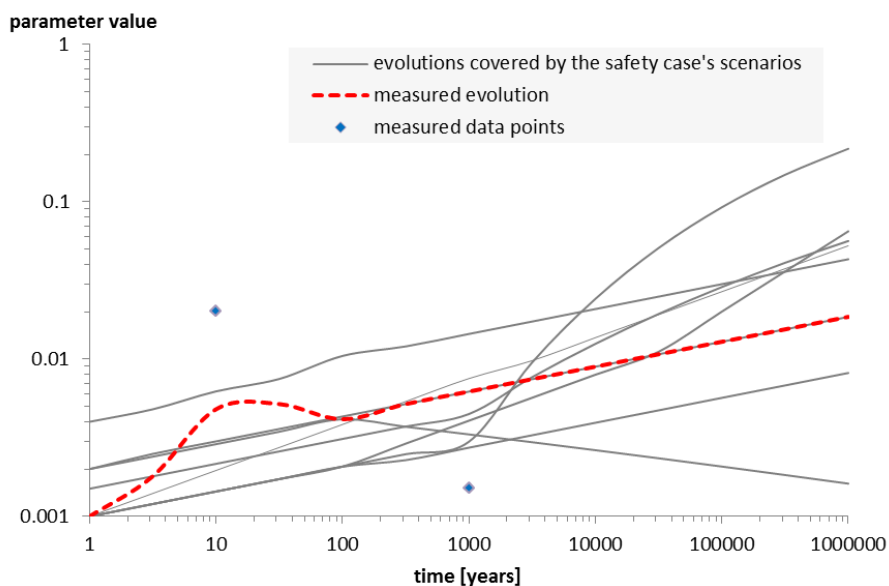


Figure 1-2: Potential evolutions of a parameter in different scenarios covered by a safety case

Finally, parameter evolutions might be identified that lead to uncertain system evolutions. Such an evolution can be used for the definition of another type of ‘scenario’ that distinguishes between deviating but safe and potentially unsafe evolutions (Figure 1-3).

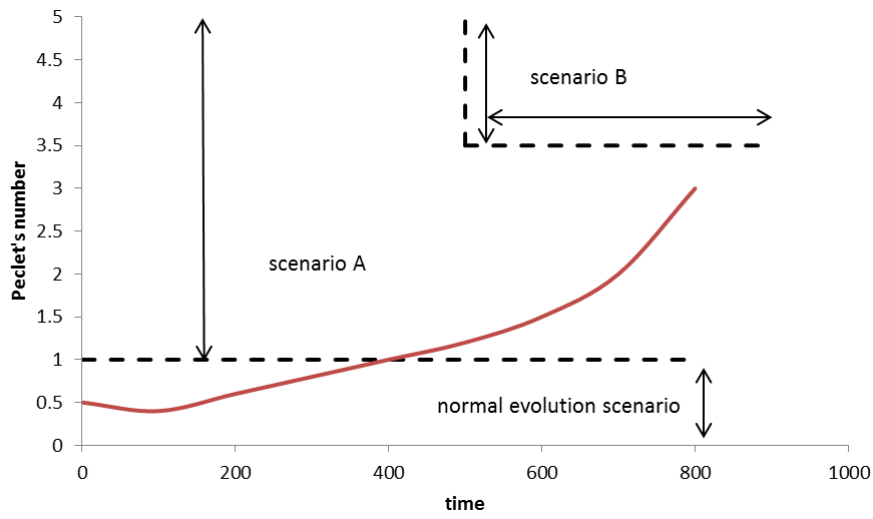


Figure 1-3: Potential evolution of a monitored parameter. ‘Scenario A’ here represents an evolution not covered by the normal evolution, but not impairing the long-term safety. ‘Scenario B’ may represent a scenario where an impairment of the long-term safety cannot be excluded.

## 1.5 Safety and Performance indicators

Geological disposal of radioactive waste in deep geological formations is based on the multi-barrier concept and implies a redundant set of safety functions for each of the individual barriers. Main purpose of safety assessments is the quantification of post-closure radiological impacts of the disposal concept. This requires an analysis of the long-term evolution of a disposal system and its individual components, the quantification of the performance of the engineered barriers and the evaluation of radiological exposure or other endpoints of the assessment. As part of the safety case's safety assessments, calculated doses and/or risks are compared to regulatory limits in order to demonstrate the overall safety of the disposal system.

The results of PA calculations for a safety case are expressed by so-called *Safety and Performance Indicators*. These indicators provide means to assess and communicate the overall safety of the system and allow analysing and understanding the behaviour of the repository at compartment or component level. The various applications of indicators within a safety case that have been identified are summarized in [NEA, 2012]:

- supporting the safety case structure and applying multiple lines of reasoning;
- increasing the transparency of safety case arguments;
- assessment of repository safety and presenting impacts in the natural environment;
- assessment of repository safety in different timeframes;
- addressing uncertainty in dose and risk calculations;
- assessment of sub-system performance;
- assessment of safety functions;
- scenario identification;
- helping with communication, especially to non-technical audiences.

A number of systematic schemes and formal definitions proposed for indicators were discussed in [NEA, 2012] and shortly presented in the next paragraphs. For this study, a classification scheme is used that is adopted from [NEA, 2012] and summarized in Figure 1-4:

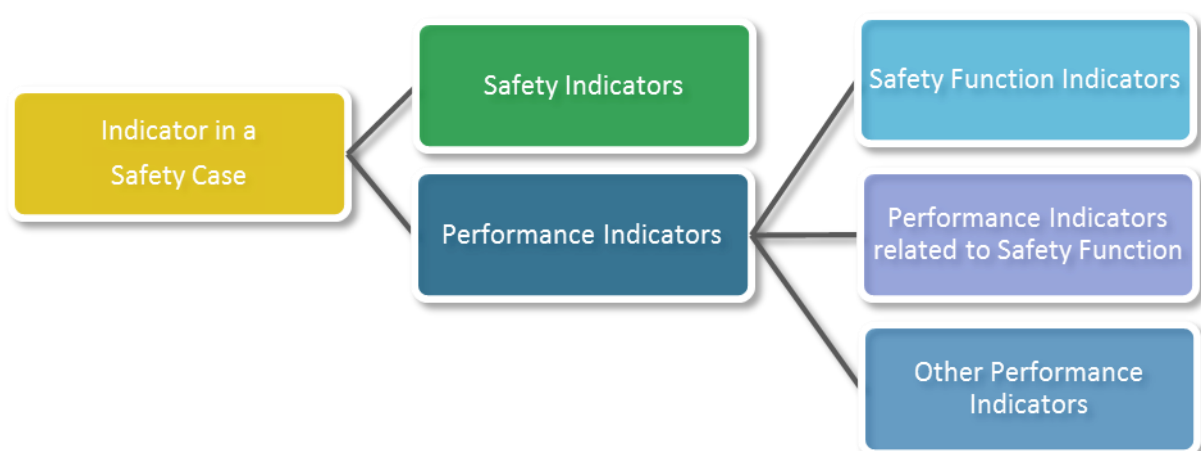


Figure 1-4: Classification of indicators

### 1.5.1 Safety indicator

In the EC project *SPIN (Testing of Safety and Performance Indicators)*, the following definition of a *safety indicator* was provided [Becker *et al.*, 2002]:

*“A safety indicator of the considered type must:*

- provide a measure of the safety of the whole system;*
- allow a comparison with a safety-relevant reference values;*
- take into account the contributions of all radionuclides;*
- be calculable using performance assessment models.”*

The *PAMINA* project [Becker *et al.*, 2009] recommended to extend the definition of the term *safety indicators* by an explicit requirement that for each safety indicator a *reference value* must be identified, to allow safety to be evaluated by means of comparison:

*“A safety indicator is a quantity, calculable by means of suitable models, that provides a measure for the total system performance with respect to a specific safety aspect, in comparison with a reference value quantifying a global or local level that can be proven, or is at least commonly considered, to be safe.”*

There are several possible ways to subdivide safety indicators further. In [NEA, 2012] an important distinction is made between *primary* and *complementary indicators*:

*“A primary indicator (typically annual dose or risk) is one that is compared to a legally or regulatory defined radiological constraint, whilst all other indicators that may be used in a safety case are referred to as complementary indicators.”*

*Primary indicators* (annual dose or risk) provide numerical values determined by means of a PA model calculation for the corresponding repository system and the scenario considered. While such indicators give a comprehensive indication of the complete system behaviour in terms of related risks, they cannot be directly or indirectly measured in demonstrators.

*Complementary safety indicators* provide alternative and independent means to assess the overall safety of the repository system. They help decreasing the uncertainties associated with exposure pathways and may help understanding the overall system behaviour by focussing on partial systems, e.g. the role of the engineered barrier system (EBS) or the host rock. Furthermore, complementary indicators may also help decreasing the uncertainties associated with the geological timescale over which PA calculation are performed. As the primary safety indicators, complementary safety indicators are the outcome of PA calculation and cannot be directly or indirectly measured in demonstrators<sup>2</sup>.

<sup>2</sup> However, monitoring may provide *reassurance* by showing that measured indicator values are not above the natural background level.

### 1.5.2 Performance indicator

The sixth report on the IAEA's Working Group on Principles and Criteria for Radioactive Waste disposal [IAEA, 2003] defines a *performance indicator* as follows:

*“A performance indicator provides measures of performance to support the development of system understanding and to assess the quality, reliability or effectiveness of a disposal system as a whole or of particular aspects or components of a disposal system.”*

Requirements on performance indicators were developed in the *SPIN* project [Becker *et al.*, 2002]:

*“A performance indicator of the considered type must:*

- provide a measure of the performance of the whole system or a subsystem;*
- allow a comparison between different options or with technical criteria;*
- take into account the contributions of all radionuclides or a single radionuclide;*
- be calculable using safety assessment models.*

*The indicators may be time-dependent or constant. Subsystems considered for performance indicators consists of one or more of the barriers or of parts of a barrier.”*

Several performance indicators were tested in the *SPIN* and *PAMINA* project [Becker *et al.*, 2009] and found to be useful:

- Inventories in compartments
- Inventories outside compartments
- Concentrations in compartment water
- Concentration in biosphere water divided by activity/ concentration in waste package water
- Activity/radiotoxicity flux from compartment
- Time-integrated activity/radiotoxicity flux from compartment
- Transport times through compartments

However, the listed indicators are not directly or indirectly measurable in a demonstrator and give no direct information about the overall safety of the system.

### 1.5.3 Safety function indicator

Some programmes distinguish a subset of the performance indicators as *safety function indicators*. [SKB, 2006a] defines a *safety function indicator* (SFI) as:

*“A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled. A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.”*

SFIs can be identified by considering the basic safety functions of the repository’s multi-barriers system and can be used to demonstrate how these safety functions are fulfilled. Comparable to safety indicators, *criteria* can be developed for most SFIs to define quantitative limits. SKB developed this conceptual approach further and provides safety functions indicators and accompanying criteria for their KBS-3 Safety Case ([SKB, 2006a]; see also Section A.1.2). They found the approach very useful for focussing on the critical issues in safety assessment and suggested to use SFIs as instruments to discuss and prioritise FEPs once a project is mature. SKB emphasises that unlike the reference values related to safety indicators, criteria of SFIs that are not met, not necessarily imply an unsafe repository. The different facets related to a safe evolution of the repository cannot be easily captured by a simple comparison to an SFI criterion [NEA, 2007]. Table 1-1 summarizes safety functions, safety function indicators and criteria related to the deposition tunnel backfill and buffer of the *DOMPLU* demonstrator.

Table 1-1: Safety functions, safety function indicators and criteria related to the deposition tunnel backfill and buffer

	Safety function	Safety function indicator	Indicator Criterion
Backfill	Counteract buffer expansion	-	
	Limit advective transport	Backfill hydraulic conductivity	$P_{Backfill, Swell} > 0.1 \text{ MPa}$
		Backfill swelling pressure	$k_{Backfill} < 10^{-10} \text{ m/s}$
		Backfill temperature	$T_{Backfill} > -2^\circ\text{C}$
Sorb radionuclides	Sorption coefficient	$K_{d, Backfill, i}$	
Buffer	Limit advective transport	Buffer hydraulic conductivity	$k_{Buffer} < 10^{-12} \text{ m/s}$
		Buffer swelling pressure	$P_{Buffer, Swell} > 1 \text{ MPa}$
	Reduce microbial activity	-	
	Damp rock shear movements	Maximum buffer density	$\rho_{Buffer, Bulk} < 2,050 \text{ kg/m}^3$
	Resist transformations	Buffer maximum temperature	$T_{Buffer} < 100^\circ\text{C}$
	Prevent canister sinking	Buffer minimum swelling pressure	$P_{Buffer, Swell} > 0.2 \text{ MPa}$
		Limit pressure on canister and rock	Buffer maximum swelling pressure
			Buffer freezing temperature
	Filter colloids	Minimum buffer density	$\rho_{Buffer, Wet} > 1,650 \text{ kg/m}^3$
	Sorb radionuclides	Element specific diffusion coefficient	$D_{e, Buffer, i}$
		Element specific sorption coefficient	$K_{d, Buffer, i}$
Allow gas passage	-		

\* at this stage

Three safety function indicators were developed in the *SPIN*-project [Becker *et al.*, 2002], related to the safety functions ‘*physical confinement*’, ‘*decay during the delayed transport*’, and ‘*dispersion and dilution*’:

- *Proportion of waste not completely isolated for a given time period* (physical confinement function);
- *Time-integrated flux from compartments divided by initial inventory* (decay during delayed transport);

- *Concentration in biosphere water divided by concentration in waste package water* (dispersion and dilution).

These indicators are conceptually close to the *performance indicator related to safety functions* that will be discussed in the next section.

A SFI criterion marks the conditions under which a safe evolution of the EBS is expected, but does not allow to make a statement on the long-term safety if a criterion is not fulfilled: this is a relevant drawback in the application of the otherwise useful indicator type. Furthermore, while the SFI concept provides an interesting approach for the purpose of this study, in a multiple barrier system, failure of a single barrier does not necessary result in any increased exposures or risks, thus the application of this conceptual indicator for PA needs further consideration.

#### **1.5.4 Performance indicator related to safety functions**

*Performance indicator related to safety functions* represents another subset of performance indicators of interest in this study. This type of indicator was tested during *PAMINA* [Becker *et al.* 2009, Schröder *et al.*, 2009a] and is applied in Dutch and Belgian research programmes [Marivoet *et al.*, 2009 & 2010; Weetjens *et al.*, 2010; Rosca-Bocancea & Schröder, 2013; Schröder & Rosca-Bocancea, 2013]. *Performance indicators related to safety functions* quantify the contribution of each safety function to the overall safety, and of the safety provided by the overall set of safety functions of a disposal concept. E.g. performance indicators related to safety functions defined for the Dutch *OPERA* project are [Rosca-Bocancea & Schröder, 2013; Schröder & Rosca-Bocancea, 2013]:

- *Containment (C-RT)*;
- *Limitation of release (R1-RT)*;
- *Retardation due to migration through buffer and host formation (R3 - RT)*;
- *Retardation due to migration through geosphere (R4 - RT)*;
- *Performance of the integrated repository system (PI-RT)*.

In conclusion, only *performance indicators* are monitorable entities and therefore of relevance with respect to the current study. In Chapter 2, the application of *performance indicators related to safety functions* will be discussed further, and examples are given.

## 1.6 Monitoring of indicators

The *monitoring* of various parameters and processes related to the geological disposal of radioactive waste is generally expected to have an important role in providing evidence for safety and contribute to the general objective of increasing confidence. 'Monitoring' in a technical context can be defined as:

*“to observe a situation for any changes which may occur over time, using a monitor or measuring device of some sort.”<sup>3</sup>*

In 2001, the IAEA defined monitoring in relation to radioactive waste disposal [IAEA, 2001] as:

*“continuous or periodic observations and measurements of engineering, environmental or radiological parameters, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment.”*

Looking into the subject in more detail shows that the topic of monitoring is a diversified, complex socio-technical question, extensively discussed in the EU-FP7 project *MoDeRn* [MoDeRn, 2013c & 2012]. Although the relevance of monitoring for the safety case is generally recognized, currently insufficient understanding exists on how to embed monitoring activities in the safety case methodology. The benefits of such an embedding would be to get a clearer picture on the role of monitoring in the overall process, and how it can interact in a beneficial way with other elements of a safety case. Despite the progress made during *MoDeRn*, a general need was expressed to understand better what monitoring can contribute to safety, how it can be integrated in a safety case and how it can be linked to decision-making. More clarity is also needed on the technical ability to detect events or evolutions that may impair the long-term safety by monitoring in the operational and post-closure phase, in order to get a realistic picture of what contribution monitoring actually can provide for decision-making. These questions are subject of the ongoing European Horizon2020-project *Modern2020* [European Commission, 2015] and will not be elaborated further here. However, while the *MoDeRn* project and the ongoing *Modern2020* project mainly focus on “*repository monitoring*” (*in-situ* monitoring activities performed in a waste disposal facility to support of the long-term safety), several aspects of interest for the monitoring of demonstrators will be discussed in the next sections.

### 1.6.1 Availability of technology

Not all parameters or processes that are identified as useful to be monitored are directly or indirectly “monitorable”. Some parameters or processes might be monitorable, but not at the desired location, with the necessary accuracy, precision, etc., or over a sufficient long period of time. The *MoDeRn* project therefore recommended that once potential parameters to be monitored

<sup>3</sup> wikipedia, <http://en.wikipedia.org/wiki/Monitoring>



*in-situ* are identified, and technical and performance requirements for candidate technologies are defined, it must be assessed which technologies are available in order to monitor a certain parameter (Figure 1-5). Careful screening of potential technologies must be performed in order to evaluate the performance of a monitoring technology in a specific setting. In case no monitoring technology of suitable maturity exists for the specific purpose, additional R&D might be considered, and several options may need to be considered ranging from improving existing technology (e.g. improving accuracy or long-term performance) to the development of new candidate technologies.

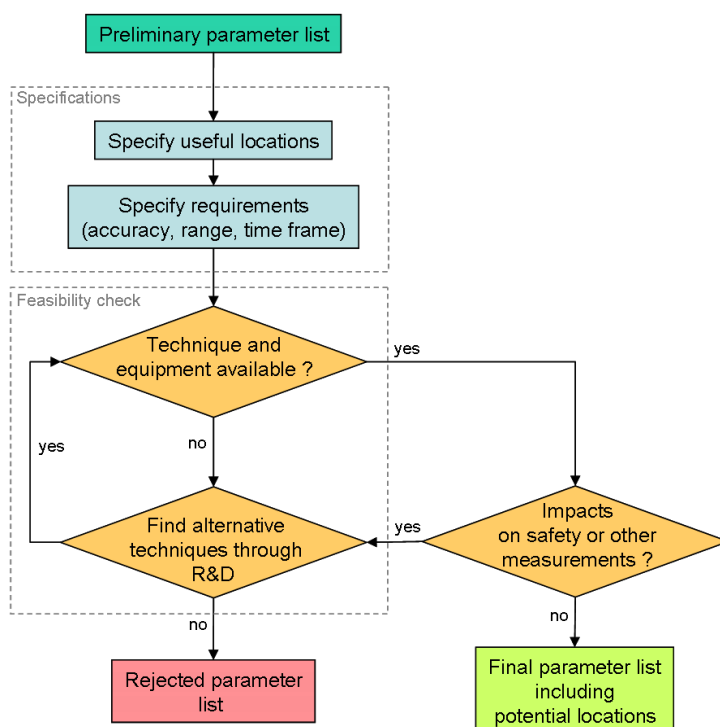


Figure 1-5: Parameter identification in MoDeRn - step 2 [MoDeRn, 2013b]

While for a demonstrator less technical limitations are applicable than for repository monitoring, it is obvious that also for demonstrators the availability of suitable technologies can result in constraints for the monitoring of relevant parameters and processes.

Another aspect of interest is that some parameters judged to be not feasible to be monitored in a repository (Figure 1-5) do might be measurable in a demonstrator. The feasibility is closely linked to the requirements on *in-situ* monitoring discussed in the next paragraph.

### 1.6.2 Requirements on monitoring

The discussion in the EU-FP7 project *MoDeRn* [MoDeRn, 2011, 2013a, 2013b, 2013c] shows that long-term monitoring under harsh environmental conditions as prevail in a geological disposal facility is currently technically challenging. A larger number of technical requirements for *in-situ* monitoring in waste disposal facilities are identified in [Modern, 2011]. These can be arranged in three interrelated groups of requirements, which, however, are all less stringent in case of monitoring of a demonstrator:

- requirements related to the preservation of safety functions
- requirements related to the specific environmental conditions present
- requirements related to the required performance of the monitoring equipment

The first group of requirements is mainly related to the fact that in an *in-situ* situation, many sensors are expected to be located behind barriers, i.e. borehole seals or plugs. The general consensus that monitoring should not impair the safety function of these barriers [MoDeRn, 2011 & 2013c] leads to a need of suitable wireless or ‘non-intrusive’ monitoring technologies (e.g. borehole tomography [Manukyan, 2011; Marelli, 2011]). These requirements are only of relevance for demonstrators if constructional aspects are involved.

The second group of requirements is related to the harsh environmental conditions the monitoring equipment must withstand over long periods (several decades). Under *in-situ* conditions, often no option exist to access the sensor (or other parts of the monitoring equipment) after emplacement in order to test, recalibrate or replace these. In case of deviating, “unexpected” results, it is important to be able to exclude failures of the monitoring system. Systematic approaches to failure detection were identified [MoDeRn, 2013b], and the ability to distinguish failure of the monitoring system from “unexpected” evolutions is essential for the usability of monitoring results for decision-making. Demonstrator monitoring allows accessing sensors or other components of the monitoring equipment for testing, recalibration or replacement more easily than in case of repository monitoring, which makes it easier to cover the aspects of reliability and failure detection. Requirements on reliability are easier met in demonstrator monitoring.

The third group of requirements is related to the performance of the monitoring components: the monitoring equipment and its set-up should be sensitive and accurate in order to allow distinguishing between ‘safe’ and ‘unsafe’ evolutions of the disposal. A proper description of the expected performance of a monitoring method is therefore necessary, including statements on sensitivity, accuracy, and precision under the given physico-chemical conditions, cross-sensitivities and possible correction methods, potential artefacts caused by the placement of sensors in a particular environment/location, and sensor reliability in the projected time interval. Demonstrator monitoring allows accessing sensors or other parts of the monitoring system for testing, recalibration or replacement more easily than in case of *in-situ* monitoring, potentially resulting in a higher performance of the used monitoring set-up.

## 2 Establishment of a generic PA demonstrator case

The primary goal of a performance assessment is to assess the performance of the disposal system as a whole and to evaluate the potential environmental impact. A PA involves large timescales and spatial domains and therefore can only be carried out through mathematical simulation of the potential evolution of the repository system. A PA model describes two main general processes:

- the evolution of the repository system and
- the radionuclide transport from the repository system to the biosphere.

These processes are quite comparable to the *primary* and *secondary safety functions* defined by SKB (Section 1.3).

### 2.1 Functional abstraction of plugs and seals

As discussed in Section 1.3, *safety functions* represent a useful tool in analysing the role of a repository component in terms of its contribution to the overall safety of the disposal system. They allow the abstraction of a disposal system for the purpose of PA calculations.

Focusing on the plugs and seals as investigated in DOPAS, the first observation is that safety function(s) attributed to an EBS component can change with time, and two main periods can be distinguished:

1. *period of full containment*, with a primary goal to ensure *favourable and stable* conditions,
2. *period after container failure*, with as primary goal to *prevent or otherwise minimize the transport of radionuclides* and other potentially hazardous substances within the repository and through the host rock.

#### ***Period of full containment***

The first period covers the interval from waste emplacement until the waste container fails. The main function of barriers during this period is related to the support of the containment function of the waste container, e.g. by keeping the backfill in place or by establishing favourable chemical and mechanical conditions for the waste container. For some designs it makes sense to distinguish other sub-phases during this period:

- **Period until full barrier performance is reached:** until the plug or seal has reached its final performance, e.g. full saturation of a bentonite seal or compaction of a salt plug, additional functions of the barrier may be of relevance. These might be related to operational safety aspects or to specific scenarios (e.g. early failure of container, flooding), or additional barriers and related safety functions may apply.

- **Period after which the barrier function is taken over by other components:** at a certain moment in time, other barriers may take over the function of a plug or seal. For example after closure of the facility, the upstream backfill may provide additional mechanical support to keep the backfill in place and may fully substitute the plugs function on the long term, when degradation and corrosion processes may lead to an impairment of the initial performance of a plug.

### *Period after container failure*

The second period starts from the moment the waste containment has failed, and radionuclides can migrate outside the container. The main function of the barrier in this period is related to delay the migration of radionuclides from the waste containers outside the disposal facility. e.g. by limiting the access of solutions to the waste or by avoiding advective solution movement. This could also include functions complementary to the previous period, e.g. keeping the backfill in place or providing suitable environmental condition to limit radionuclide solubility.

#### **2.1.1 Generic functional abstraction of plugs and seals during the period of full containment**

By definition, in the period of full containment no radionuclide migration takes place. This period is usually not modelled in detail in PA: often a predefined moment of container failure and eventually its probability distribution is applied. The predefined moment of container failure is based on external process models and -studies that support the conservative assumptions used in PA. Nevertheless, in order to identify processes relevant for the long-term safety and eventually monitorable parameters, it is necessary to provide a general functional abstraction of plugs and seals for the period of full containment.

In the most generic case, a plug or a seal consists of a constructional element (abutment) that keeps the downstream backfill in place. After closure, also upstream of the plug or seal a backfill is present that may take over the abutment function of the plug or seal on the long term. As part of the multi barrier concept, several sequential abutments can be applied, e.g. a plug for each disposal cell, upstream seals or dams to close access drifts, and shaft seals to isolate the overall disposal facility. Figure 2-1 provides a graphical representation of the simplified system.

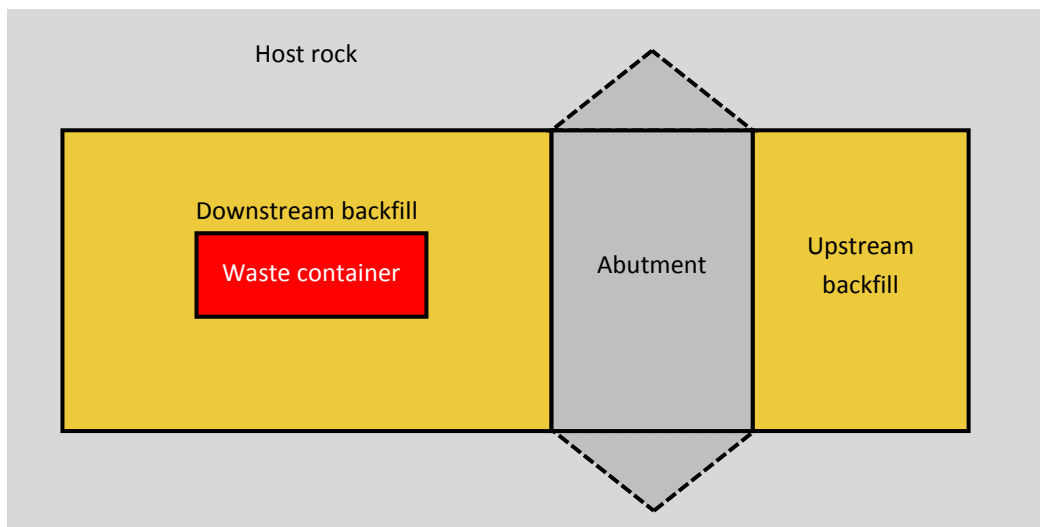


Figure 2-1: Simplified functional abstraction of seals and plugs during the period of full containment

In many cases, an additional, often watertight sealing element is added, resulting in the need of an additional abutment. Here, one or two concrete blocks and a sealing element are the main structural elements of a plug/seal (see Figure 2-2). Auxiliary components such as concrete walls or filters may be applied to facilitate the construction of the plug.

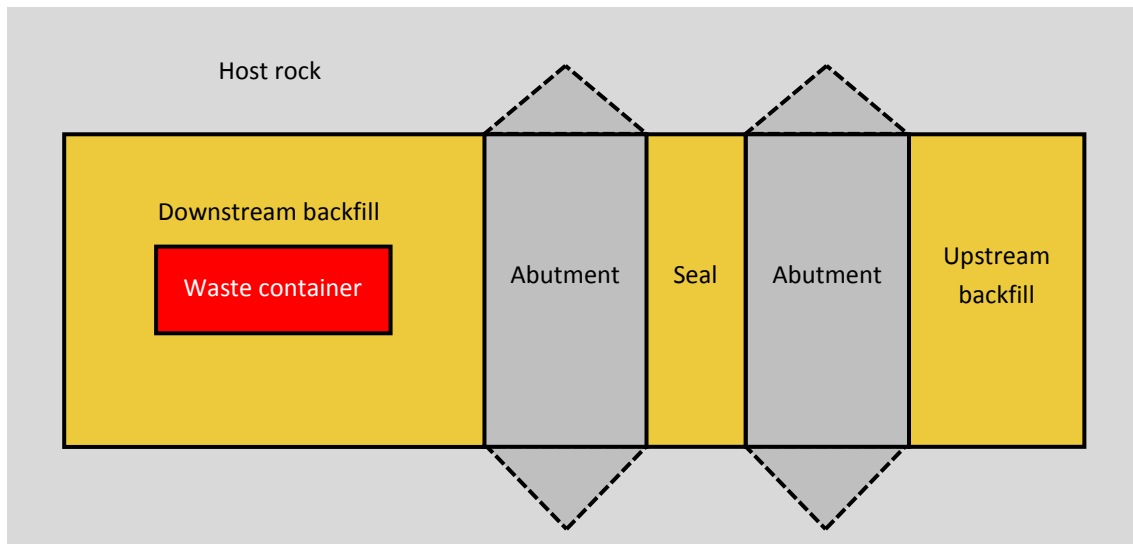


Figure 2-2: Generic design of a plug or seal with sealing function (based on *DOMPLU*, *POPLU*, *FSS* and *EPSP* plug designs)

The host rock has a significant impact on the design of the plugs and seals:

- The main function of the deposition tunnel plugs for repositories in *crystalline rock* is a mechanical one - to keep the backfill in place. The backfill on its turn ensures that no

advective transport of water and/or contaminated solutions takes place. The sealing element of the plug in this case has mainly the function to seal any cracks present in the concrete block and the space between the concrete block and the host rock, ensuring a low permeability of the overall plug construction until full saturation of the backfill is reached.

- The plugs developed for repositories in *argillaceous host rocks* have the main function to restrict water flow within the repository structure. The concrete blocks have the function of keeping the sealing element in place. The seal of the plug ensures low hydraulic conductivity (and by this solute transports within the repository structure by diffusion only) until the host rock and the backfill are (re)saturated and have reached their full hydraulic performance.

The functional periods of the plugs designed for repositories in granitic rock are shorter (~100 years) than the plugs designed for geological disposal in argillaceous formations and salt rock (~1000s of years).

The concrete block(s) have both mechanical and hydraulically functions: to keep the sealing element and/or backfill/buffer in place and to hydraulically isolate the repository structures until the bentonite elements of EBS are re-saturated and will have regained their hydraulic isolation properties. The concrete block(s) and the host rock serve as abutments for the sealing elements of the repository.

### **2.1.2 Generic functional abstraction of plugs and seals after failure of container**

After failure of a container, the waste matrix can get in contact with a solute, resulting in dissolution of radionuclides from the matrix. The modelling of the release of radionuclides from the waste matrix and their migration from the container to the biosphere, including estimations of the resulting exposure, is main purpose of PA calculations. Figure 2-3 shows a generic functional abstraction of a plug or a seal for that purpose. With respect to radionuclide migration, three principal routes exist on which these can leave the disposal system and enter the environment, eventually resulting in an exposure:

- through the plug or seal,
- through the excavation damage zone, and
- through the (undisturbed) host rock.

Dependent on the host rock, disposal concept and considered scenario, these three pathways can provide different contributions to the overall radionuclide release from the disposal, in some cases resulting in no relevant function of the barrier with respect to retardation.

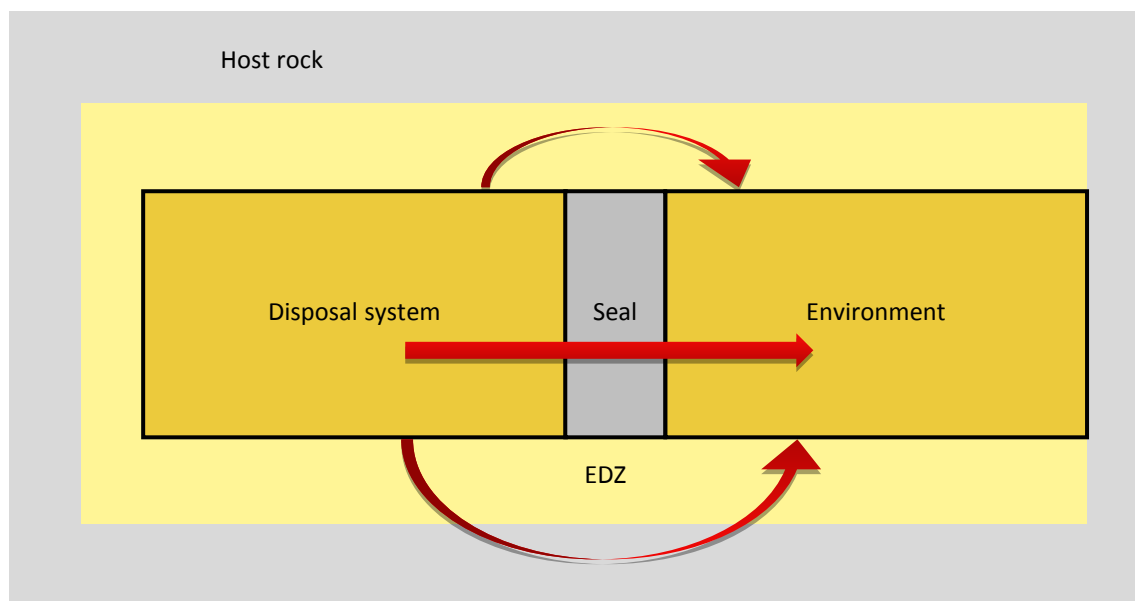


Figure 2-3: Generic functional abstraction of a plug or seals for performance assessment

In general, two migration processes need to be considered for the computation of radionuclide migration in PA:

- diffusion
- advection

Advective mass transport can relate to solutes and gas, and goes always in combination with diffusion (convective transport). In presence of a solute, diffusion is unavoidable and therefore represents the normal evolution for most disposal concepts. Advective mass transport is usually diminished by the barriers of a disposal concept as much as possible. Main features and processes necessary to quantify *diffusion related migration* in PA are:

- porosity of the barrier material,
- diffusivity of the radionuclides,
- sorption of radionuclides, and
- solubility of radionuclides.

Main feature in order to quantify *advective transport* in PA are:

- gas and solute permeability of the barrier material,
- pressure gradient over the barrier,
- sorption of radionuclides, and
- solubility of radionuclides.

Figure 2-4 summarizes the main processes for the assessment of radionuclide migration in PA, and the most relevant features and processes that are usually accounted for. These features and processes are determined by system specific, underlying processes and parameters, which do not necessary have to be part of a PA model. The underlying processes and parameters are characteristic for the considered disposal concept and host rock. Understanding of these underlying processes and parameters is of relevance, because most of the parameters used in PA are not directly measurable, i.e. indirect measurements need to be combined with process models and/or measurements performed in supporting experimental studies.

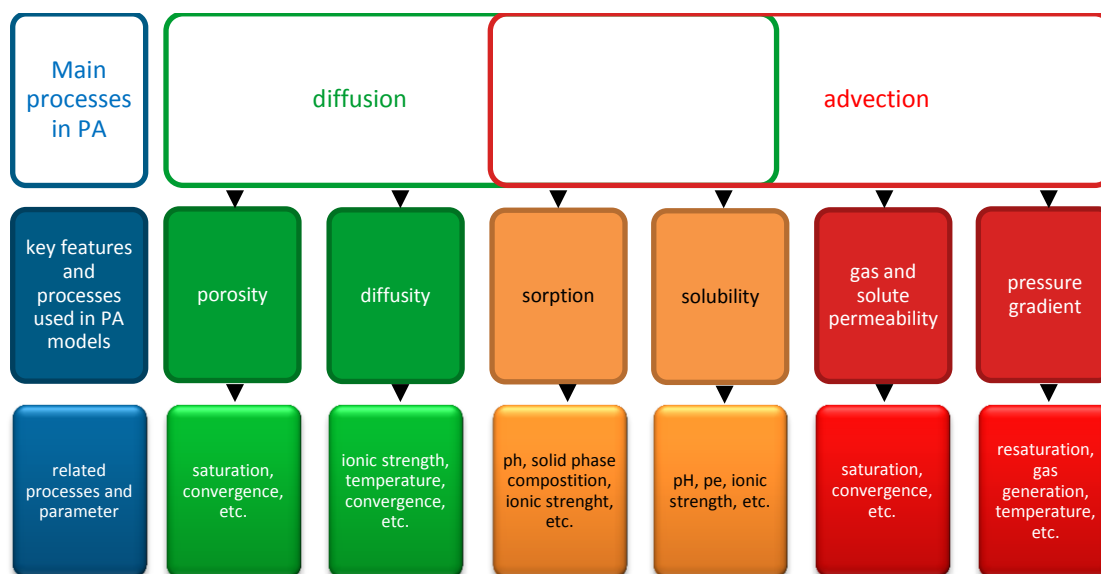


Figure 2-4: Main processes for the assessment of radionuclide migration in PA, key features and parameters, and underlying relevant processes and features

The main processes covered by PA, diffusion and/or advection, the related parameters and their “monitorability” will be more closely reviewed in the next section. The section concludes by some examples on how underlying processes and parameters can be linked to the parameters used in PA modelling.

### 2.1.3 Key processes for migration modelling

As discussed in the previous section, there are two main mechanisms of mass transfer: diffusion and advection.

#### **Advection**

Advective transport describes the movement of some quantity via the bulk flow of a fluid. An advective movement of liquids within the repository and/or host rock is possible in fractures and fissures and is determined by the *permeability* (or *hydraulic conductivity*) and *pressure gradient*



within the system. The advective transport may be minimized by achieving a low hydraulic conductivity within the system. In this case diffusion becomes the principal transport process.

A radionuclide may be present in both dissolved (solution) and gaseous form. At low concentrations the gas molecules will be in solution and will be transported, like the dissolved species, by advection and diffusion. A discrete gas phase may be formed and if the pressure of the gas phase becomes sufficiently high, gas will enter the engineered barrier or the host rock. In this case the movement of gas will take place by two-phase flow.

The transport of radionuclides with the bulk flow is dependent on the soluble fraction of radionuclides, usually determined by the *solubility* of the radionuclides and their *sorption* to the solid phase. Permeability's of EBS components often decrease in time, due to convergence (rock salt) or (re)saturation (bentonite). After resaturation is reached, pressure gradients over barriers also tend to decrease in long term. However, gas generation due to corrosion processes may increase local pressures.

*Pressures* (pore, swelling or total pressure) are relatively easy to measure *in-situ* or in demonstrators. The *hydraulic conductivity* on the other hand is difficult to measure *directly* in other than in laboratory conditions, but can be determined *indirectly* by measuring other features or parameters and link these to the hydraulic conductivity by suitable process models. E.g. the hydraulic conductivity of swelling clays depends strongly on the density of the component made of swelling clay. Although the density is not directly measurable *in-situ*, it is possible to estimate the evolution of this parameter by balancing the mass of the swelling clay in the system (initially installed density, losses by erosion caused by leakages, volume changes caused by displacements within the system) or by the measurement of the swelling pressure which is dependent on the dry density of the swelling clay.

The transport of radionuclides by both diffusion and advection is related to the soluble fraction of radionuclides either dissolved or bound to soluble colloid particles, with the fraction of dissolved or soluble radionuclides depending on the physico-chemical properties of the matrix of the EBS component, host rock or geosphere. The main parameters characterising the chemical behaviour of radionuclides are:

- The *solubility limit* representing the maximum concentration of a nuclide present in the aqueous phase,
- The *sorption behaviour*, often expressed as  $K_d$ -value, representing the interaction of a nuclide with the solid phase.

Both properties can be determined *a priori* by laboratory or in-situ experiments in URLs, covering all chemical conditions expected during the evolution of the waste disposal and enclosing environment.

### ***Diffusion***

Diffusion represents the net movement of particles from a region of high concentration or high chemical potential to a region of low concentration or low chemical potential. From the atomistic point of view, diffusion is the result of the random walk by their thermal energy. Diffusion results in mixing or mass transport, without requiring bulk motion. The key parameter *porosity* and *diffusivity*, which describe the migration of radionuclides through diffusion, are often expressed in PA as:

- *diffusion accessible porosity*, which is the total physical space available for transport of a nuclide, and
- *pore diffusion coefficient* for a particular condition.

Their magnitude is influenced by factors such as temperature, anisotropy, degree of compaction and/or confinement pressure, pore water chemistry, and ionic strength. Some of these factors (e.g. temperature, pressures) are measurable in demonstrators and/or *in-situ* conditions, and can be used to estimate the evolution of the diffusion related parameters by making use of dependencies established *a priori* in laboratory experiments. However, even if *porosity* and *diffusivity* can be measured indirectly, such measurements cannot be performed in the time period of interest, i.e. after container failure, usually expected after ten thousand years or more.

The mass transport of soluble radionuclides within a repository and through the host rock by diffusion can only be completely avoided in the absence of a soluble phase. Even then, after container failure mass transport may occur via gas phase. From the different disposal designs considered in DOPAS, considering the absence of a solution phase is only of relevance for the disposal concept in rock salt: rock salt is practically impermeable to gases and liquids having a porosity of about 1%, with permeability values around  $10^{-19} \text{ m}^2$  or even lower<sup>4</sup>.

#### ***2.1.4 Link between key processes in PA and underlying process models***

As discussed in the previous section, most of the parameters used in PA are not directly measurable. However, a combination of indirect measurements with process models and/or measurements performed in supporting experimental studies can link measurable parameters with the parameters of interest for the PA (Figure 2-4).

Figure 2-5 give an example for such a link: it depicts the porosity-permeability relation of a compacted salt grit plug used to seal disposal cells in rock salt: the grey diamonds show measured data, and the black line depicts 1000 porosity-permeability relations based on calibrated process models and the parameter distributions used for PA.

<sup>4</sup> eventually, a break-down of the pore-network may occur, leading to impermeability of the rock salt

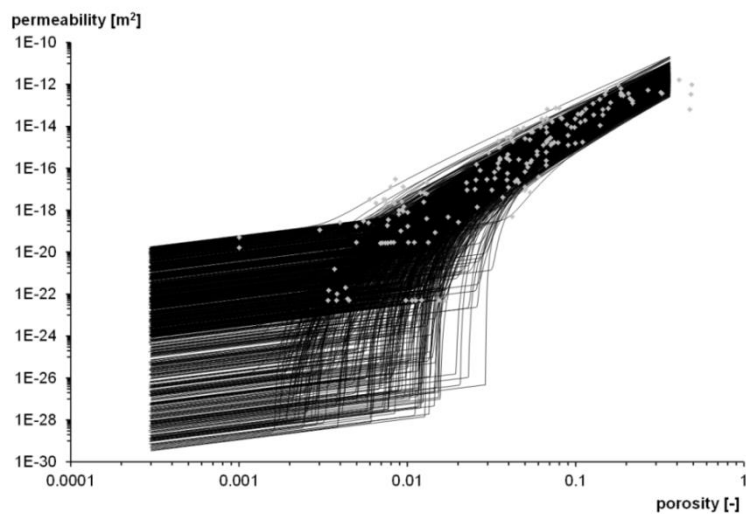


Figure 2-5: Measured porosity-permeability relation of compacted salt grit (grey diamonds) and sample realizations of the relation based on a calibrated model and its parameter distribution (based on Schröder *et al.*, 2009b)

Figure 2-6 and Figure 2-7 show the evolution of respectively the hydraulic conductivity (here expressed as permeability) and the stress of the plug material as function of time. The figures are based on the porosity-permeability relations in Figure 2-5 and a calibrated process model for the pressure-dependent creep of the salt grit, computing the compaction of salt grit as result of interaction of convergence, pressures, strain rates and porosity<sup>5</sup>. The numerical uncertainty of the related process parameter (see Table 3-4) is included in the analysis and results in the depicted parameter evolutions.

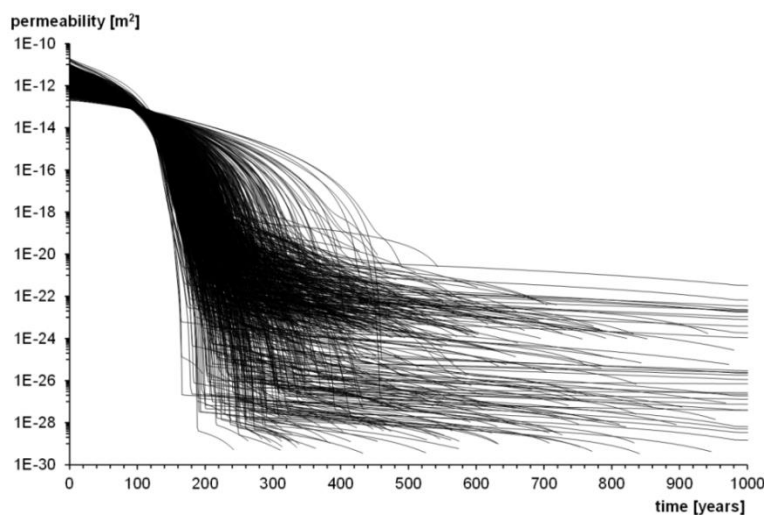


Figure 2-6: Evolution of the permeability of a salt grit plug (based on Schröder *et al.*, 2009b)

<sup>5</sup> for more information on the porosity-permeability relation and the creep behaviour of salt grit see (Schröder *et al.*, 2009b) and Section 3.2.

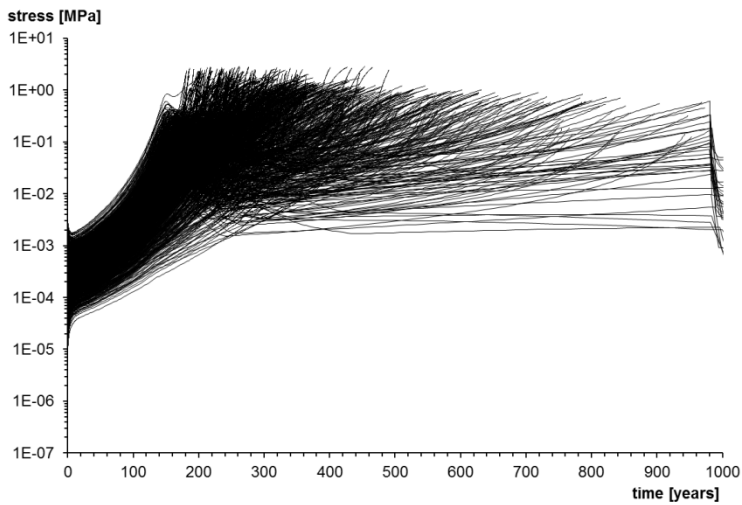


Figure 2-7: Evolution of stress in a salt grit plug (based on Schröder et al., 2009b)

While the *permeability* and *porosity* as parameters of interest for the PA are not direct measurable, they can be linked by process models to the stress in the plug or the pore pressure (not shown), which are in principle measurable.

Monitoring data might be used for calibration of the process models, in order to decrease the *a priori* assumed numerical uncertainties and resulting parameter distribution. However, because the relation between permeability and stress is time dependent (Figure 2-8), any interpretation of monitored data requires access to the process model calculations.

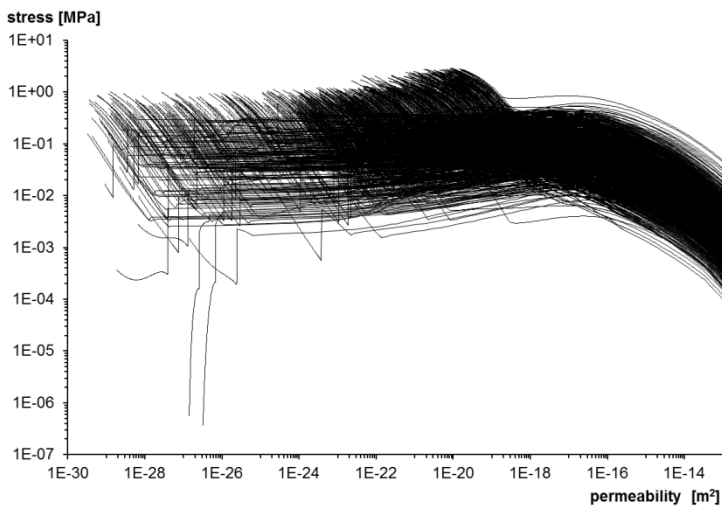


Figure 2-8: Relation between permeability and stress in a salt grit plug for the calculated time interval (based on Schröder et al., 2009b)

## 2.2 Definition of indicators

Based on the considerations in the previous section, this section discusses several indicators related to radionuclide migration, which are of interest because these are directly or indirectly measurable in demonstrators, and thus provide - direct or indirect - information on the total system behaviour.

### 2.2.1 Hydraulic conductivity

The *hydraulic conductivity* is, as discussed in Section 2.1.3 and 2.1.4, a key feature with respect to the assessment of advective radionuclide transport. The hydraulic conductivity in seals and plugs usually decreases in time, either by saturation in case of swelling clay or by creep in case of rock salt grit. Low permeability is linked to low porosity, and thus provides a measure of the performance of a plug. Eventually, permeability can be so low that diffusion is becoming the leading process for radionuclide migration. The ratio of advective vs. diffusive transport represents another useful indicator for PA: the *Péclet number*, which will be discussed in the next section.

### 2.2.2 Péclet number

The *Péclet number* provides a good indication of the hydraulic regime in the engineered structures of the repository by showing the ratio between the characteristic times of diffusion and advection and is used e.g. by Andra to determine the transport regime in the engineered structures of the repository as follows [Andra, 2005]:

$$Pe = (T_d/T_c) \quad \text{Eq. 2-1}$$

with

$T_d$  characteristic migration time by diffusion [a]

$T_c$  characteristic migration time by advection [a]

and

$$T_d = L^2\omega/D_e \quad \text{Eq. 2-2}$$

and

$$T_c = L\omega/K \cdot \nabla H \quad \text{Eq. 2-3}$$

with

$L$  migration distance [m],

$\omega$  total porosity in the backfill of the drift [-],

$D_e$  effective diffusion coefficient in the backfill [m<sup>2</sup>/a],

$K$  permeability of the backfill [m/a],



$\nabla H$  the hydraulic head [m/m] in the drift, calculated from simulations in homogeneous media.

The Péclet number expresses the ratio between advection and diffusion: at low values of the Péclet number ( $<1$ ) the hydraulic regime is dominated by diffusion (Figure 2-9). The Péclet number calculated for a natural or engineered barrier does not indicate the rate at which each type of transport takes place, and give no direct indication of the performance or related risks. However, it can be used to establish if the barrier acts in favourable conditions or not, assuming that diffusion is unavoidable.

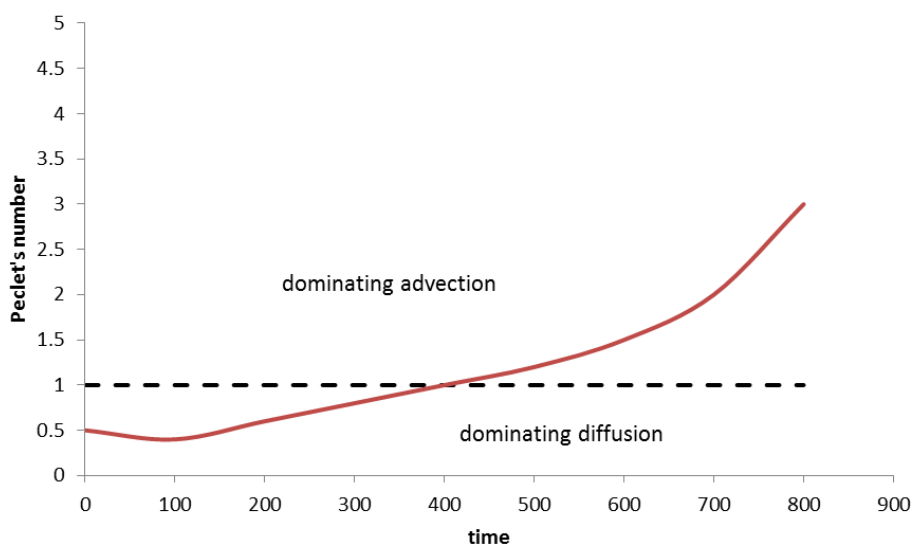


Figure 2-9: Indicator based on Péclet number. In case the indicator is  $<1$ , diffusion is the dominating process for radionuclide diffusion. Because diffusion of radionuclides released from the waste will always occur in saturated porous media, this can be considered as covered by the normal evolution scenario.

The Péclet number provides more information than the hydraulic conductivity, because it integrates a number of relevant system properties (Eq. 2-2 to Eq. 2-4) and is a more preferable indicator because it provides more direct information (Figure 2-10).

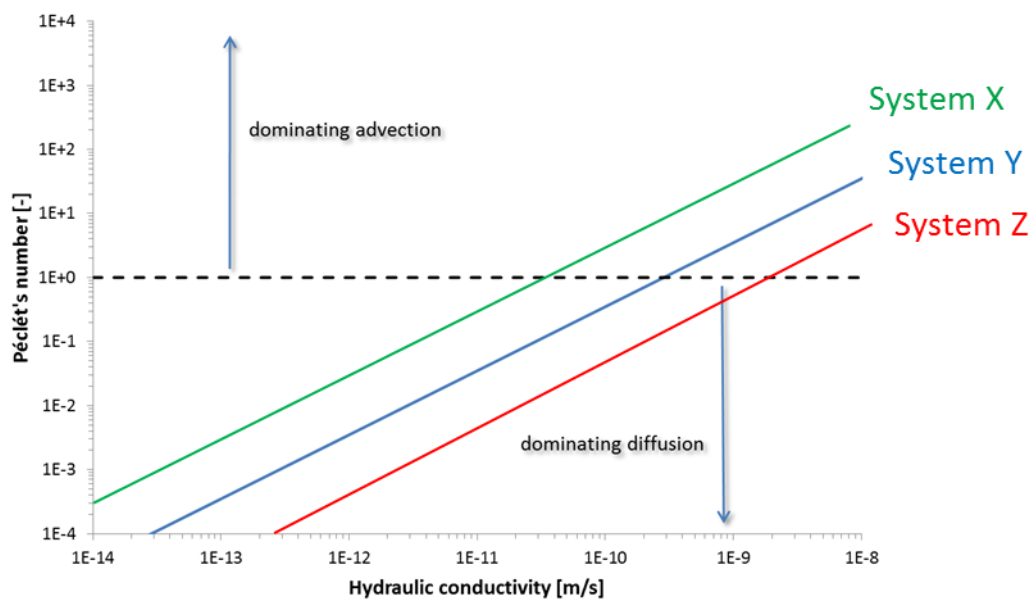


Figure 2-10: Péclet number vs. hydraulic conductivity for different systems. For different systems, different hydraulic conductivities define the transition from an advection to a diffusion dominated system. For the Péclet number, this happens always at  $Pe = 1$ .

A comparable approach is used by SKB (SKB, 2006b) to approximate under which conditions transport by flow is more important than diffusive transport:

$$D_e / \Delta L < ki \quad \text{Eq. 2-4}$$

Where:

- $D_e$  the effective diffusivity,
- $\Delta L$  the transport length,
- $k$  the hydraulic conductivity,
- $i$  the hydraulic gradient.

A comparable indicator that makes a distinction between the advective and diffusive transport is used by Andra. The *advective and diffusive flow indicator* provides a comparison of the advective and diffusive flows in the clay enclosing the repository (Figure 2-11).

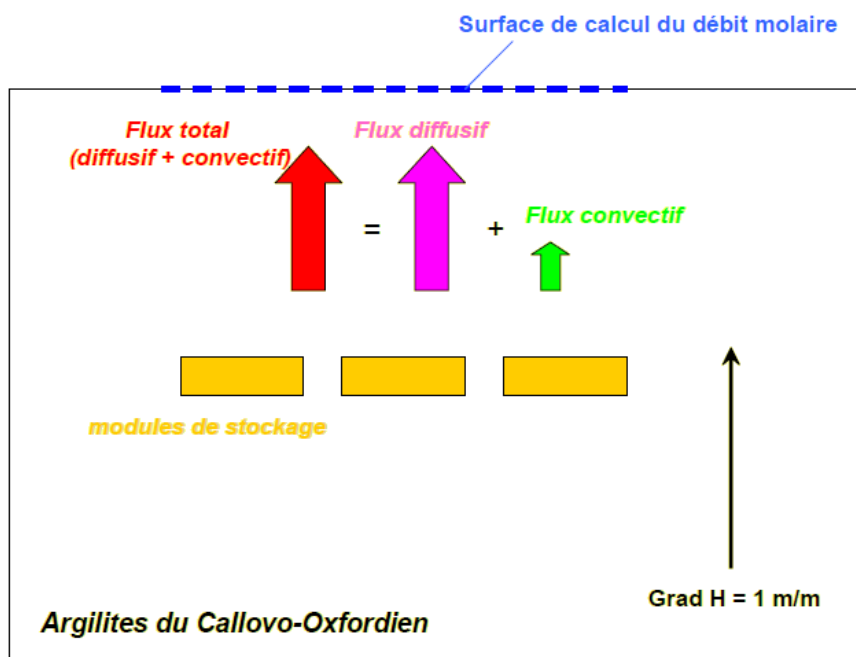


Figure 2-11: Distribution of advective and diffusive transport paths (from [Marivoet *et al.*, 2008, p. 362])

In case of the concept evaluated by Andra, it was argued that for  $i = 10^{-2}$ ,  $D_e = 10^{-12} \text{ m}^2/\text{s}$ , and a buffer thickness  $\Delta L$  of 0.35 m requires that  $k$  has to exceed  $3 \cdot 10^{-10} \text{ m/s}$  before transport by advection predominates.

### 2.2.3 Travel-time based indicator

Radionuclide breakthrough curves in a disposal system in Boom Clay depend on a number of factors, with as most relevant parameters the radionuclide inventory, the half-life of the radionuclides, and their sorption to the host rock and EBS components made of bentonite. However, from a calculated breakthrough curve it is not always apparent which factors are the most influential. As part of the EU project PAMINA, NRG developed a travel-time based indicator [Schröder *et al.*, 2009a] that supports the understanding of the relevance of barrier features and processes for the long-term safety of a disposal system, by visualizing the evolution of the repository with the three most important variables in a single graph.

Figure 2-12 shows the indicator in its most complex visualisation, mainly meant for geochemists and PA experts. However, the main message is simple: if the radiotoxicity is below the calculated normalized breakthrough curve, the reference value of the considered indicator is met.



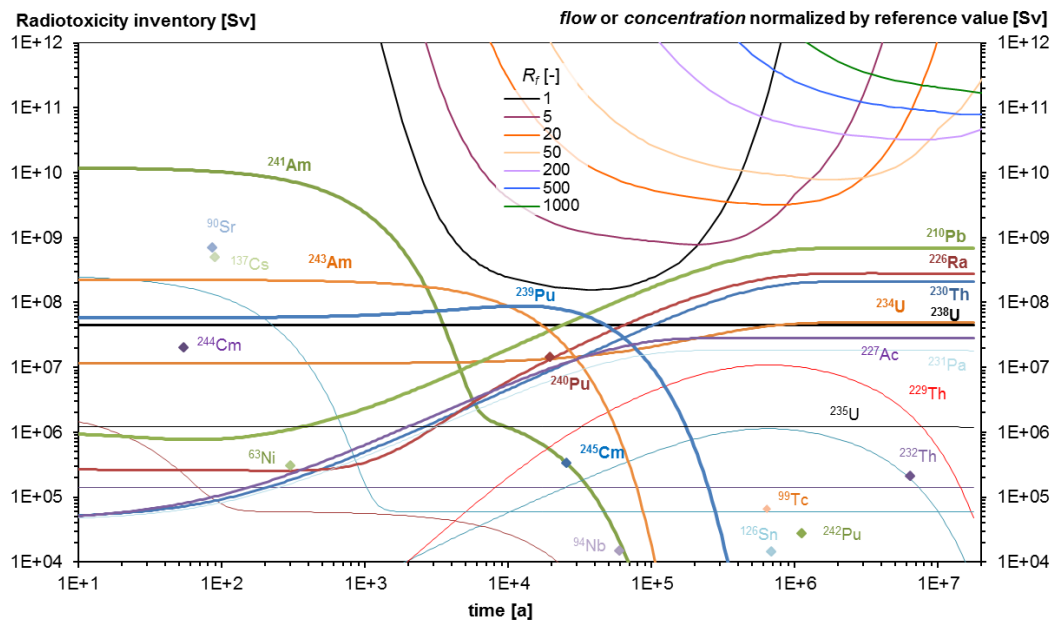


Figure 2-12: Representation of the travel-time based indicator developed by NRG

This type of indicator can be applied with all safety functions considered, and can be either flow or concentration related (e.g. *dose rate in the biosphere*, *radiotoxicity concentration in groundwater*, *radiotoxicity flow to biosphere*). Normalised breakthrough curves (Figure 2-13) represent the *upstream side* of a barrier and can be computed independently, without any knowledge of waste inventory (Figure 2-14). The indicator can be calculated for all scenarios of interest and, in principle, can be applied to other systems, too. The computer models that are used to calculate the breakthrough curves thus do not need to have a sub-model incorporated that account for radionuclide decay (chains). Dependent on the system of interest, other parameters can be varied (e.g. hydraulic conductivity, porosity), or several scenarios can be combined for comparison in a single graph.

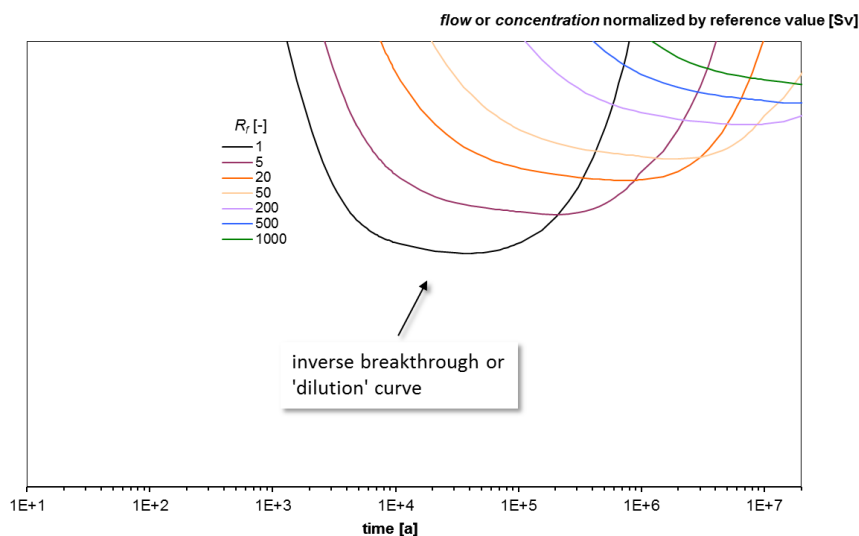


Figure 2-13: Normalized breakthrough curves.

The evolution of the radiotoxicity inventory represents the *downstream side* of the barrier, e.g. the radionuclide inventory of a waste canister as shown in Figure 2-14. It can also be used to depict the radiotoxicity evolution in a compartment downstream of the barrier of interest (see Section 3.5 for an example case).

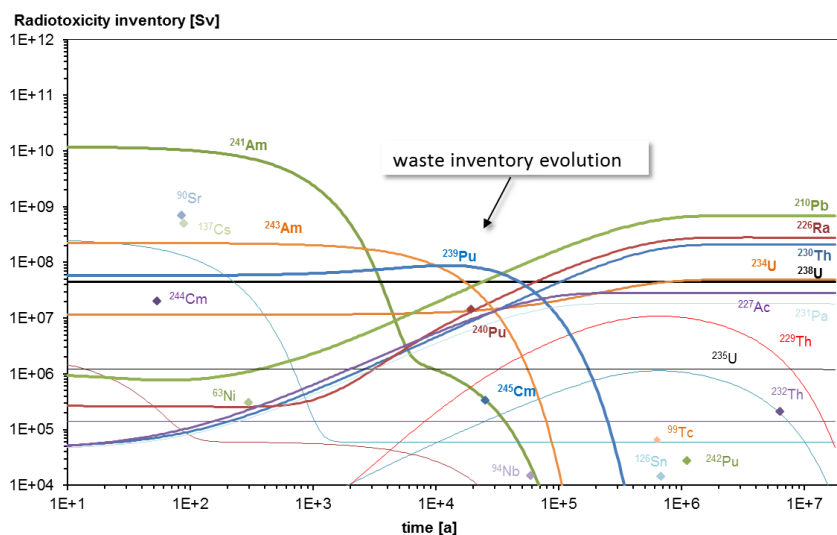


Figure 2-14: Radiotoxicity evolution of the inventory.

The principle usefulness of the travel-time based indicator representation for the analysis of the performance of plugs and sealing systems is evaluated in a case study in Chapter 3. In order to do so, the indicator representation is refined for the system of the case study.

### 2.2.4 Integrated amount of brine inflow

An indicator based on the integrated amount of brine inflow was calculated by GRS [Rübel *et al.*, 2016]. This *integrated amount of brine inflow* permits the representation of sealings in integrated performance assessment models for radioactive waste repositories in salt. It shows the cumulative brine inflow through the sealing until the sufficient high compaction of the crushed salt in the access drifts of the repository becomes the main quantitative performance requirement of the permeability of the shaft sealing.

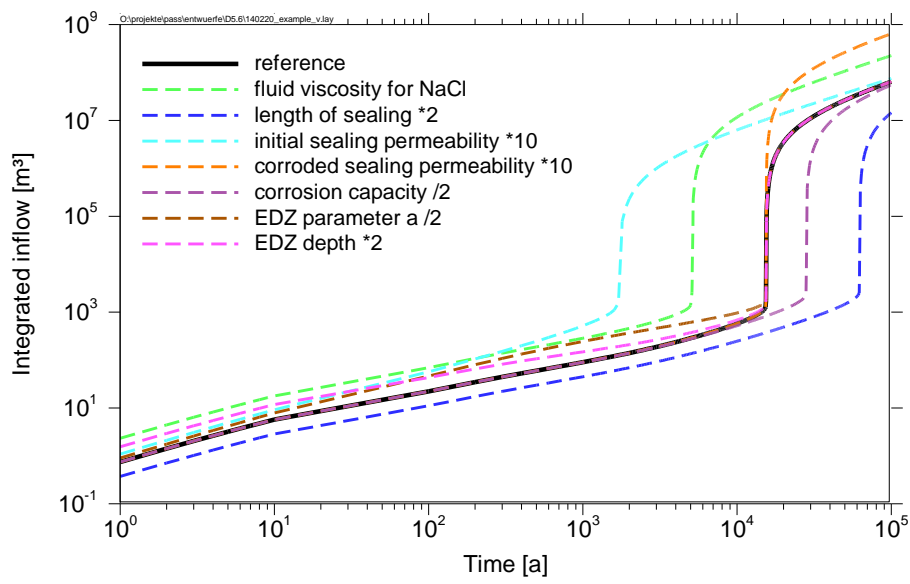


Figure 2-15 Integrated amount of brine inflow (from [Rübel *et al.*, 2016])

## 2.3 Analysis of the relevance of indicators, processes and parameter for the long-term safety

In order to set technical and monitoring priorities, it is important to understand the relevance of potential parameters for the system behaviour and the long-term safety [MoDeRn, 2013c]. *Performance indicators related to safety functions* were used in *PAMINA* to quantify the contribution of a safety function to the overall safety [Becker *et al.*, 2009]. They can be computed for each scenario, including altered scenarios that are part of the safety case (e.g. subsrosion, earthquake, abandonment, human intrusion, early failure).

Specifying such an indicator on barrier level rather than on safety function level allows evaluating the relevance of each component of a multi-barrier system in more detail, and potential failures modes of EBS components can serve for the identification of additional “*what-if*” scenarios. These synthetic “*what-if*”-scenarios or ‘*Design-Based-Accident*’ type of analyses assume systematic (fictional) failures or inadequate performance of barriers components. They allow analysing e.g. the influence of a poor performance of a plug on displacement, permeability, porosity & density of backfill & buffer, (local) erosion of backfill & buffer, and effects on canister corrosion.

Figure 2-16 shows an example of the contribution of a borehole plug for a disposal concept in rock salt (denoted as “*R2-RT*”), for a generic scenario of a flooding event as result of abandonment, with the additional assumption of instant failure of HLW container with vitrified waste (Schröder *et al.*, 2009b)<sup>6</sup>. The indicator presents a kind of “risk dilution factor”, i.e. a low value represents a large contribution to the safety, and a value of one indicates no contribution to the safety at all.

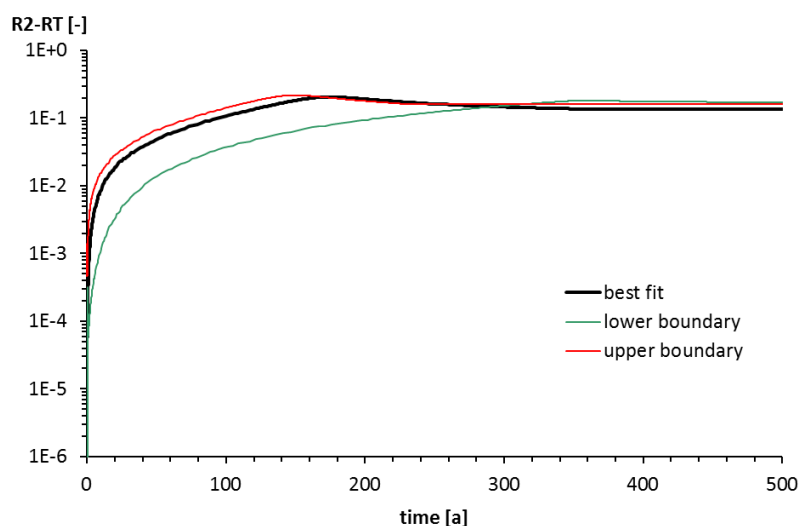


Figure 2-16: Performance indicator related to the safety function “*R2-RT*” of a borehole plug for three parameter sets (based on Schröder *et al.*, 2009b)

<sup>6</sup> see also Section 2.1.3 and Chapter 3 for further information

Figure 2-17 shows the relative contribution of the plug to the overall safety. For this synthetic scenario, the contribution of the plug to the overall safety is small (<0.1%), compared to e.g. the dilution and decay of radionuclides in the geosphere.

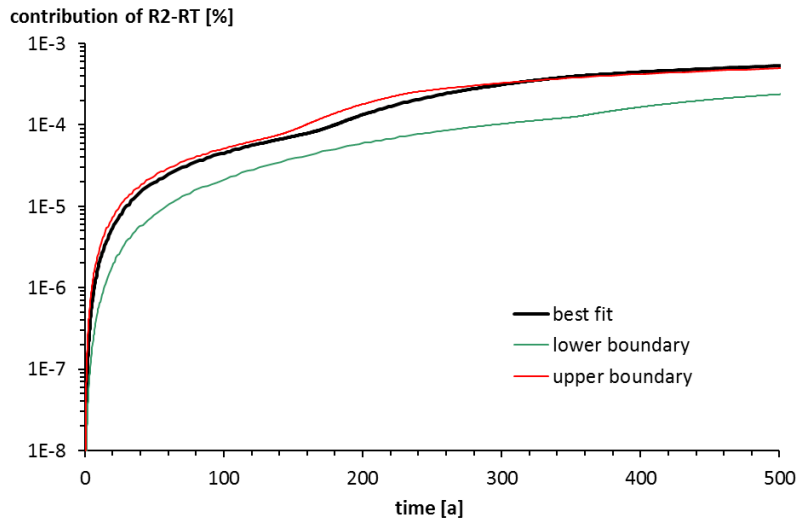


Figure 2-17: Relative contribution of the safety function ‘R2-RT’ of a borehole plug to the overall safety for three parameter sets (based on Schröder *et al.*, 2009b)

Next to the analyses of *performance indicator related to safety functions* on barrier- and component level, *sensitivity-* and *uncertainty analyses* allow for analysing barrier functions on process- and parameter level, hence allowing the link with monitorable entities. Figure 2-18 shows an example of more detailed uncertainty analyses of the behaviour of the borehole plug discussed above.

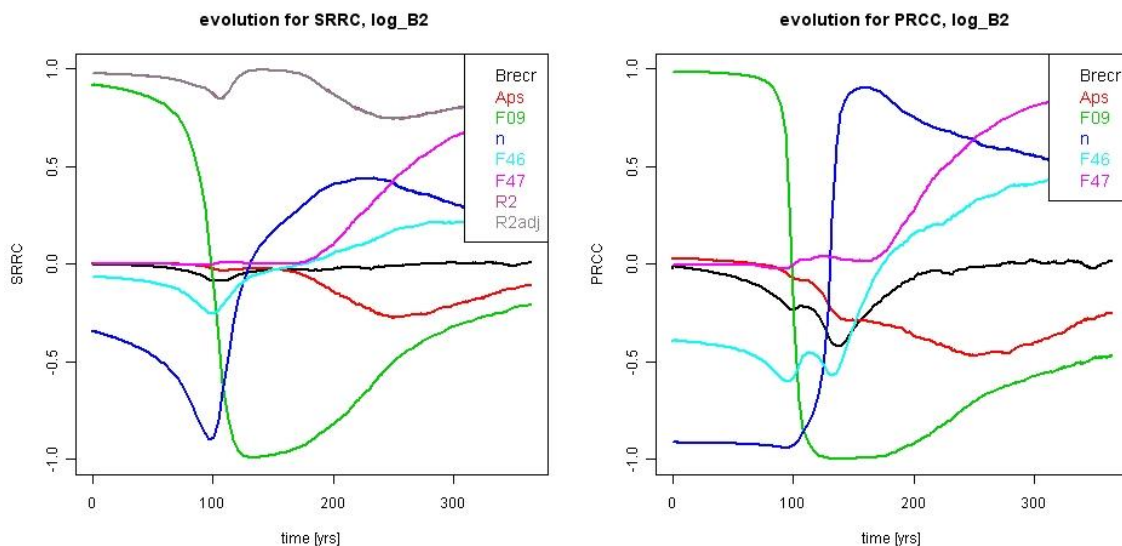


Figure 2-18: Standardized rank regression coefficients (SRRC), partial rank correlation coefficients (PRCC), and the adjusted coefficient of determination  $R_{adj}^2$  for the performance indicator ‘permeability of the plug’ (Schröder *et al.*, 2009b)

It depicts the evolution of the *standardized rank regression coefficients (SRRC)*, the *partial rank correlation coefficients (PRCC)*, and the *adjusted coefficient of determination ( $R^2_{adj}$ )* for the performance indicator ‘*permeability of the plug*’. This indicator provides information on the process model parameters that are most influential for the permeability evolution of the borehole plug. Figure 2-19 provides the same statistical indicators for the safety indicator ‘*dose rate in the biosphere*’.

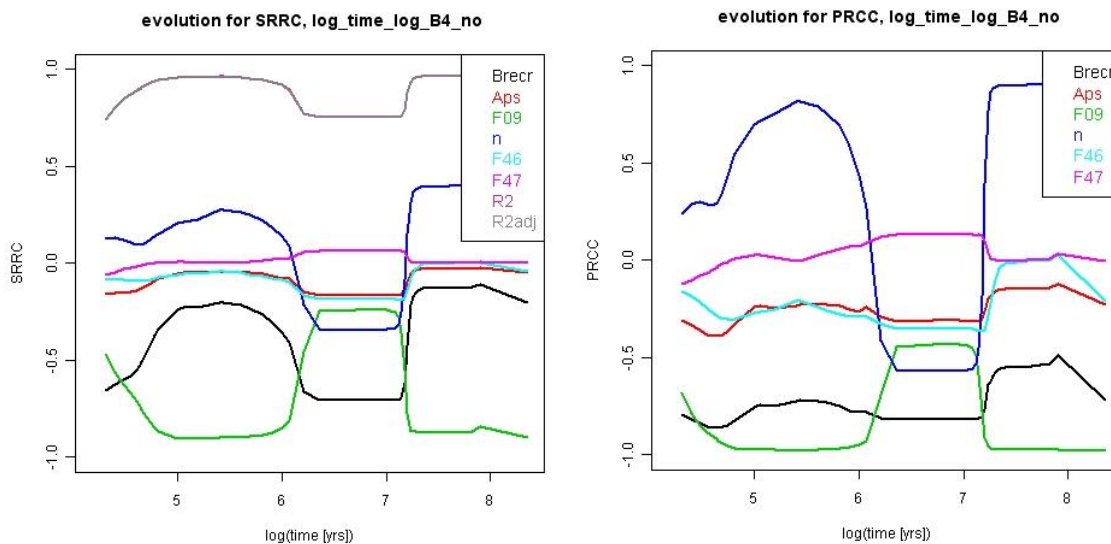


Figure 2-19: Standardized rank regression coefficients (SRRC), partial rank correlation coefficients (PRCC) , and the adjusted coefficient of determination  $R^2_{adj}$  for the safety indicator ‘*dose rate in the biosphere*’ (Schröder et al., 2009b)

The figures show that some of the parameters are of little relevance for the evolution of the plug’s permeability at any time step. But they also points out that the underlying processes are interacting in a complex manner, leading to varying influence of model parameters on the permeability of the plug or dose rate in the biosphere as time progresses.

Figure 2-20 summarizes how *performance indicators related to safety functions* and statistical uncertainty analysis can be used in a systematic approach for the quantification of the relevance of barriers, barrier components, and their underlying process models and parameters on the overall safety for a variety of scenarios and assumptions.

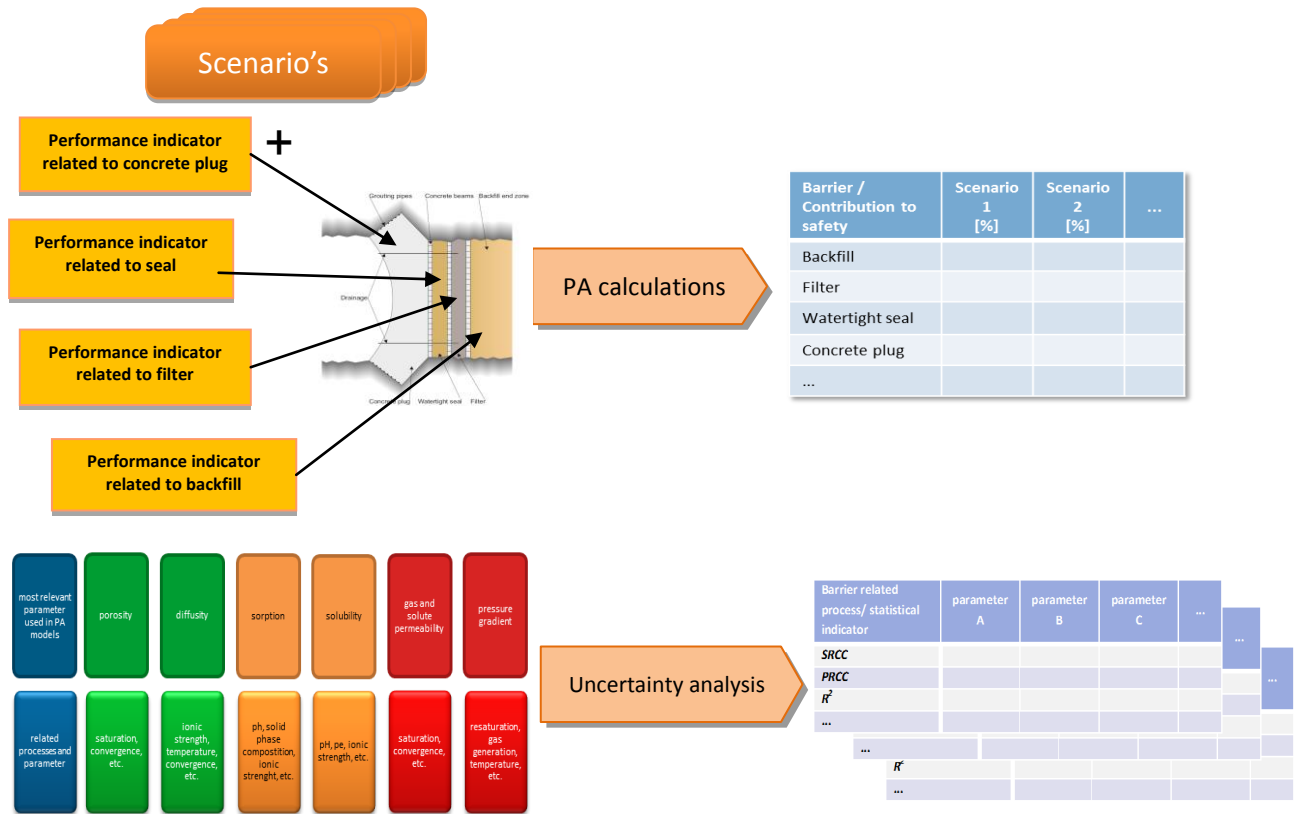


Figure 2-20: General approaches to access the relevance of individual barrier elements and the related processes and parameter on the long-term safety

## 2.4 Synthesis: indicator analysis workflow

Based on the considerations and analyses presented in the previous sections, a stepwise approach is proposed in order to identify indicators and evaluate their monitorability:

- In a first step, the general properties of the disposal concept, and the related safety functions, FEPs, considered scenarios, and - if available - existing indicators and criteria related to the barrier of interest have to be analysed. Appendix A provides some examples of such analyses for the demonstrators considered in DOPAS, based on the information provided in the project.
- In a second step, key features and processes, and the system-specific underlying processes and parameters have to be established. In case of advective determined transport, the key features are the hydraulic conductivity, porosity, and the expected pressure gradient, all of which are not directly monitorable. This raises the need to understand the underlying processes and parameters that provide additional options for monitoring. Besides, the understanding of the underlying processes is necessary to set up a PA representation of the barrier of interest.
- In a third step, potential indicators and the related parameters are evaluated. This is mainly based on a screening of the indicators discussed in Section 2.2, and the system-specific underlying processes and parameters.
- In a fourth step, the relative contributions of diffusive and advective processes to the overall mass transport of radionuclides is estimated, e.g. by determination of the Péclet number. This allows reducing the number of processes to be investigated and represented by the PA model. Furthermore, the relevance of the barrier of interest for the overall safety can be deduced by relevance based indicators. These indicators can be used to establish for each scenario in which time interval a barrier contributes relevantly to safety, allowing a further breakdown of the processes of relevance into underlying processes and parameters, supplemented by uncertainty analyses.
- In the last step, the technical feasibility to monitor the parameters of interest has to be investigated. Part of that investigation is to perform uncertainty analyses in order to (1) establish the relevance of each feature or parameter to the overall performance of the barrier, and (2) to define requirements for performance of the monitoring set-up. The latter is necessary to be able to evaluate the feasibility to provide significant evidence by monitoring on the long term evolution of the barrier of interest, within the (limited) period when monitoring can be performed.

The developed overall methodology is summarized in Figure 2-21 and will be tested in a case study in Chapter 3.



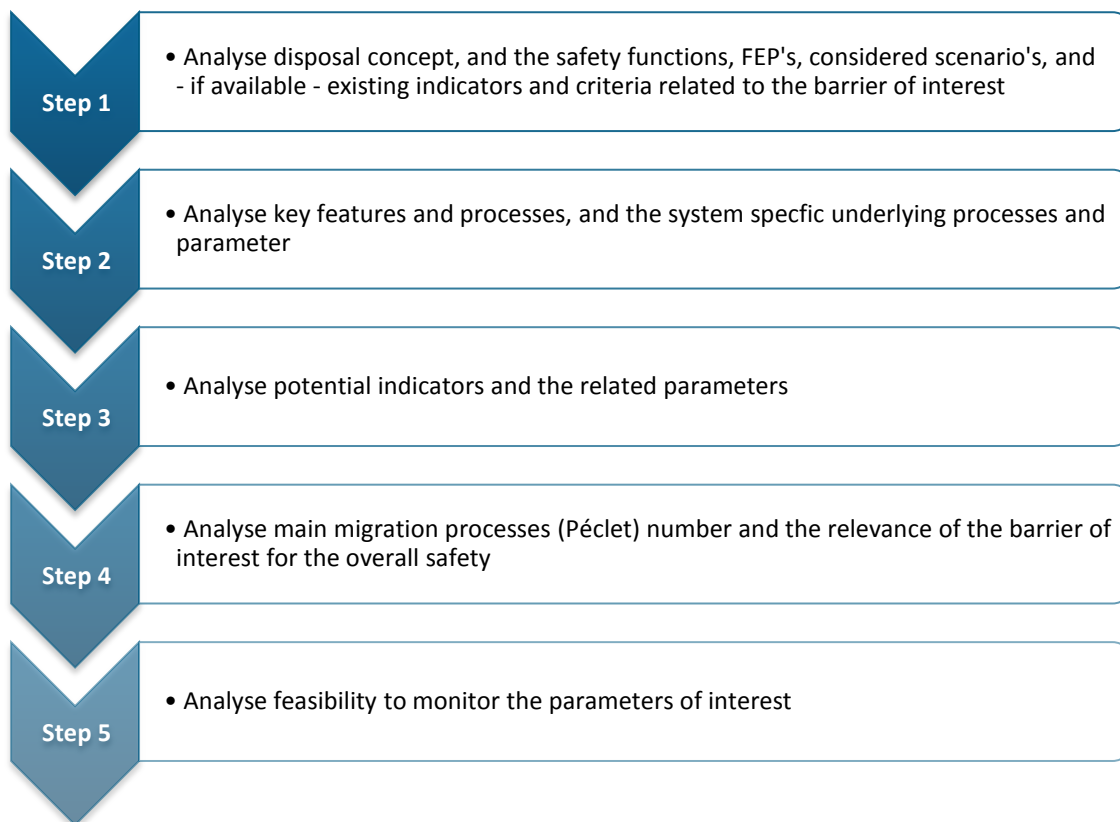


Figure 2-21: Proposed indicator analysis workflow



### 3 Example PA demonstrator case: *ELSA* shaft sealing

For assessing potential evolutions in time of the indicators discussed in the previous chapter, a case study for a generic demonstrator PA was performed, based on the workflow depicted in Figure 2-21. That case study is documented in the remainder of this chapter and is based on the *ELSA* shaft sealing investigated by GRS: GRS developed a PA model as part of the DOPAS project, in order to assess the performance of the *ELSA* shaft sealing concept by utilizing the *LOPOS* computer tool [Rübel *et al.*, 2016]. The main objective of the *LOPOS* simulations was to assess the amount of brine inflow through the different shaft layers into the model repository, given the situation of brine presence on top of the shaft.

In a first step, disposal concept, safety functions, FEP's, considered scenarios, available existing indicators and criteria related to the shaft seal were screened. A general overview of the disposal concept, the shaft sealing concept, and the related safety functions, FEP, and scenarios can be found in Appendix A.3.

The safety function allocated to the shaft is “sealing against water” [MoDeRn, 2013b]. In [MoDeRn, 2013b], two scenarios with respect to the performance of seals and dams were identified:

- Early failure of the shaft seal;
- Early failure of dams that seal connecting galleries.

Early failure or reduced performance of a shaft seal or dams can manifest itself as follows:

- Increased permeability of the sealing elements;
- Increased permeability of the surrounding of the sealing elements;
- Decreased stability of the structures involved;
- Reduced retardation capability of the sealing elements;
- Reduced lifespan of the sealing elements.

A failure or reduced performance of the shaft seals or dams can be indicated by the inflow of brine through the shaft into the repository. In that case, alternative readouts of monitoring equipment can be expected:

- The stress and pressure evolutions measured on opposite sides of the shaft seals provide information on the seals performances;
- The convergence of backfilled drifts may be affected so that displacements occur, which may differ from expected values or which may vary at different locations in the repository;
- The presence of water/humidity can be detected at various locations.

The following sections detail on some of these aspects by means of a generic example of a PA demonstrator case, viz. the *ELSA* shaft sealing.

In a second step, Section 3.2 provides a functional abstraction of the *ELSA* shaft seal and deduces the key features and processes, and underlying processes and parameter of relevance, reflecting the geophysical convergence and creep behaviour of rock salt. Section 3.3 shortly summarizes the general set up of the generic PA model representation of the *ELSA* shaft by NRG. As third step, potential indicators and the related parameters are analysed (Section 3.4). In a fourth step, the main migration related processes were analysed (Section 3.5), and the relevance of the shaft for the overall safety was discussed (Section 3.6). Section 3.7 concludes this chapter by a short discussion on the feasibility of monitoring (Step 5).

### 3.1 Functional abstraction of the shaft seal

In the *ELSA* shaft sealing case, properties of the shaft and repository (e.g. porosity, permeability) are assumed as constant. No assumptions made on disposal cell or waste behaviour, e.g. the moment of container failure. Brine is entering the repository infrastructure via the shaft, until the shaft is saturated with brine. No inflow or outflow of brine through the EDZ or host rock is assumed. Due to the long time-scales involved until brine is pressed out (several ten thousands of years), for the PA demonstrator case it is conservatively assumed that outflow of brine is directly entering the surrounding geosphere, rather than entering the shaft. Conservatively, a perfect mixing of the brine in the infrastructure area is assumed.

A sketch of the model segment structure for the *ELSA* shaft sealing concept (GRS, left) and the resulting functional abstraction of the generic demonstrator case (NRG, right) are depicted in Figure 3-1. Details of the LOPOS model developed by GRS are documented in [Rübel *et al.*, 2016].

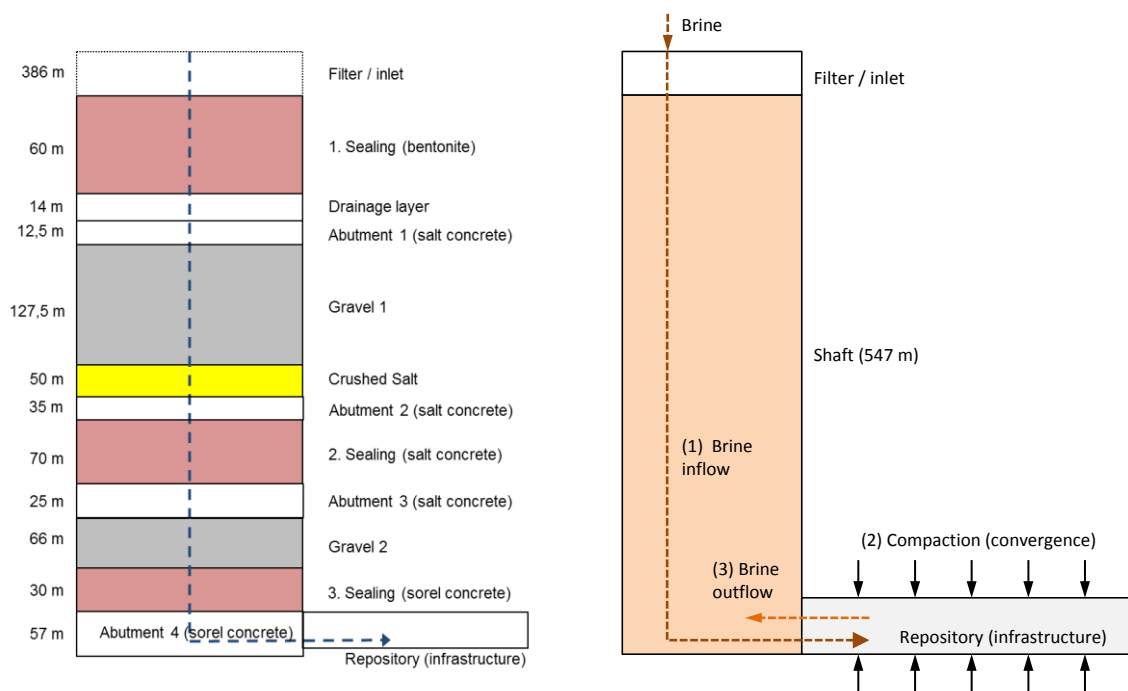


Figure 3-1: Set-up of NRG's *ELSA* demonstrator case (right) based on GRS's PA *LOPOS* model (left)

NRG adopted the following assumptions for the demonstrator case:

- The shaft was modelled as a single porous medium with properties averaged from the *LOPOS* data.
- On top of the shaft a 50 m thick layer of brine with constant properties models a flooding scenario; as a result of the hydraulic gradient over the shaft, brine percolates through the shaft into the repository (1).
- The infrastructure area of the repository is modelled as a single segment containing salt grit backfill, enabling the repository volume to converge as a result of pressure exerted by the overburden (2). This assumption differs from the German repository concept and the simulations that have been made by GRS in DOPAS. The development of the convergence rate in dry (initially) and wet (after start of the brine inflow) is simulated according to the models describing the compaction behaviour of salt grit in [Schröder *et al.*, 2009b], see also Sections 3.2.1 and 3.2.2.
- As soon as the volume of the brine inside the infrastructure area of the repository equals the pore volume of the compacting repository, the inflow of brine is terminated and is subsequently reversed (3) due to the ongoing compaction of the repository volume. This effect has not been taken into account in the *LOPOS* simulations.

Model parameters are summarized in Table 3-1 (*ELSA*, GRS) and Table 3-2 (NRG).

Table 3-1: Model parameters for the components of the shaft sealing (*ELSA*, GRS)

Functional component	Length [m]	Cross section [m <sup>2</sup> ]	Permeability [m <sup>2</sup> ]	Porosity [-]	Initial saturation [-]
Filter / inlet (sand/gravel), including a 50 m layer of brine on top	436	5 x 5	$1 \cdot 10^{-12}$	0.30	1.0
1. sealing element (bentonite)	60	8 x 7.31	$1 \cdot 10^{-17}$	0.27	0.45
Drainage layer (gravel)	14	7 x 6.53	$1 \cdot 10^{-12}$	0.25	0.6
Abutment 1 (salt concrete)	12.5	7 x 6.53	$1 \cdot 10^{-12}$	0.10	0.85
Reservoir 1 (gravel)	127.5	7 x 6.53	$1 \cdot 10^{-9}$	0.23	0.065
Long term sealing (crushed salt)	50	7 x 6.53	$1.3 \cdot 10^{-15}$	0.10	0.29
Abutment 2 (salt concrete)	35	8 x 7.65	$2 \cdot 10^{-15}$	0.10	0.85
2. sealing element (salt concrete)	70	8 x 7.65	$7 \cdot 10^{-19}$	0.10	0.85
Abutment 3 (salt concrete)	25	8 x 7.65	$2 \cdot 10^{-15}$	0.10	0.85
Reservoir 2 (gravel)	66	7 x 6.53	$1 \cdot 10^{-9}$	0.38	0.065
3. sealing element (sorel concrete)	30	8 x 8.36	$5 \cdot 10^{-17}$	0.16	0.8
Abutment 4 (sorel concrete)	57	8 x 8.36	$5 \cdot 10^{-17}$	0.16	0.8
Infrastructure (horizontal)	1000	57 x 10	$1 \cdot 10^{-14}$	0.40	0.0

Table 3-2: Model parameters for the components of the shaft sealing (NRG)

Functional component	Length [m]	Cross section [m <sup>2</sup> ]	Permeability [m <sup>2</sup> ]	Porosity [-]	Initial saturation [-]
Filter / inlet (sand/gravel)	436	5 x 5	$1.0 \cdot 10^{-12}$	0.30	1.0
Shaft	547	54.2	$5.7 \cdot 10^{-18}$	0.19	-
Infrastructure (repository)	1000	57 x 10	$1.0 \cdot 10^{-14}$	0.40	0.0

The main difference between GRS's *LOPOS* model and NRG's demonstrator case relates to the assumptions made for the backfill of the infrastructure area of the repository: in the *LOPOS* model the infrastructure volume is backfilled with non-compacting gravel, whereas in NRG's demonstrator case compacting salt grit is assumed as backfill.

The purpose of backfilling the infrastructure areas with non-compacting gravel (GRS) is to allow potential brines and gases to accumulate there. Additionally, the gravel impedes the convergence of this volume due to pressure exerted by the overburden, and therefore also any outflow of brine trapped inside the repository.

Assuming a compactible salt grit backfill (NRG) enables the infrastructure (repository) volume to converge, thereby squeezing out of trapped brine and, if present, any dissolved radionuclides.

## 3.2 Key processes for migration modelling

An important feature of rock salt as a host rock for a repository is the plastic behaviour of the material. Induced by the pressure of the surrounding rock, openings in salt rock tend to converge, leading to the compaction of salt grit used as backfill. Comparable to the role of bentonite backfill used in the other DOPAS demonstrators, compaction of salt grit leads to decreasing porosity and permeability, and finally to the isolation of waste containers from its surroundings. Convergence leads also to transport of brine - if present - out of the repository. Convergence, compaction and creep behaviour of salt grit are thus key processes for understanding of the long-term safety of a disposal concept in rock salt, and the underlying process models that allow to link these to the migration-related parameters *porosity*, *permeability* and *pressure gradient* are therefore discussed in the following.

### 3.2.1 Convergence behaviour

From the outcomes of earlier EU projects (e.g. *BAMBUS II*, *NF-PRO*) it appeared that an important factor for the safety of a repository in salt is the compaction behaviour and the permeability development of the salt grit plugs that are applied to seal the disposal cells. The compaction rate not only depends on the pressure exerted by the host rock on the (compacted) salt grit, but is counteracted by the pressure built up in the salt grit by material stress and the hydrostatic pressure if brine is present in the pores of the salt grit.

Another important phenomenon is *compaction creep*. The compaction of salt grit determines the time at which seals or backfills may become impermeable for brine in- and outflow. Compaction creep of salt grit is a complex phenomenon for which the development of theoretical models is still in progress. At present two relevant mechanisms for compaction creep of salt grit as a result of its convergence have been determined: (*dislocation coupled*) *recrystallization creep* and *pressure solution (PS) creep*. These mechanisms will be discussed in Section 3.2.2.

The convergence behaviour influences the safety of a rock salt based repository in several ways:

- Convergence leads to a reduction of open volumes in the repository and a decrease of the permeability of seals, plugs, and backfill. The reduction of the open volumes reduces also the amount of brine that may come in contact with the stored waste. In addition, the decrease of the permeability decreases the inflow of brine into a disposal cell as well as the outflow of any contaminated brine from the disposal cells to the geosphere.
- Convergence can reduce the porosity of backfill material, seals and plugs to such an extent that they will become impermeable. As a consequence, any existing flow paths to the outside will be closed and release of radionuclides will become impossible.
- In case any brine will penetrate the disposal cells before all flow paths are closed, brine may get contaminated by radionuclides released from failed waste canisters. Subsequent convergence may press the contaminated brine outside the repository. In that case, convergence is the driving force for the release of radionuclides.

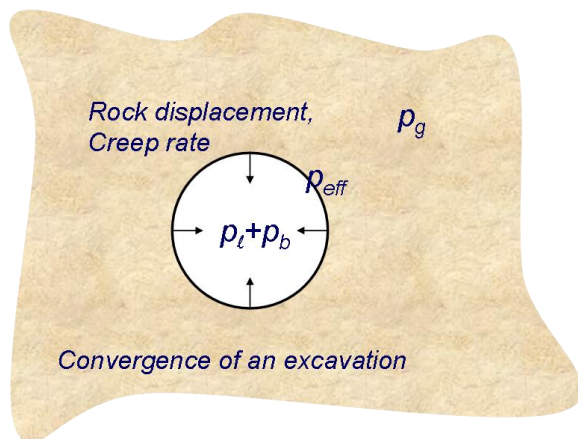


Figure 3-2: Schematic representation of the convergence of an excavation ( $p_g$ : undisturbed rock pressure;  $p_b$ : backfill pressure;  $p_t$ : brine pressure;  $p_{eff} = p_g - (p_t + p_b)$ ).

It is assumed that the decrease of an excavated volume at any time is related to the volume itself according to:

$$\frac{d}{dt}V(t) = -K(p, \phi, T) \cdot V(t) \quad \text{Eq. 3-1}$$

The quantity  $K(p, \phi, T)$  denotes the relative change of volume and is referred to as *convergence rate*. This quantity is time-dependent since it is a function of the time-dependent pressure  $p$ , porosity  $\phi$  and temperature  $T$ .

The temperature and pressure dependency of the convergence rate  $K$  can be described by an Arrhenius-type equation [Heijdra *et al.*, 1998]:

$$K = \alpha \cdot A \cdot e^{\frac{-Q}{RT}} \left( \frac{\alpha \cdot p_{eff}}{m} \right)^m \cdot k \quad \text{Eq. 3-2}$$

with:

$\alpha$	geometrical form factor [-] ( $\sqrt{3}$ for cylindrical and $3/2$ for spherical openings)
$A$	creep constant [ $\text{MPa}^{-m}/\text{a}$ ] (experimentally determined constant)
$Q$	activation energy [J/mol]
$R$	gas constant; 8.314 [J/(mol·K)]
$T$	effective temperature of rock salt [K]
$p_{eff}$	pressure difference in rock salt [MPa]
$m$	creep exponent [-] (experimentally determined constant)
$k$	normalized convergence rate of rock salt [-]

### 3.2.2 Compaction

When an external pressure is exerted on a core of precompacted granular rock salt, the salt core will deform as a result of the viscoplastic properties of rock salt. This phenomenon is referred to as *compaction creep*. By compaction creep, empty spaces between the salt grains will reduce in size, resulting in a compaction of the core and a decrease of the porosity. The compaction creep phenomenon was one of the main subjects of the *NF-PRO* project [e.g. Zhang, 2006]. In that project it was established that compaction creep can take place by two mechanisms, namely:

- (dislocation coupled) recrystallization creep
- pressure solution creep

These two mechanisms are independent creep mechanisms that work in parallel (Figure 3-3).



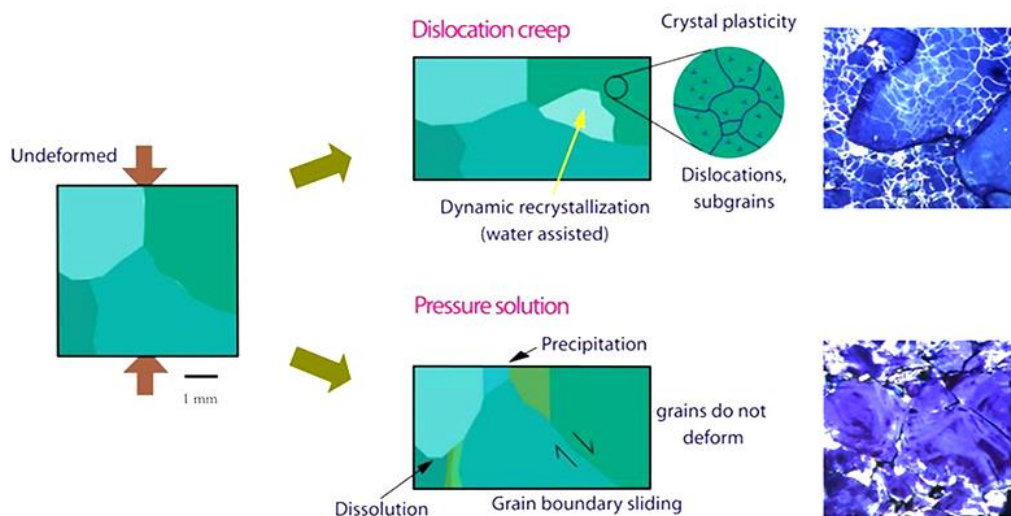


Figure 3-3: Deformation mechanisms of (dislocation coupled) recrystallization creep and pressure solution creep

Characteristic of *recrystallization creep* is the appearance of sub-grains (see right hand side of Figure 3-3). Dynamic recrystallization of the salt is often associated with this deformation mechanism. During *pressure solution creep*, the highly stressed parts of a grain boundary dissolve, followed by diffusion along the grain boundary and precipitation on the less stressed part, forming very different microstructures.

During the *NF-PRO* project the so-called ‘*Coupled Creep Model*’ (*CCM*) was developed describing the compaction rate of salt grit [Grupa, 2000]. The *CCM* is based on mechanistic considerations but also includes constants that need to be fitted by the measurement of several model parameters during compaction experiments.

### ***Recrystallization creep***

Plastic deformation of rock salt occurs, when the pressure is large enough to enable the movement of dislocations or irregularities in the crystal structure in the slip plane (Figure 3-3). During high-strain deformation, recrystallization creep is the dominant creep process, driven by differences in chemical potential between low-stress locations and locations subject to high stresses. Recrystallization creep is promoted by the presence of a thin water film on the grain surfaces as is usually in natural rock salt. This water film increases the mobility of grain boundaries.

An equation describing dislocation coupled recrystallization creep ( $\epsilon_{recr}$ ) has been developed in the *NF-PRO* project [Zhang, 2006] and was slightly modified by NRG within *PAMINA* WP.2.1.D [Schröder *et al.*, 2009b; Section 3.2.1]:

$$\varepsilon_{recr} [s^{-1}] = \frac{B_{recr}}{d_g^2} * e^{-dH/RT} * h(\phi) * \sigma^5 \quad \text{Eq. 3-3}$$

with:

$dH$	activation-energy: 65 kJ
$R$	gas-constant: 8.314 J/mol·K
$T$	temperature: 293.15 K
$\sigma$	stress [MPa]
$d_g$	grain-size [ $\mu\text{m}$ ]

and a grain-size dependent factor  $B_{recr}$  according to

$$B_{recr} [\mu\text{m}^2 \cdot \text{MPa}^{-5} \cdot \text{s}^{-1}] = A_{recr} * d_g^2 \quad \text{Eq. 3-4}$$

$B_{recr}$  is the recrystallization creep constant that was determined experimentally from *NF-PRO* data. The function  $h(\phi)$  is a geometrical term solely dependent on the porosity  $\phi$ .

$$h(\phi)[-] = \frac{\phi^{1.5}}{(1 - 1.20899 \cdot \sqrt[3]{\phi^2})^{15}} \quad \text{Eq. 3-5}$$

Eq. 3-3 shows that recrystallization creep depends to the fifth power on the applied stress  $\sigma$ , meaning that at low stress values the recrystallization creep is very small, whereas at high stresses it may be the dominant process determining the strain rate.

### ***Pressure solution creep***

Pressure solution creep is a water-assisted mass transfer by diffusion. The presence of a thin water layer on the surface of the salt grains acts as a medium of reaction and transport. Pressure solution deformation is driven by stress gradients along the grain surface involving three processes:

- 1) salt ions dissolve around the contact plains of the salt grains due to the higher chemical potential. As result, the water layer in high stress areas is oversaturated in respect to the concentrations elsewhere.
- 2) ions in the water layer diffuse along the grain surface to areas with lower concentrations.
- 3) precipitation takes place somewhat distant from the contacts plains where the dissolved ion concentration exceeds the solubility limit.

As a result of this mechanism small pores inside the rock salt can slowly be silted up, resulting in a reduction of the pore sizes.

For the present work, the equation for pressure solution creep derived by Zhang & Grupa in the *NF-PRO* project [Zhang, 2006], which had inverse cubic grain size dependence and underestimated the effect of porosity, was modified by NRG on the basis of experimentally determined values within the *NF-PRO* project [Schröder, 2009b]. The modified pressure solution creep model fits better with the experimental data provided in [Zhang, 2006]:

$$\varepsilon_{ps} [s^{-1}] = \frac{A_{ps}}{T \cdot d_g^2} * g(\phi) * \sigma \quad \text{Eq. 3-6}$$

where:

$T$	temperature [K]
$\sigma$	stress [MPa]
$d_g$	grain-size [ $\mu\text{m}$ ]
$A_{ps}$	pressure creep constant [ $\mu\text{m}^2 \cdot \text{K}/(\text{MPa} \cdot \text{s})$ ]

$g(\phi)$  is a complex function of the porosity  $\phi$  as follows:

$$g(\phi)[-] = \phi \frac{1 + 3.5\phi}{(1 - 1.20899 \cdot \sqrt[3]{\phi^2})^2} \frac{\sqrt[3]{\phi}}{(1 - \sqrt[3]{\phi})} \quad \text{Eq. 3-7}$$

### Compaction Creep

The two mechanisms for compaction creep, as discussed in the previous paragraphs, are independent creep mechanisms that act simultaneously. The total creep rate  $\varepsilon$  is the sum of the two contributions  $\varepsilon_{ps}$  and  $\varepsilon_{recr}$ . However, an extra correction factor is needed to account for the amount of water present in the pore volumes, due to the fact that pressure solution creep is dependent on the presence of water [Spiers, 1988]:

$$\varepsilon = Q \varepsilon_{ps} + \varepsilon_{recr} \quad \text{Eq. 3-8}$$

where the factor  $Q$  is used to scale the creep behaviour of brine-saturated salt to unsaturated conditions or conditions with other backfills:

$$Q = \min \left\{ 100 \cdot RC_0 \cdot \frac{\phi_{brine}}{\phi} \cdot \frac{\rho_{brine}}{\rho_{backfill}}, 1 \right\} \quad \text{Eq. 3-9}$$

with

$\phi_{brine}$	fraction of brine-filled volume [-]
$\phi$	porosity [-]

$\rho_{brine}$  density of brine [kg/m<sup>3</sup>]  
 $\rho_{backfill}$  density of backfill (i.e. of rock salt: 2000 kg/m<sup>3</sup>)

For the factor  $RC_0$ , a value of  $0.05 \pm 0.03$  is derived in [Spiers, 1988].

Because dislocation coupled recrystallization creep depends on  $\sigma^5$  while pressure solution creep depends on  $\sigma^1$ , the former predominates at high stresses while the latter dominates at lower stresses.

### 3.2.3 Porosity and permeability

With convergence of the host rock and creep of the salt backfill, the size of any open pore spaces present in seals, and/or salt grit will decrease. Ongoing creep will result in a further decrease of the size of the interconnecting spaces, eventually leading to the cut-off of the interconnections of the pore network, eventually resulting in a sharp decrease of the permeability. Finally, the porosity  $\phi$  reaches the percolation threshold where no single continuous flow path will remain and thus the pore network is broken down. The salt then becomes impermeable, although its porosity may not have been reduced to zero due to the presence of unconnected open pore spaces (Figure 3-4, “Final configuration” [Zhang, 2006; Section 5.5]).

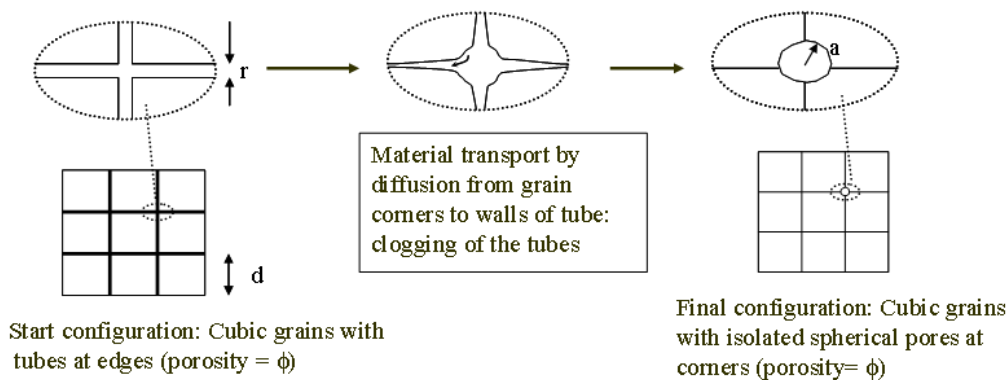


Figure 3-4: Schematic representation of the *NF-PRO* pore healing model

In [Schröder, 2009b], the following equation has been applied representing the long-term permeability-porosity relation for salt grit that includes both the presence of a threshold porosity below which the permeability  $k$  decreases sharply, and the possibility to keep the permeability on a level that is covered by measured data:

$$k[m^2] = \begin{cases} F_{47} * \phi + F_{09} * (\phi - F_{46})^n & \phi \geq F_{46} \\ F_{47} * \phi & \phi < F_{46} \end{cases} \quad \text{Eq. 3-10}$$

where  $n$ ,  $F_{09}$ ,  $F_{46}$ , and  $F_{47}$  are model parameters that have been determined within the present study on the basis of experimentally determined values:

Table 3-3: Parameter values of  $n$ ,  $F_{09}$ ,  $F_{46}$  en  $F_{47}$

Parameter	Value
$F_{09}$	$1.4 \cdot 10^{-10} \text{ m}^2$
$n$	4.2
$F_{46}$	0.005
$F_{47}$	$1.7 \cdot 10^{-19} \text{ m}^2$

This relationship between permeability and porosity is depicted in Figure 3-5, together with measured values [Zhang, 2006].

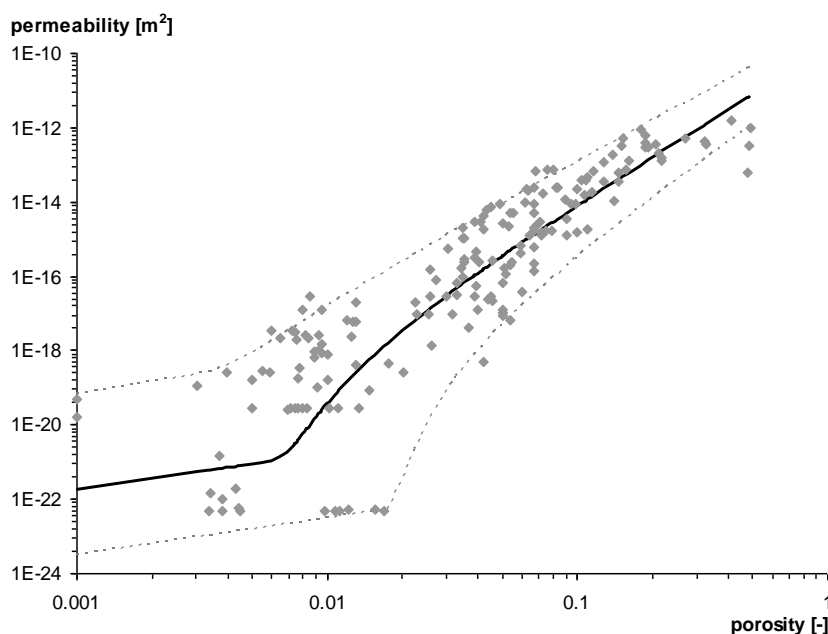


Figure 3-5: Permeability as a function of porosity. Solid curve: Eq. 3-10 with model data from Table 3-3. Dashed curves represent the 95%-confidence interval (upper and lower boundaries)

### 3.3 Model representation

A simple numerical scheme for the models for the convergence and compaction of salt grit described in Sections 3.2.1 and 3.2.2 was implemented in Excel. Table 3-4 provides an overview of the model parameters, including ranges of the low and high values which are based on experimental values [Zhang, 2006]. By varying model input parameters it could easily and straightforwardly be assessed how the compaction of the repository infrastructure evolves over

time, and how that affects any outflow of (contaminated) brine. The results of the simulations are presented and discussed in Section 3.4.

Table 3-4: Model parameters for the convergence/compaction models

Parameter	Low	Best fit	High
$K_{init}$ [1/a]	$5 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
$B_{recr}$ [ $\mu\text{m}^2 \cdot \text{MPa}^{-5} \text{s}^{-1}$ ]	16.7	204	2501
$A_{ps}$ [ $\mu\text{m}^2 \cdot \text{K}/(\text{MPa} \cdot \text{s})$ ]	0.23	0.83	1.04
$F_{09}$ [ $\text{m}^2$ ]	$3.43 \cdot 10^{-11}$	$1.39 \cdot 10^{-10}$	$5.62 \cdot 10^{-10}$
$n$ [-]	3.67	4.18	4.69
$F_{46}$ [-]	0.00158	0.005	0.0158
$F_{47}$ [ $\text{m}^2$ ]	$2.95 \cdot 10^{-21}$	$1.70 \cdot 10^{-19}$	$6.31 \cdot 10^{-17}$

## 3.4 Definition of indicators

This section briefly describes the definition of the indicators used for the example case. The outcomes are presented and discussed in Section 3.5.

### 3.4.1 Péclet number

The Péclet number allows to judge whether the given system is dominated by advection or diffusion. Besides its use as indicator, the Péclet number is also relevant to justify the chosen PA modelling approach (i.e. exclusion of mass transport by diffusion). To estimate the Péclet number, the numerical outcomes of the demonstrator case calculations (limited to advective mass transport) are compared with analytical estimation of diffusion fluxes by Eq. 2-2, with:

- migration distance  $L$ : 1000 m,
- initial porosity in the backfill of the drift  $\phi$ : 0.40,
- effective diffusion coefficient in the backfill  $D_e$ :  $4.7 \cdot 10^{-2} \text{ m}^2/\text{a}$  [Brenner *et al.*, 2000].

### 3.4.2 Travel-time based indicator

To apply the travel time indicator, the reference value for the safety indicator *radiotoxicity flux to the geosphere*, of 0.1 Sv/a at the exit of the repository has been applied [Becker *et al.*, 2009; Table 5.8]. Given the long time period until the outflow of brine actually starts (several ten thousands of years), it is conservatively assumed that all brine from the disposal will enter directly the geosphere, rather than entering the shaft (i.e. the reference value is applied to the interface repository/shaft).

### 3.4.3 Integrated amount of brine inflow

The *Integrated amount of brine inflow* is only used to compare the outcome of NRG's demonstrator case model with the calculations performed by GRS.

## 3.5 Results of the simulations

The Péclet number for the drift connecting the repository and the vertical shaft can be estimated using the calculated results of the brine outflow, the dimensions provided in Table 3-1 and Table 3-2, and a conservative assumed diffusivity of  $1.5 \cdot 10^{-9} \text{ m}^2/\text{s}$  [Brenner *et al.*, 2000]. The result is shown in Figure 3-6 depicting the calculated Péclet number for the outflow of brine from the repository for three different initial convergence rates  $K_{init}$ . The figure shows that during the outflow of brine the Péclet number is at least 20, which implies that the brine outflow from the repository back into the vertical shaft is dominated by advection and mass transport by diffusion is negligible in the first million years.

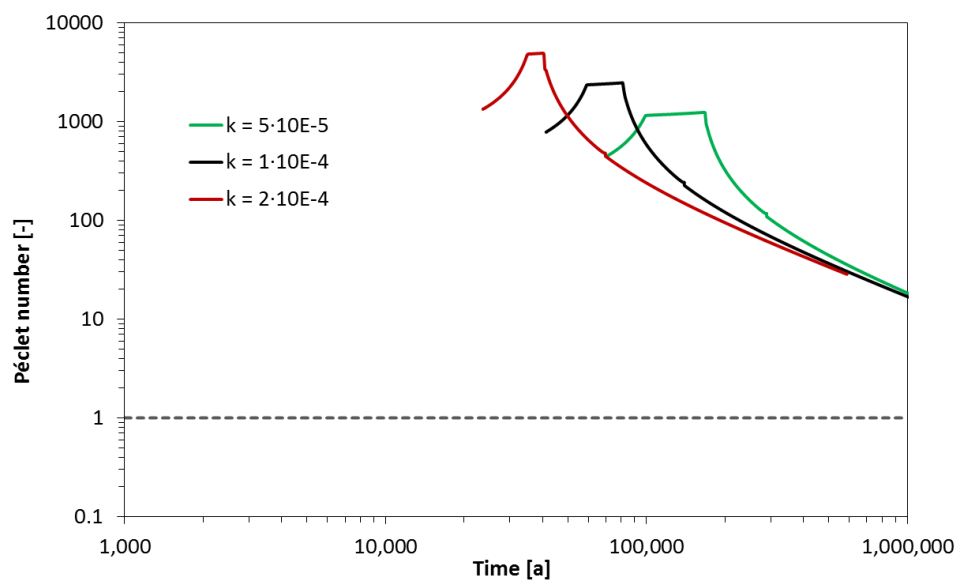


Figure 3-6: Evolution of the Péclet number for the brine outflow from the repository into the vertical shaft for three initial convergence rates  $K_{init}$ .

The overall system behaviour of the modelled repository is shown in Figure 3-7. By imposing an initial convergence rate ( $K_{init} = 1 \cdot 10^{-4}/\text{a}$ ) until full saturation is reached, the repository pore volume decreases in time (green curve). Starting from 700 years, brine slowly percolates into the repository (red curve), until the volume of the infiltrated brine equals the decreasing repository pore volume,

at approximately 41'000 years. From that time on brine present inside the repository is squeezed out due to the ongoing convergence of the repository (red and blue curves). It is noted that the convergence rate of the repository is restricted in the time interval 41'000 to 58'000 years due to the hydraulic resistance of the vertical shaft upon brine leaving the repository.

As a result of the ongoing convergence of the repository, the salt grit backfill experiences stress from the surrounding host rock and will therefore be compacted according to Eq. 3.8 as time progresses. Consequently the porosity and therefore also the permeability of the plug will decrease. When the repository's effective pressure equals the backfill stress - at about 80'000 years in Figure 3-7, the ongoing convergence rate is slowed down significantly, as is the outflow of brine.

At the end of the simulation a total amount of approximately 4300 m<sup>3</sup> of brine is squeezed out of the repository into the vertical shaft. This amount of brine would fill up the shaft from below up to the "Gravel 1"-layer (cf. Figure 3-1).

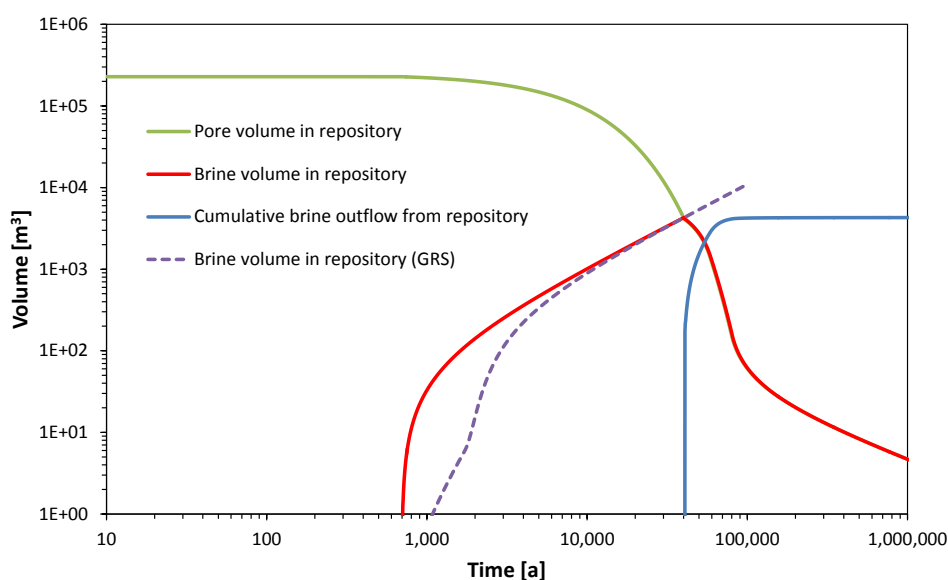


Figure 3-7: Evolution of repository and brine volumes

The effect of the variation of the parameters describing the convergence and compaction of salt grit (Sections 3.2.1 and 3.2.2) for  $K_{init} = 10^{-4}/a$  is shown in Figure 3-8. By imposing the best-fit (solid curve), and minimum/maximum (dashed curves) values of the model parameters given Table 3-4 the variation of the repository and brine volumes was established. Only the pressure creep constant  $A_{ps}$  has some but limited influence on the late phase of the evolution of the repository and brine volumes. The pressure creep constant  $A_{ps}$  affects the rate of the dissolution of salt particles at grain-to-grain contacts into an aqueous pore fluid in areas of relatively high stress. From Figure 3-8 it is evident that under the considered conditions the pressure creep constant affects the system only after about 100'000 years.



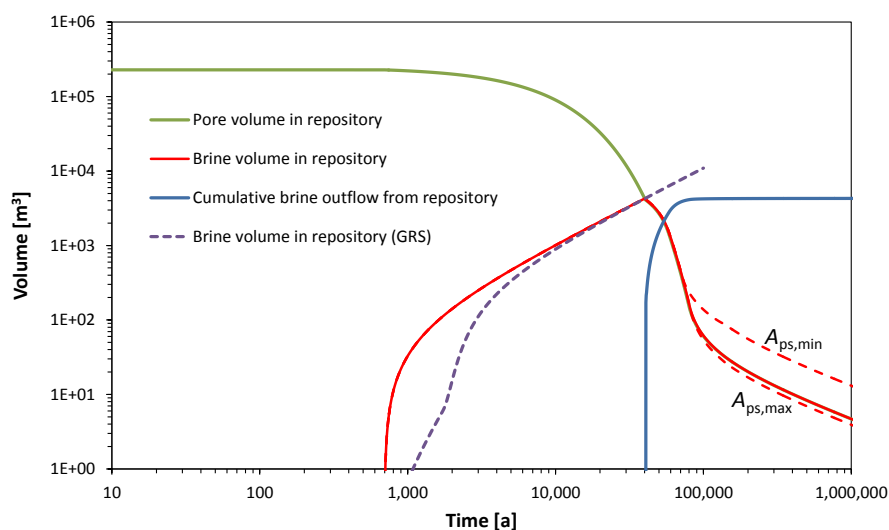


Figure 3-8: Evolution of repository and brine volumes – effect of parameter variation

Combining the system behaviour described above with the travel-time based indicator described in Section 2.2.3 provides insight about the breakthrough of radionuclides in the repository. Three different initial convergence rates  $K_{init}$  for the repository pore volume were assumed for estimating their effect on this indicator, viz  $0.5 \cdot 10^{-4}/a$ ,  $1.0 \cdot 10^{-4}/a$ , and  $2.0 \cdot 10^{-4}/a$ .

The travel time indicator is calculated by dividing the reference value (see Section 3.4.2) by the outflow of brine from the repository, and is depicted in Figure 3-9 (red, black, and green curves). It shows the maximum radiotoxicity inventory that can be present in the infrastructure volume of the repository without exceeding the given reference value for the case considered.

For comparison, the evolution of the total radiotoxicity in the repository<sup>7</sup> has been indicated in Figure 3-9 (blue solid line), including parameter uncertainties of the process model parameters discussed in Section 3.2 and Table 3-4 (blue dotted lines). The blue curves are based on an assessment of the generic Dutch disposal concept in rock salt [Schröder et. al., 2009a], quite comparable to the German concept, with a borehole plug from salt grit compacting according to the processes discussed in Section 3.2 and elsewhere in this report. The inventory of the borehole consists of 300 CSD-V containers<sup>8</sup> with vitrified high-level waste (HLW). A synthetic assumption of a flooding scenario was made, combined with an immediate failure of all canisters (see also Section 3.3). The figure shows - even for the very conservative and unlikely scenario assumptions - that the radiotoxicity in the repository remains below the indicator value at all times and for all assumed repository convergence rates.

<sup>7</sup> The *center field* connects the disposal area with the shaft, comparable to the *infrastructure area* in the GRS concept.

<sup>8</sup> CSD-V: Colis de Déchets Vitriifiés

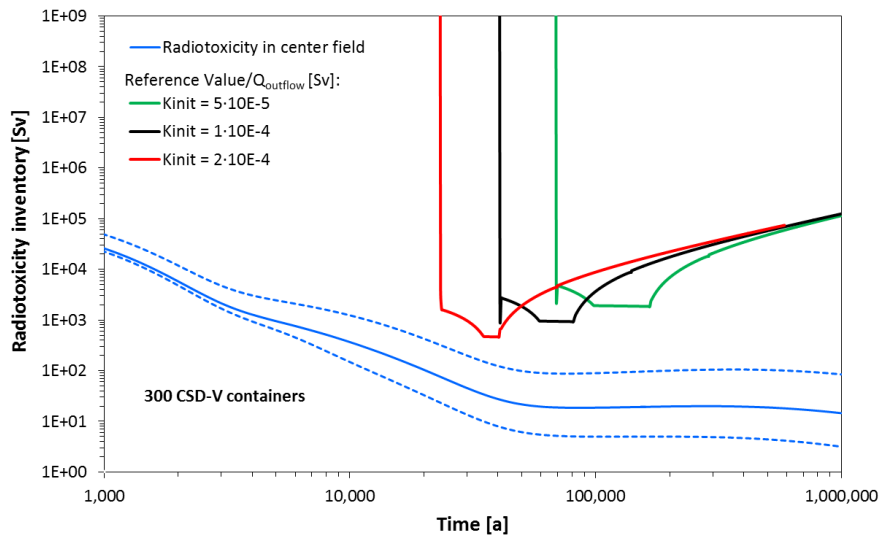


Figure 3-9: Evolution of indicator and radiotoxicity in repository for three initial convergence rates  $K_{init}$  and an inventory of 300 CSD-V containers

Assuming a larger inventory, e.g. 3.735 CSD-V containers (Table. 3.15 in [Peiffer *et al.*, 2011]) would increase the radiotoxicity by a factor of 12. In that case, the indicator would fall below the radiotoxicity in the repository for the highest convergence rate  $K_{init}$  between 20.000 and 45.000 years, and for the best convergence rate  $K_{init}$  between 60.000 and 80.000 years (Figure 3-10). Consequently, assuming the larger CSD-V inventory, additional measures or barriers would be necessary to comply with the reference value. Additionally, the simplified and overconservative PA model representation and underlying assumptions may be reviewed.

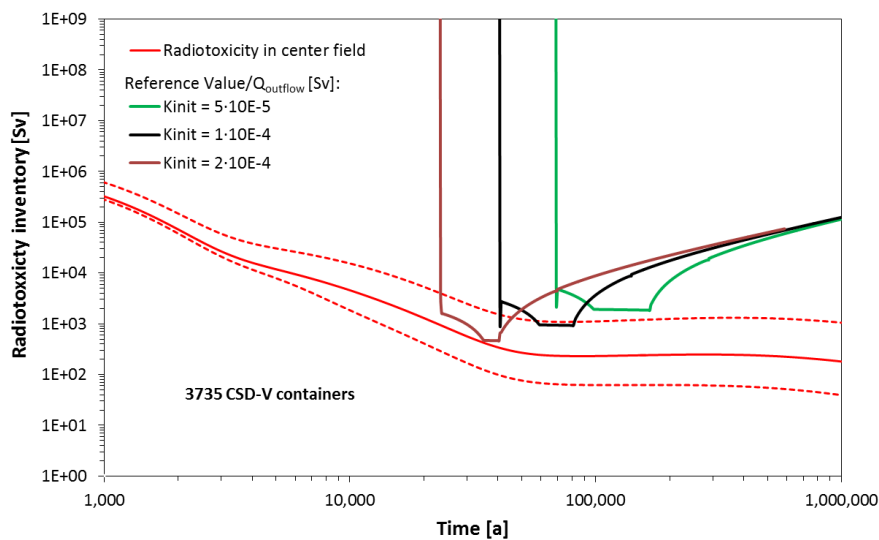


Figure 3-10: Evolution of indicator and radiotoxicity in repository for three initial convergence rates  $K_{init}$  and an inventory of 3735 CSD-V containers

### 3.6 Analysis of the relevance of indicators, processes and parameters for the long-term safety

To establish priorities for monitoring, it is important to understand the overall system behaviour and the contribution of barriers and related features, processes and parameters to the long-term safety: frequently measured parameters as e.g. temperature, although important for the qualification of a barrier, might have no relevance at all for the long-term safety. A second step is to investigate the feasibility to monitor these processes: this topic is discussed in the next section.

In the present PA demonstrator example, the main function of the shaft seal is to prevent or at least significantly slow down the inflow of water or brine from the overburden into the repository after its closure. Furthermore, in the event that radioactive nuclides are mobilised during the post-closure phase, the sealing function of the shaft seal is to retain these radionuclides in the repository. The sealing function in both directions ensures compliance with the safety functions *limitation of the water flow through the disposal system*, and *limitation of contaminant releases from the waste forms* (cf. Section 1.3).

The processes that influence a shaft sealing construction and that are relevant regarding the safety concept are [MoDeRn, 2013b; Section 4.3.3]:

- the *convergence* of the shaft,
- the *hydraulic load development* on one or on both sides (top and bottom) of the sealing elements of the shaft seal,
- the *inflow of potentially corrosive fluids*, and
- the *subsidence* of the entire sealing construction.

The parameters characterising these processes are:

- the *displacement* of the sealing construction, individual components or surrounding host rock;
- the *convergence rate* in the vicinity of the sealing elements;
- the *radial pressure* in the vicinity of the sealing elements;
- the *pore pressure* above and below the sealing elements;
- the *brine filled porosity* above and below the sealing elements;
- the *chemical composition* of the water/brine.

The main function of the shaft seal, i.e. preventing or at least significantly slowing down the inflow of water or brine from the overburden into the repository after its closure, implicates that the hydraulic load evolution is an important safety-related feature, which is characterized by pore pressure and humidity at different locations in the shaft. However, for the *ELSA* concept of shaft sealing, the present analysis of the PA demonstrator case shows that a potential hydraulic load evolution is a slow process that may take place over a period of several centuries, and only under the condition of flooding of the facility.

For the evaluation of the relevance of barrier components and the underlying processes and parameters, the modelling outcome of GRS was combined with additional process model analyses carried out by NRG. These model analyses are based on the generic Dutch disposal concept in rock salt, which is comparable to the German concept and covers the same aspects of rock salt compaction behaviour. Figure 3-6 showed that diffusion has only a minor contribution to radionuclide migration, i.e. all further evaluations can be limited to advective transport, which is caused by the ongoing convergence of the repository pore volume<sup>9</sup>. The analysis provides some leads on the relevance of barriers, processes and parameters:

- **Shaft seal:** The *hydraulic conductivity* is the key parameter until full saturation is reached, assuming that the *pressure gradient* is mainly influenced by the geometry of the shaft and the density of the brine, and that uncertainties of the shaft seal behaviour will not lead to varying radionuclide *sorption* or *solubilities*. After saturation, the hydraulic gradient will depend on a complex interaction of convergence, brine flow, and backfill creep behaviour in the disposal volume, but not on the (static) properties of the shaft, because it is assumed conservatively that from the moment of brine outflow (i.e. after more than 20.000 years) the shaft has no barrier function with respect to the flow of brine into the geosphere. It is evident from the properties of the stacked shaft layers that the overall hydraulic conductivity during the inflow phase is dominated by the 2<sup>nd</sup> sealing element (Figure 3-1; Table 3-1). The results so far point to a limited relevance of the shaft seal on the long-term safety for the scenarios covered by the analyses, and the assumed static properties of the shaft. Additional analyses could be performed to elucidate the relevance of the convergence of the three sealing elements of the *ELSA* shaft concept on the overall performance of the disposal facility, and possibly identify any other key processes.
- **Infrastructure area backfill:** The *convergence* of the salt rock in the unsaturated state is an important process if salt grit is applied as backfill for the infrastructure area (Figure 3-9). It influences the amount of brine that can enter the repository. The model assumption of immediate release of radionuclides upon brine intrusion leads to increasing radiotoxicity concentrations for larger convergence values, resulting in less brine present in the repository in which the released radionuclides will be dissolved. After saturation of the infrastructure area backfill, the *hydraulic gradient* and *permeability* in the disposal facility depends on a complex interaction of convergence, brine flow, and backfill creep behaviour as described in Section 3.2. The analyses of the related parameter show that, for the assumed scenario, the pressure creep related parameter  $A_{ps}$  is the most influential for the brine transport (Figure 3-8). This parameter would affect the brine transport only at later time steps (>70.000 years, Figure 3-8). However, the radiological consequence would be negligible because after that time the amount of brine squeezed out of the repository would be very low, if not insignificant (Figure 3-9).

<sup>9</sup> Note that due to the immediate mixing of the brine in the single cell that represents the infrastructure area in the PA model, potential heat- or density-driven convection is accounted for.

### 3.7 Monitoring of indicators

In the previous section, the hydraulic conductivity of the shaft seal, the convergence of the host rock and the creep behaviour of the backfill have been identified as most relevant parameters for the long-term safety.

As discussed in [MoDeRn, 2013b], monitoring of the pressure evolution at several locations of the *shaft seal* may allow to distinguish several scenarios. Although not analysed in the present generic demonstrator case, the pressure inside the shaft can provide information about the convergence of (parts of) the shaft, and the further reduction of the permeability of the stacked layers and resistance to brine intrusion. Additionally, the presence of brine at various locations inside the shaft can in principle be detected. A complication related to monitoring is that measuring points within the sealing elements of a shaft seal are to be avoided in order to not impair the sealing function of individual sealing elements [Modern, 2013b; Section 4.3.3]. The evidence that can be provided by monitoring on the shaft's performance under the normal evolution conditions is also limited, because measurements can only be performed in a rather short period, compared to the very slow inflow of brine. Potential uncertainties on the initial saturation and permeability of the various shaft sealing elements might lead to additional limitations in the interpretation of monitoring outcomes.

According to [MoDeRn, 2013b; Section 4.3.3] *convergence* measurements in the filled and sealed repository are not possible. It is argued that monitoring radial displacements of the rock would require that additional boreholes are drilled into the adjacent rock mass, which should be avoided to not affect the geologic barrier adjacent to the shaft seal adversely. Similar but indirect information about the rock movement can be obtained by monitoring the radial pressure.

Because relevant compaction of the *infrastructure area backfill* and a consecutive build-up of stress will take place only in a long term (>1.000 years), monitoring will be difficult. However, monitoring may be helpful in reducing the uncertainty of the material-specific backfill behaviour (see e.g. Figure 2-6). A parameter that is relatively straightforward to measure and that provides relevant information about the development of the repository system is the pressure (pore pressure, total pressure). As discussed in Section 2.1.4, pressure evolutions in the backfill can be linked to porosity and permeability evolutions by process models.

The absence of brine (or humidity) in the *disposal cells* is crucial for the long-term safety of the repository. Determination of the presence of brine by monitoring can be easily achieved, e.g. by measurement of the electrical conductivity. Because of the long time scales involved - percolation of brine through a long vertical shaft is expected to occur over a period of several hundred years under a *normal evolution* - currently no mature technology is available to monitor the process, neither in the infrastructure volume nor in the disposal cells. However, from analyses performed in *PAMINA* [Schröder *et al.*, 2009a & 2009b] it can be concluded that the determination of brine inside a disposal cell in case of a *flooding scenario* might be of value, because the creep of a disposal cell plug proceeds comparable faster than the backfill in other areas, leading to a faster decrease of the permeability of the plug (in about 100 to 200 years after seal placement, see Figure 2-6).



## 4 Analysis of the DOPAS demonstrators

This chapter summarizes the lessons learned from case studies on the five seal and plug systems examined in DOPAS. Descriptions of the disposal concept, the related safety functions, scenarios, FEPs, and potential indicators and indicator criteria corresponding to each of the DOPAS seals are summarized in Appendix A.1 to A.5. Table 4-1 summarizes the parameters monitored in the four DOPAS demonstrators per barrier component.

Table 4-1: Parameters monitored in the DOPAS demonstrators DOMPLU (Dome Plug, SKB), FSS (Full Scale Seal, Andra), EPSP (Experimental Pressure and Sealing Plug, SURAO), and POPLU (POsiva PLUG, Posiva)

Location	Monitored parameter	DOMPLU	FSS	EPSP	POPLU
<b>Concrete block/containing wall/concrete dome</b>	Gap to rock	+			+
	Displacement/Deformations	+		+	
	Strain	+		+	+
	Total pressure				+
	Pore pressure				+
	Relative humidity				+
	Temperature	+	+	+	+
	Shrinkage		+		
Contact stress between plug and rock			+		
<b>Gap between rock and plug</b>	Total pressure	-			+
	Pore pressure	+			+
	Relative humidity	+			-
<b>Sealing element</b>	Total pressure	+		+	
	Pore pressure	+		+	
	Relative humidity	+		+	
	Displacement	+			
	Backfilled volume	+	+	+	
<b>Filter layer</b>	Total pressure	*			+
	Pore pressure	*			+
	Relative humidity	*			
	Displacement	+			+
<b>Backfill</b>	Total pressure	+	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
	Pore pressure	+	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
	Relative humidity	+	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
	Displacement	+	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
<b>Leakage and pressurisation system</b>	Leakage	+			+
	Water inflow	+		+	+
	Water pressure	+			+
<b>Tunnel back wall</b>	Temperature	<i>n.a.</i>	<i>n.a.</i>	*	+
	Relative humidity	<i>n.a.</i>	<i>n.a.</i>	*	+
<b>Test-box</b>	Tilting	<i>n.a.</i>	+	<i>n.a.</i>	<i>n.a.</i>
	Pitch	<i>n.a.</i>	+	<i>n.a.</i>	<i>n.a.</i>
	Deformation	<i>n.a.</i>	+	<i>n.a.</i>	<i>n.a.</i>
	Ambient temperature	<i>n.a.</i>	+	<i>n.a.</i>	<i>n.a.</i>
	Humidity	<i>n.a.</i>	+	<i>n.a.</i>	<i>n.a.</i>
<b>Near-field measurements</b>	Total pressure				+
	Water leakage**	+			+
	Temperature				+
	Strain				+
	Rock movements				+
	Amount of EDZ				+

\* unclear \*\*other than through the plug n.a.: not available

## 4.1 Key processes for long-term safety

The main objectives for the measured features and parameters summarized in Table 4-1 can be summarized as follows:

- The monitoring of the *gap to rock* indicates whether the concrete dome releases from the rock because of shrinkage.
- The *deformation* and *strain* measures the response of the concrete dome to high loads. The *strain* is also measured to have an indication on whether the concrete dome is released or not from the rock.
- The *temperature* measurements of the concrete dome give an indication about the heat development during the hardening of concrete and cooling of the concrete dome.
- The *relative humidity* follows the saturation process and permits the estimation of the water content and the degree of saturation of a material.
- The *total pressure* gives an indication of the development and distribution of swelling pressure.
- The *displacements* measurements are performed to detect displacements that occur when high pressures are developed due to the swelling of bentonite or when pressure differences between different zones and/or components cause displacements of barrier elements. Displacements can jeopardise the sealing capacity of plugs and seals and also can produce a variation of the total confined volume and hence the total density of the barrier.
- *Pore pressure* is necessary to estimate effective stresses from calculated total stresses.
- Knowledge of *mechanical stresses* is of use in assessing the safety of the operation of a disposal facility.
- Mechanical stresses lead to *deformation* of the medium which means that the measurement of deformation at specific positions can reveal the stress sources.

Some constructional elements of the plug- and sealing systems are not parts of the actual repository design, or have no relevance for the long-term safety and are therefore not be considered in the analysis:

- The *test-box* used in the *FSS* demonstrator is a specially constructed concrete box that can be closed at each end to allow environmental conditions (temperature and relative humidity) representative of those of the underground. The test box is not a part of the disposal design. The monitoring of the test-box stability and of the ambient conditions in the *FSS* demonstrator is carried out to show that the test-box is stable during the construction and filling operations and that the subsurface disposal conditions are correctly reproduced.
- A *tunnel back wall* is present in the *POPLU* and *DOMPLU* demonstrators. The back wall is not part of an actual repository design. The wall helps to control the back surface of the tunnel and to realize the specific dimension of the tunnel needed for the demonstrator. The casting of the back wall represents also a practice for the casting of



the actual concrete plug (formwork erection, monitoring methods, concrete delivery sequence, concrete pumping and quality control methods) [DOPAS 2016b].

- The main function of the *concrete block(s)* is to hydraulically isolate the downstream structures (in all five considered designs) and to keep in place the downstream backfilling and buffer materials (in case of *DOMPLU*, *POPLU*, *ELSA*) or the bentonite seal situated between two concrete blocks (*EPSP*, *FSS*). The hydraulic isolation and mechanical stability of the concrete blocks are required during the operational phase of the repository. After repository closure the functions of the concrete block(s) are taken over by other repository components: the role of the abutment is ensured by the upstream backfill, and the hydraulic isolation is ensured by the saturated sealing elements, backfill, buffer and host rock. The monitoring of concrete blocks has therefore no relevance for the performance assessment.
- The *filter layer* has the function of keeping the water pressure low at the concrete plug until it has cured. The monitoring of the filter layer is thus not relevant for the long-term safety of the repository.
- Two types of sealing elements can be distinguished in the DOPAS demonstrators: thin sealing elements (*DOMPLU*, *POPLU*) having the function of sealing the EDZ around the concrete block, the gap formed between the concrete block and the host rock, and eventually the fine cracks in the concrete block that may form as result of one or a combination of factors such as shrinkage, thermal contraction, external or internal restraints and applied loads. These types of seals ensure the hydraulic isolation by the concrete block and their properties are, just as the properties of the concrete block, relevant only until the repository structures on both sides of the plug are backfilled and full water pressure is reached on both sides. They will not be considered in the further analysis. The other plug and seal designs (*ELSA*, *FSS*, *EPSP*) are provided with a sealing element with a length of several meters. These seals are required to ensure diffusional transport through the repository structures after the backfilling and closure of the repository. The properties of these sealing elements are relevant for the long-term safety of the repository and will be considered further in the analysis.
- In *POPLU*, the near-field measurements are carried out in a demonstration tunnel, excavated next to the plug tunnel to host the instrumentation and pressurization equipment. The goal of these measurements is to assess the responses of the near field during the experiment. These measurements are quite difficult to interpret in relation to the long-term safety since there are no safety functions defined for the near-field, and will be not considered further.

The safety functions of the backfill and the related safety function indicators for the Swedish (and Finnish) disposal designs are summarized in Table A-2 (see Appendixes A.1 and A.5) for more detail). The DOPAS demonstrator's barrier components of relevance for the long-term safety - based on Table 4-1, Table 4-2, Table 4-3 and the considerations in the previous section - are the *backfill end zone* and the *sealing element* of the plug. These components consist of swelling clay. They have the main function of preventing advective transport within the repository structure, also after the function of the concrete block is lost.

Table 4-2: Safety function indicators linked to safety functions of the deposition tunnel backfill.

Safety function		Density	Swelling pressure	Hydraulic conductivity	Temperature	Sorption coefficient	Diffusion coefficient
Backfill	Counteract buffer expansion	+					
	Limit advective transport		+	+	+		
	Sorb radionuclides					+	

Table 4-3: Selection of relevant indicators for Safety function indicators for deposition tunnel backfill

Safety function	Parameter	Directly measured in demonstrators	Indirectly measured in demonstrators	Overall safety of the system
<i>Limit advective transport</i>	Backfill temperature	-	-	-
	Backfill swelling pressure	+	+	-
	Backfill hydraulic conductivity	-	+	-
<i>Sorb radionuclides</i>	Backfill $K_d$	-	-	-
<i>Counteract buffer expansion</i>	Backfill density	-	+	-

Features and expected performances and/or indicators related to seals within the repository galleries and the seals around ILW disposal cell in the French disposal design are summarized in Table 4-4 (see Appendix A.3 for more detail).

Table 4-4: Performances, indicators and criteria expected from the seals within the galleries in relation to the long-term safety functions [MoDeRn, 2013b]

Relevant disposal component	Safety function of the component	Features and/or expected performances and indicators as basis for the safety
Seals within repository galleries	Limit water flux through the repository structure	Performance of gallery seal close to source: <ul style="list-style-type: none"> <li>Permeability <math>10^{-11}</math> m/s</li> <li>Dry density related to swelling pressure</li> <li>Swelling pressure between 1 and 7 MPa</li> </ul>
Seals ILW disposal cells	Limit water flux in or out the disposal cell	Cf. gallery seal

The next step is to see whether safety function indicators are measured in the demonstrator (see Table 4-3 in the case of the *DOMPLU* demonstrator). The safety function indicators provided by SKB which are directly or indirectly measured in the demonstrator components made of swelling clay are:

- density (indirectly measurable)
- hydraulic conductivity (indirectly measurable)
- swelling pressure (directly measurable)

It must be noted that these indicators provide only limited and indirect information about the overall safety of the repository system. The breaching of these criteria does not mean that the repository is unsafe but rather that more elaborated analyses are needed to evaluate its safety [SKB, 2011].

It is important to note that the three identified measurable safety function indicators are related to each other since they provide information about coupled hydro-mechanical processes. The monitoring of these parameters during the saturation phase gives an indication about the evolution of the saturation process but does not provide direct information about the long-term safety of the system nor about the fulfilment of the corresponding safety functions: this has to be established by coupling of these parameters by process modelling, or by comparison of parameter evolutions with expected ones. E.g., at equilibrium and full water saturation the pressure in a confined volume is closely related to the water ratio (mass of water/ mass of solid) in the clay, which is related to the density of the clay-water system.

The parameters monitored in the DOPAS demonstrators which can be related to the safety functions of the swelling clay in seal and backfill are:

- Temperature
- Pressure (pore pressure, swelling pressure, total pressure)
- Relative humidity
- Displacement
- Leakage

These parameters and the processes related to these parameters as well as their relevance for the long-term safety have been briefly analysed in the next section.

## 4.2 Relevance of monitored parameters for the long-term safety

The demonstrator components relevant for the long-term safety were identified in the section above. These are the *backfill end zone* in the case of *DOMPLU* and the *sealing element* made of swelling clay situated between two concrete abutments in the case of *FSS*, *ELSA* and *EPSP*. The *POPLU* demonstrator contains no component for which a long-term safety function is defined.

The main function of the components made of swelling clay materials is to restrict the water flow within the repository structure to avoid a transfer bypass of host formation during permanent, post-closure conditions. This is achieved by a sufficiently low hydraulic conductivity making diffusion the dominant transport mechanism and by a swelling pressure ensuring the self-sealing (self-healing) of the swelling clay component. A first quantitative requirement for the hydraulic conductivity can be derived from the Péclet number of the seal (Section 3.4.1): a Péclet number smaller than one leads to a (favourable) diffusion-dominated behaviour. To fulfil this requirement:

- all initially-present gaps in the repository should be (back)filled and/or healed,
- the contact between the backfill and/or sealing components (buffer, backfill, seal) of the repository and the host rock must be tight, and
- a minimum swelling pressure of the swelling components must be reached<sup>10</sup>.

The *hydraulic conductivity* and *porosity* of a swelling clay plug is primarily dependent on its geometry, composition and density, the salinity and composition of the pore water, and the temperature. The hydraulic conductivity is strongly affected by the degree of saturation of the swelling materials. It varies strongly with the degree of saturation and reaches a constant value when the swelling clay reaches its saturation: unsaturated clay manifests a high hydraulic conductivity that decreases with increasing saturation and reaches its minimum value at complete saturation. Not all factors are equally important for the performance of the plug: e.g. the influence of salinity on the hydraulic conductivity of saturated swelling clays is found to be insignificant at densities chosen as optimal for the swelling materials.

There are two critical processes that may affect the long-term performance of the engineered barriers made of swelling clays:

- Loss of clay material by piping or erosion;
- Chemical alteration of the swelling clay material.

Both these effects are driven by groundwater flow and chemistry, which are dependent on the characteristics of the site and on climate evolution.

<sup>10</sup> Usually, this requires a minimum hydraulic conductivity in case of non-swelling materials (concrete, sand, etc.).

The effect of the mass loss on the performance of the barrier made of swelling clay depends on the amount of mass loss and the spatial distribution of the mass loss. A localised mass loss can have a significant effect on the properties of the clay and its barrier performance at that location. The effect of the mass loss will also depend on redistribution processes within the repository structure: if the mass loss in the disposal cell is small, effects on the hydraulic conductivity or the swelling pressure on the long term are expected to be limited. Next to mass loss by piping and erosion, mass loss by chemical alterations due to the potential occurrence of dilute groundwater can occur.

Parameters characterizing the sealing elements made from swelling clay and monitored in the DOPAS demonstrators (temperature, pressure, relative humidity, displacement and leakage) and the processes related to these parameters and their relevance for the long-term safety are discussed in the following sections.

#### 4.2.1 Temperature

Temperature represents one of the three key parameters in a repository in order to monitor and assess the THM evolution of both engineered and natural barriers. The elevated temperature in a repository is basically caused by radioactive decay of the high-level radioactive wastes while the lower temperatures may be dictated by future climatic changes such as glacial periods and permafrost.

Usually, an increase in temperature is accompanied by an increase in the chemical reaction and transport processes rates. A general rule of thumb for most chemical reactions is that the rate at which the reaction proceeds will approximately double for each 10°C increase in temperature. Typical values (and ranges) of activation energies ( $E_a$ ) for chemical and transport processes and the relative increase of the rate coefficient ( $k$ ) when temperature increases from 10 to 20°C according to Arrhenius equation are given in Table 4-5.

Table 4-5: Temperature dependency of several processes [Appelo & Postma, 2005, Tab. 4.8]

Process	$E_a$ (kJ/mol)	$k_{20^\circ\text{C}}/k_{10^\circ\text{C}}$
Diffusion in water	20	1.34
Dissolution/Precipitation	20 (20-80)	2.4
Biochemical reactions	63 (50-75)	2.5

Elevated temperature also directly influences the hydraulic conductivity by changing the viscosity of the water, whereby a temperature increase from 20°C to 90°C entails an approximate increase in conductivity by a factor of 3.

Other effects of *elevated temperatures* on the clay barrier's properties include:

- An increase in ion concentration leads to a *reduction of the swelling pressure* and changes in the pore geometry, affecting the *hydraulic conductivity* at low saturated densities.

- *Thermal expansion* of a plug can be detrimental for the host rock and the canister, especially in the case of crystalline host rock. This effect is only relevant if the component made of swelling clay is water-saturated: the temperature increase leads to a considerable increase of the pore pressure since the water is unable to expand.
- *Thermal induced pore water pressure* can be detrimental in case of insufficient drainage. The magnitude of the pressure increase is moderated by drainage of the water through the rock and EBS. A slow temperature increase in combination with sufficient drainage through the rock and EBS should not be detrimental to the host rock and canister.
- The interaction of swelling clays with *iron-rich fluids* at high temperature (~100 °C) leads to transformation from smectite to illite. Such transformations alter layer charges and affect the swelling pressure. This can finally lead to a higher hydraulic conductivity of the swelling clay.
- Based on the influence of temperature on the diffusivity of ions in free water, it can be expected that *diffusion coefficients* will increase about twofold when temperature is increased from ambient conditions to about 50–60°C [SKB, 2010].

Lowered temperatures may lead to:

- a completely loss of swelling pressure [SKB, 2010; p.54];
- *Freezing* of water saturated clay resulting in an increase of the clay volume and the mechanical pressure on the canister and rock.

#### 4.2.2 Pressure

*Mechanical pressure* is, next to temperature, another key parameter in the THM evolution of a repository. It provides information on the evolution of the clay saturation and consecutive swelling and thus the performance of the seals in terms of permeability and porosity.

*Hydraulic pressure* provides information on the state and behaviour of the rock or soil under investigation. In soils, hydraulic pressure is more commonly designated as *pore water pressure*. The monitoring of hydraulic pressure during construction and operational phase aims to identify whether and how the facility impacts the parameter in question, to provide data for adaptation of the facility to the bedrock and to verify that the design premises are fulfilled. The *pore water pressure* is an important variable, which, from geotechnical view, can be described according to Eq. 4-1 [SKB, 2010a]:

$$\psi = (u_a - u_w) + \pi \quad \text{Eq. 4-1}$$

with:

- $\psi$  free energy of the soil water (usually named total suction),
- $u_w$  pore water pressure,
- $u_a$  pore gas pressure,

$\pi$  osmotic suction of the external groundwater (dependent on differences in ionic concentration),

$u_a - u_w$  matric suction (stems from capillary effects).

The total suction can also be expressed in terms of relative humidity of the clay. Eq. 4-2 shows the relation between the partial vapour pressure  $p$  and the suction,  $\psi$ , with the ratio  $p/p_s$  corresponding to the relative humidity:

$$\psi = -\frac{R \cdot T}{v_{w0} \cdot \omega_v} \ln\left(\frac{p}{p_s}\right) \quad \text{Eq. 4-2}$$

with:

$\psi$  suction [kPa]  
 $T$  absolute temperature [K]  
 $R$  universal gas constant (=8.31432 J/(mol·K))  
 $v_{w0}$  specific volume of water [m<sup>3</sup>/kg]  
 $\rho_w$  density of water [kg/m<sup>3</sup>]  
 $\omega_v$  molecular mass of water vapour (=18 kg/kmol)  
 $p$  partial pressure of pore water vapour [kPa]  
 $p_s$  saturation pressure of water vapour over a flat surface of pure water at the same temperature [kPa].

At full saturation, the swelling pressure and the pore water pressure are independent quantities and give a total pressure that is the sum of the pressures according to:

$$\sigma = \sigma' + u \quad \text{Eq. 4-3}$$

where:

$\sigma$  total stress  
 $\sigma'$  effective stress (= swelling pressure)  
 $u$  pore water pressure

The *mechanical pressure* in multi-barrier system is determined by following processes:

- The *swelling* of the clay that leads to mechanical pressure on the canister and rock surface.
- The *water pressure* added to the swelling pressure gives the isostatic load within the repository. The highest isostatic load will occur during glacial periods when the groundwater water pressure is at its maximum.
- *Corrosion* leads to corrosion products that have a lower density than the original material and thus result in an increase of the volume. This material expansion will result in elevated pressures and may result in compression and consolidation of the components made of

swelling clay and thereby increase the pressure from these components on the canister and rock surface.

- The *thermal expansion* of the swelling clay is dependent on the saturation degree of the clay: in saturated clay, the water will be unable to expand, and the resulting pressure increase towards the surrounding components can be significant. This pressure increase is counteracted by drainage of the water, especially when the temperature increase is slow and a drainage path is available.
- High *gas pressures* can be expected as a possible consequence of corrosion processes within the system.
- *Freezing* of the components made of swelling clay may lead to an increase in volume and respectively to an increase of the pressure.

The mentioned processes lead to a combination of processes affecting the pressures in the repository. An equilibrium is typically established after complete water saturation and pore water pressure stabilization, which includes stress differences and shear stresses in the EBS elements made of swelling clay. Pressure can also be related to the safety function of *containment* attributed to the waste canister: the release of contaminants from the waste canister is maintained as long as the canister can withstand the pressure loads. At isostatic loads higher than in the design specifications of the canister, no containment function for the canister can be guaranteed.

A number of processes may lead to a *low pressure* or a *pressure drop* in an EBS component made of swelling clay:

- *Swelling pressure drop with temperature*: under certain circumstances, the swelling pressure can be completely lost with freezing [SKB, 2010a; p.54].
- When a *canister is damaged*, the clay may penetrate into the voids inside the canister leading to a pressure drop in the buffer or backfill. The influence of this process is thought to be small due to the small void volume available inside the canister [SKB, 2010a, p.94].
- Clay may also *penetrate into the fractures* of the host rock around the deposition hole or deposition tunnel and, depending on the conditions in the near-field rock, the clay in the fractures could be washed away by groundwater, allowing new portions of clay to penetrate into the fractures, eventually leading to gradual erosion of the clay. If there is no loss in clay material due to erosion, the overall effect on the long-term safety can be positive since it implies a sealing of the fracture [SKB, 2010a, p.86].
- *Degradation of concrete* in cementitious components of the EBS will cause the mechanical function of the concrete barrier to cease and will lead to the transfer of the swelling pressure from the clay components to other compartments, and also to a loss in the total density of the barrier made of swelling clay that may facilitate transport.
- high pressures developed within the repository system may lead to *displacements of EBS components* and may result in a change of backfill volumes that may also affect the density of the swelling clay.



### 4.2.3 Relative humidity

The third key parameter in the THM evolution of a repository is the *water content* and *relative humidity*. The degree of saturation of the engineered barrier is directly linked with its performance over time, hence the importance of its monitoring.

The pore water pressure in unsaturated clay is strongly affected by the water content and can be represented by a retention curve, showing the relation between the total suction (or relative humidity according to Eq. 4-2) and the saturation.

As example, a retention curve of MX-80 clay material is shown in Figure 4-1:

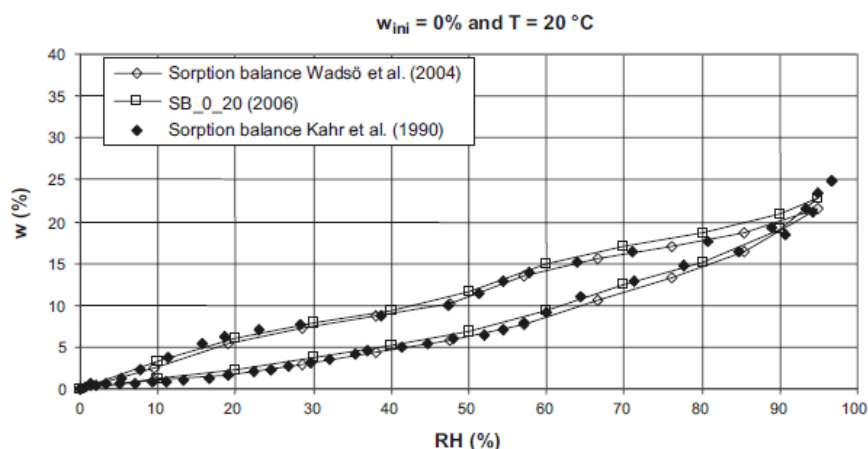


Figure 4-1: Retention curve of MX-80 (from [SKB, 2010a, p. 62]). The lower curve is absorption and the upper is desorption.

The retention curve describes an important relationship for modelling the wetting of materials made of swelling clay. This process is influenced by factors such as [SKB, 2010a]:

- *Wetting path:* There is a significant hysteresis effect, which means that wetting yields lower water content than drying at the same relative humidity.
- *Initial conditions:* After mixing with water, the measured relative humidity lies between the wetting and drying curve.
- *Temperature:* An increase in temperature yields an increased relative humidity at the same water content.
- *Confining conditions:* If the swelling clay is confined and thus not allowed to swell, relative humidity will be higher than if it is not confined.
- *External stress:* An increased external stress increases relative humidity at constant water content.

A commonly used relationship between hydraulic conductivity and the degree of water saturation is provided in the following equation:

$$K_p = S_r^\delta \cdot K \quad \text{Eq. 4-4}$$

Where:

- $K_p$  hydraulic conductivity of partly saturated soil [m/s]
- $S_r$  degree of water saturation [%]
- $K$  hydraulic conductivity of completely saturated soil [m/s]
- $\delta$  parameter  $\approx 3$  for MX-80 at buffer densities

The porosity  $\phi$  is also affected by the degree of saturation. The void ratio  $e$  and degree of saturation  $S_r$  can be determined according to [Dueck, 2010; p.9]:

$$e = \frac{\phi}{1 - \phi} = \frac{\rho_s}{\rho} \left( 1 + \frac{w}{100} \right) - 1 \quad \text{Eq. 4-5}$$

$$S_r = \frac{\rho_s \cdot w}{\rho_w \cdot e} \quad \text{Eq. 4-6}$$

Where:

- $\rho_s$  particle density [ $\text{kg/m}^3$ ]
- $\rho_w$  density of water [ $\text{kg/m}^3$ ]
- $w$  water content [%]
- $\rho$  bulk density of the specimen [ $\text{kg/m}^3$ ]

#### 4.2.4 Displacement

High pressures developed within the confined space of an underground repository or degradation processes of EBS materials may lead to *displacements* of EBS components of the facility. The displacements may lead to a change in volumes that may affect the density of the EBS components with a sealing function and by this their sealing capacity.

#### 4.2.5 Leakage

The leakage through the plug or seal gives an indication of its tightness and of the hydraulic conductivity of the sealing component of the plug and/or the downstream backfill material. The erosion of swelling clay may damage the barrier function of the buffer, backfill and seal. This may result in a decrease of the total density of the sealing element and/or downstream backfill and consequently an increased supply of corrosive agents to the canister and a larger nuclide release from the waste. When a certain amount is lost, the remaining clay, at least locally, can have a hydraulic conductivity high enough to allow water to flow through it.

The measurement of the plug leakage combined with the measurement of the turbidity of the leaking water can give an indication about the quantity of clay washed through the plug out the deposition tunnel. The total mass of clay eroded throughout the plug and/or other identified leakage locations can be determined, based on the volume of the leaked water and the measured concentration of solids in this water. This method does not account for the erosion of the swelling clay to unidentified and/or unmonitored fractures in the rock and thus may underestimate the total amount of eroded clay.

An estimation of the density of the backfill that includes potential mass losses through the host rock can be carried out through the monitoring of the swelling pressure, as discussed in Section 4.2.2. Unlike the measurement of leakage and turbidity, the measurement of swelling pressure provides only useful information on the clay density after saturation of swelling clay is reached.

### 4.3 Monitoring results

As summarized in Table 4-1, a variety of parameters are monitored in the DOPAS project. The relevant parameters of interest, as discussed in the previous section, are the ones that give an indication about the degree of saturation of the clay material and the related property changes caused by this process. As also established in the previous section, those are the components of interest for monitoring the seal or plug elements made of swelling clay. Additionally, leakages out of the disposal tunnel and displacements of EBS components also could provide (indirect) information on the performance of the clay barriers.

However, a principle problem valid for all DOPAS demonstrators is the rather short duration of monitoring that could be performed during the DOPAS project, i.e. compared respect to the period necessary for resaturation and full performance of the barriers. The short duration of the experiments does not allow to make any conclusions on the expected performance of the relevant barrier systems on the long term. Therefore in the remainder of this section, only short, qualitative discussions on some example results are provided.

Figure 4-2 shows results from the measurements of displacement carried out in *DOMPLU*. The displacement sensors registered a movement inwards as result of the swelling of the bentonite sealing and compression of the gravel filter and the pellet filled slot inside the LECA wall. A total displacement of about 30 mm was registered on the day 385 after the start of the experiment, as result of the increasing swelling pressure of the saturation of the sealing element.

Displacements (20130130-20140930)

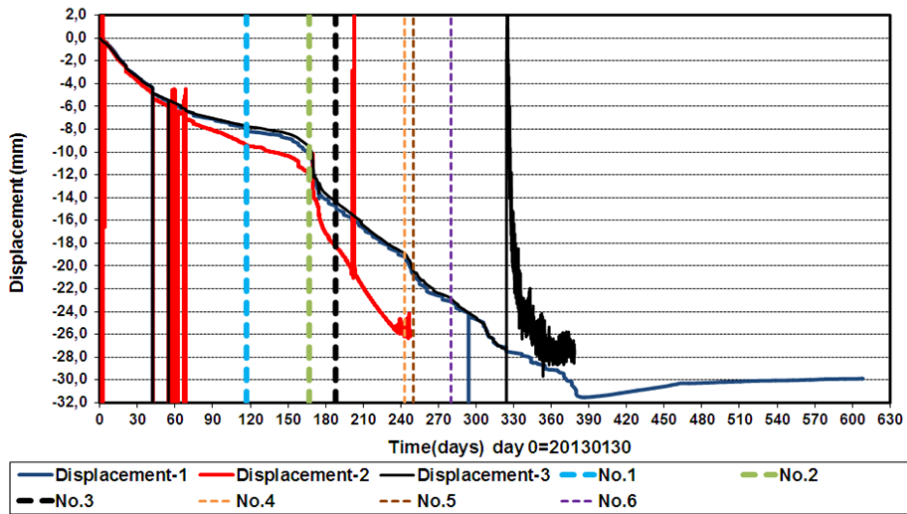


Figure 4-2: Measured displacement of the seal (2) and LECA (1 and 3) respectively compared to the concrete back wall (from [Grahm *et al.*, 2015, Chapter 9]).

Figure 4-3 depicts measurements of leakage rate in the *DOMPLU* demonstrator. This measurement in combination with measurement of the solids content in the leaking water can give an indication about the quantity of clay lost through the plug out the deposition tunnel.

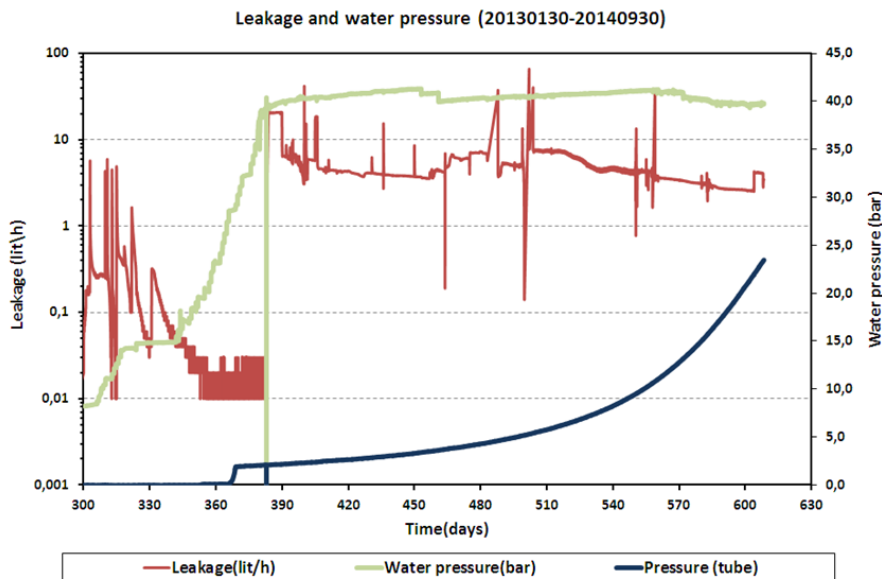


Figure 4-3: Measured leakage from the weir and the applied water pressure (from [Grahm *et al.*, 2015, Chapter 9]).

The determination of mass loss by leakage may, however, as stated in the previous sections, underestimate the total amount of eroded clay since it does not account for the erosion of the swelling clay at the interface between the clay and the host rock or erosion by water flow through unidentified and/or unmonitored fractures in the rock.

The pressures (pore and total pressure) and relative humidity of the clay material give an indication about the saturation process. At full saturation maximum and constant pressure and relative humidity will be reached. Some results from the measurements of total pressure and relative humidity carried out in *DOMPLU* are shown in Figure 4-4 and Figure 4-5.

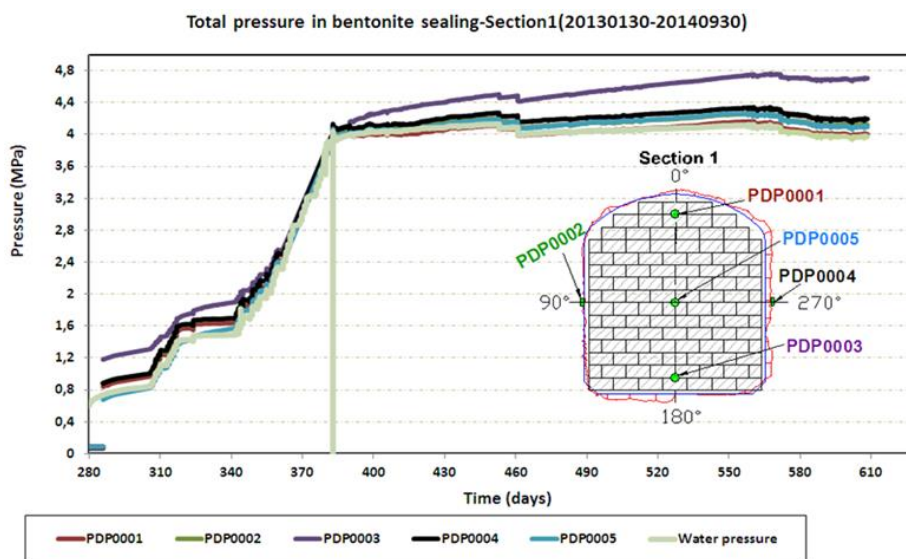


Figure 4-4: Total pressure in Section 1 in the bentonite seal [Grahm *et al.*, 2015].

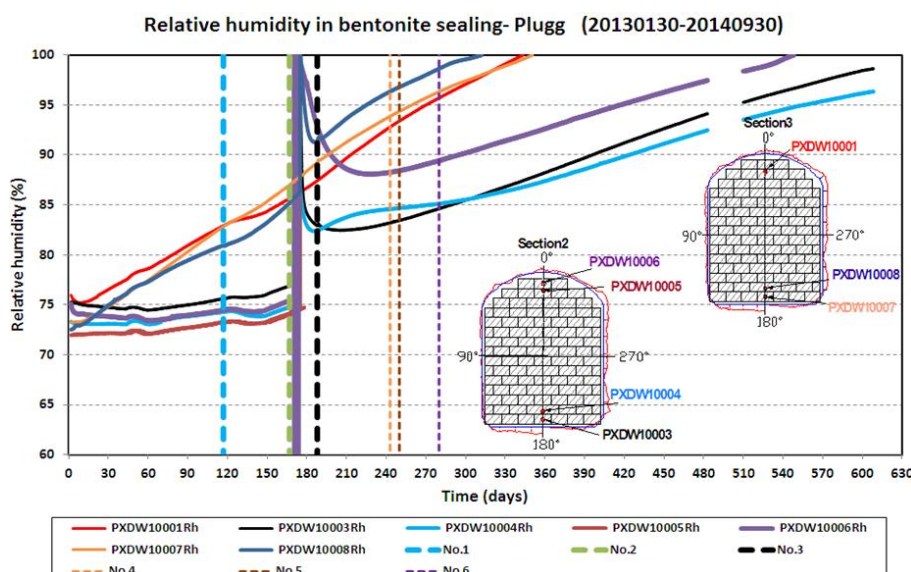


Figure 4-5: Relative humidity recordings in the bentonite seal [Grahm *et al.*, 2015].

After full saturation is reached, the swelling pressure reaches its maximum value that can be related to the dry density and hydraulic conductivity by *a priori* established process models or dependencies discussed in Section 4.2.2 and 4.2.3. Figure 4-6 and Figure 4-7 show respectively swelling pressure and the hydraulic conductivity as functions of the dry density of several swelling clays, and Figure 4-1 on page 75 show the relation between swelling pressure and saturation for MX-80 swelling clay.

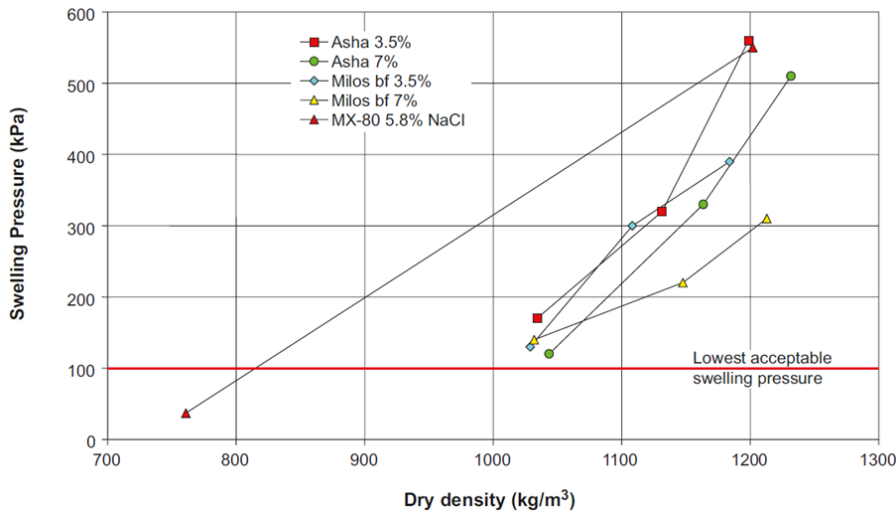


Figure 4-6: Material specific relation between density and hydraulic conductivity for three materials with variable salinity [SKB, 2010b].

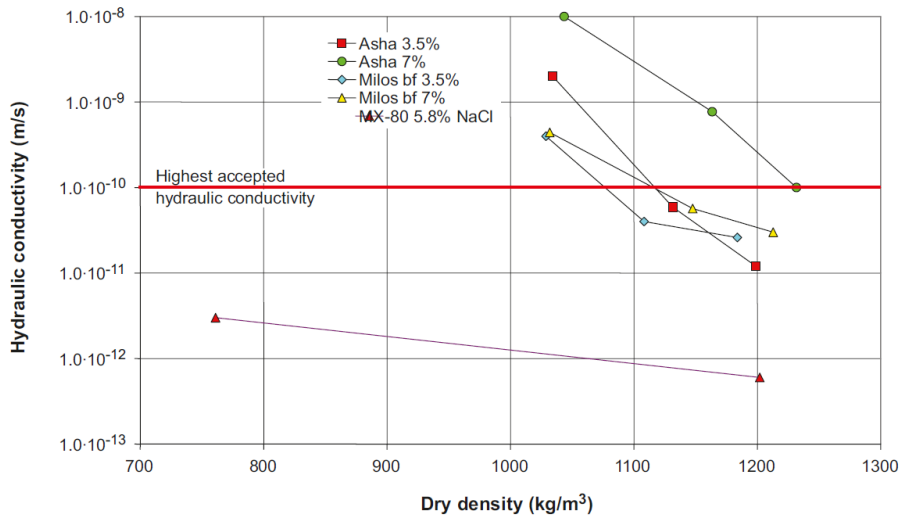


Figure 4-7: Material specific relation between density and swelling pressure for three materials variable salinity [SKB, 2010b].

The monitoring of the temperature in the plug or seal or in the sections next to them gives an indication about the heat developed as result of hydration of cement. Figure 4-8 shows the temperature increase due to the hydration heat developed during the curing of the *DOMPLU* plug dome. The evolution of the temperature is rather complex due to the cooling system installed in the demonstrator, however, the rather limited temperature increase is not expected to impair the function of the clay seal and backfill and thus the safety functions of the plug and backfill on the long term.

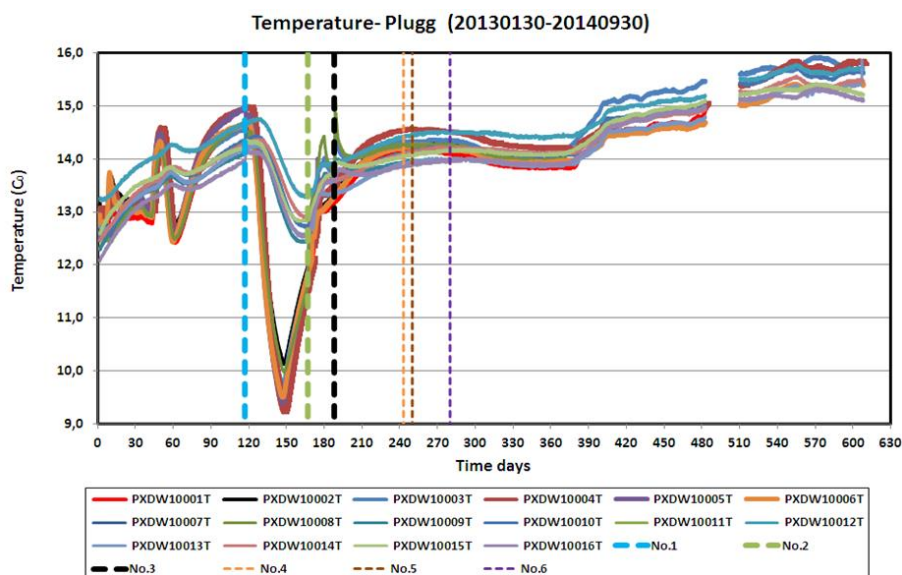


Figure 4-8: Recordings of temperature at several locations in the *DOMPLU* demonstrator [Grahm *et al.*, 2015]





## 5 Synthesis & conclusions

The demonstration of the proper performance of relevant EBS components can provide valuable evidence for safety: part of such a demonstration is the monitoring of the evolution of relevant features or process parameters in time. Monitoring is generally seen as beneficial for confidence building, and monitoring of demonstrators can do so in advance of the actual disposal of waste, facilitating the implementation process. NRG's interest in understanding the potential role of demonstrator activities in an early stage of the national implementation process - with a disposal facility not foreseen before the next century - was related to elaborate options to use (monitoring data from) demonstrator activities for the purpose of safety analysis. Furthermore, monitoring of demonstrators knows fewer technical limitations than *in-situ* repository monitoring, offering effective options to provide evidence for safety in an early stage.

The objective of NRG's contribution to WP5 of the DOPAS project was to investigate how demonstrator monitoring activities can be coupled more closely to PA calculations, and to develop and test approaches that allow the integration of technical demonstrator's results into a safety case. NRG aimed to develop a strategy for integration of monitoring results by identifying meaningful indicators that have two characteristics:

- the indicator is directly or indirectly measurable in demonstrators, and
- the indicator allows assessing the complete system behaviour.

SKB's concept of *safety function indicators*, including quantitative *criteria*, provides a good starting point for identifying such indicators. These safety function indicators and related criteria are useful tools in providing evidence for safety. However, they do not provide direct information on the long-term safety in case criteria are not met: due to the multi-barrier principle and the complex interactions of repository components, non-compliance with a criterion not necessarily implies an unsafe repository, and relevantly increased risks might be limited to few scenarios with limited likelihood. Figure 5-1 depicts the resulting dilemma: systematic screening of safety case elements as disposal design, safety functions, FEPs, and scenarios can result in a well-supported definition of monitorable indicators and criteria that can be assessed in a demonstrator. However, it is difficult to substantiate the consequences for the long-term safety in case criteria are not met. As consequence, these indicators and criteria have limited value for PA, because these are based on identifying what 'guarantees' safety rather than evaluating under which unfavourable circumstances long-term safety will be impaired.

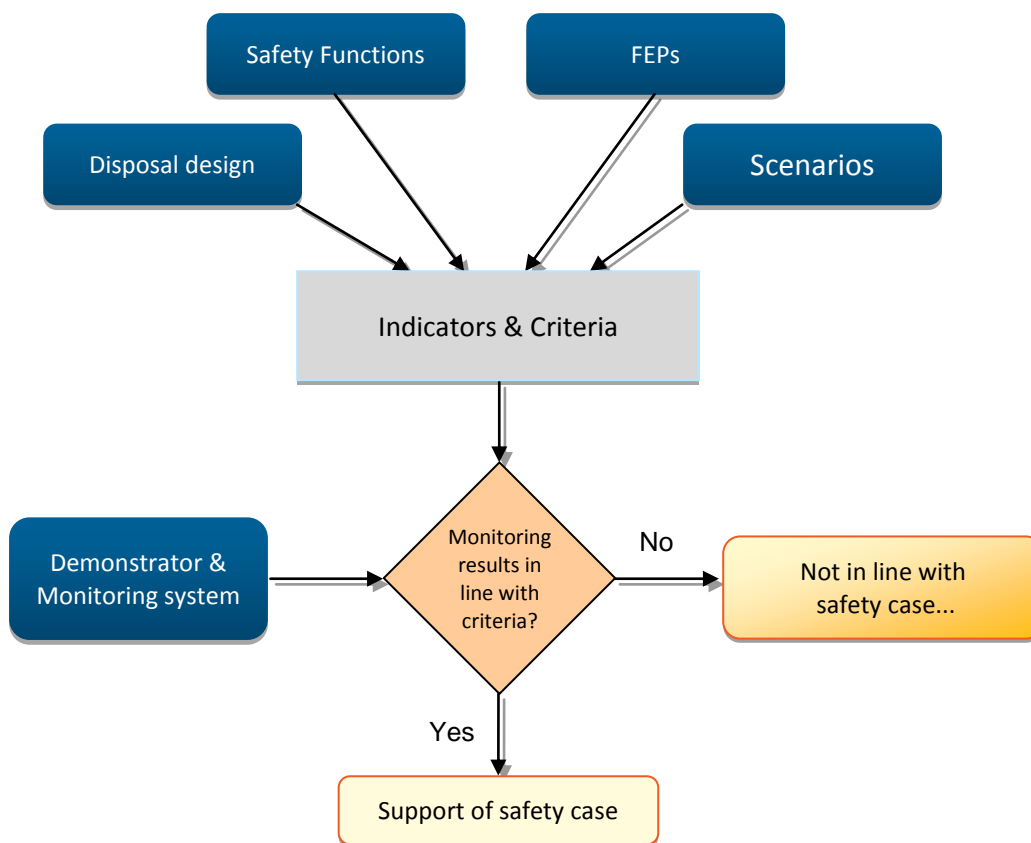


Figure 5-1: Indicator analysis and demonstrator monitoring

Nevertheless, the identification of *safety functions* for repository components is of vital importance for the development of a monitoring programme. On the one hand, the safety functions are key elements of the safety concept and on the other hand they are the handles for identifying processes that may impair the proper performances of each individual repository component.

A second principal limitation noted for the DOPAS demonstrators was the operation time: relevant processes, e.g. the resaturation of swelling clay, are rather slow and full resaturation of the barrier often exceeds the operational life time of the demonstrator. The slow evolution of the identified processes may hamper the practical determination of parameters regarded relevant for these processes. Assuming an operation of the repository according to prescribed procedures, and a normal evolution of the repository upon closure of (parts of) the facility, monitoring of processes may provide significant evidence for a safe evolution only over time intervals that cannot be realized due to technical limitations.

With these limitations in mind, Section 2.4 provides a generic approach for the identification of monitorable parameters relevant for the long-term safety, based on the DOPAS input, distinguishing between two safety functions: (1) isolation and containment of the waste, and (2) retardation of radionuclide migration. The latter is of relevance for PA, and hydraulic abstraction of

the sealing system together with known source terms and/or reference values allows the assessment of the long-term safety. The approach makes use of basic elements of a safety case:

- *Safety functions* as useful abstractions of the safety concept on a barrier level.
- *Indicators* as important tools in communicating safety. For “monitorable” indicators, only performance indicators are of relevance. From these, the *safety function indicators* and *performance indicators related to safety functions* are of most interest for the identification of relevant, monitorable parameter:
  - *Safety function indicators* and their related criteria are useful tools in providing evidence for safety. However, they do not provide direct information on the long-term safety in case criteria are not met.
  - *Performance indicators related to safety functions* allow to quantify the contribution of each safety function or EBS-(sub)component to the long-term safety, eventually broken down to process- and parameter level by the use of uncertainty- and sensitivity analysis. Such analyses can be performed for each considered scenario. For better system understanding, “what-if”-scenarios can be defined in order to challenge each barrier component within a multi-barrier approach.
- *Scenario definition and -analysis* as useful tools: they allow identifying conditions in which the performance of an individual barrier can be of relevance for the overall safety. Furthermore, the full set of scenarios considered in a programme defines for each parameter a value range in which monitoring data should fall.

The EBS components with a safety function for the long-term safety in DOPAS are either the backfill or the sealing element made of swelling clay. The *structural components* of plugs and seals *made of cementitious materials* as considered in DOPAS have no safety function on the long term, i.e. the period after container failure.

The tested travel-time based indicator was judged useful, because it allows addressing processes upstream and downstream of the barrier independently. Different assumptions and scenarios can be coupled, and can directly be related to relevant parameters.

The principal parameter identified as relevant for the long-term safety is the *hydraulic conductivity* of barriers. The hydraulic conductivity can be related to the swelling pressure and the density in case of a swelling clay material, or to the salt compaction and backfill pressure in case of salt grit. It varies strongly with the degree of saturation or compaction and reaches a constant value when equilibrium within the system is established: saturation in case of swelling clay or full compaction in case of salt grit. The value of the hydraulic conductivity at equilibrium is directly relevant for the long-term safety, while the evolution of the conductivity in earlier stages needs to be linked with process models in order to allow safety evaluations. Other relevant key features and processes identified are the pressure gradient over the barrier, sorption of radionuclides, and solubility of radionuclides, with the latter two usually determined in independent batch experiments. Diffusion related processes are assumed to be of less relevance for monitoring, because for most concepts and host rocks, diffusion cannot be avoided and is part of the expected normal evolution.



Identification of *monitorable parameters* relevant for PA should therefore focus on *hydraulic aspects*, related to permeability, pressure, porosity, compaction, and convergence etc. Because most of the related parameter cannot be monitored either in demonstrators nor *in-situ*, they must be determined through indirect measurements or laboratory experiments. The derivation of these parameters involves process assumptions as a rule. For disposal systems in rock salt, the presence of brine is an important factor, which is monitorable by e.g. measurement of the electrical conductivity.

None of the indicators relevant for the long-term safety analysed in this report is *directly* measurable in the DOPAS demonstrators. Indicators providing information about the long-term safety are based on *indirect* measured parameters in combination with a set of assumptions related to the rest of (not monitored) compartments of the system. Only on the longer term, i.e. after several decades, in the case of resaturation of clay or compaction of rock salt grit, these indicators may provide relevant information about the evolution of the seals and plugs in a geological disposal.

## Appendix A: Case Studies

### A.1 Deposition tunnel end plug of the Swedish disposal concept in granite: *DOMPLU*

#### A.1.1 Disposal design, Safety Functions, FEP's & Scenario's

##### *Disposal concept*

The Swedish concept for final disposal (KBS-3) is based on three protective barriers: copper canisters, bentonite clay and crystalline bedrock. Copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited in vertical holes (each for deposition of one canister) at approximately 500 m depth in saturated, granitic rock (see Figure A-1; from [SKB, 2006a, p.11]).

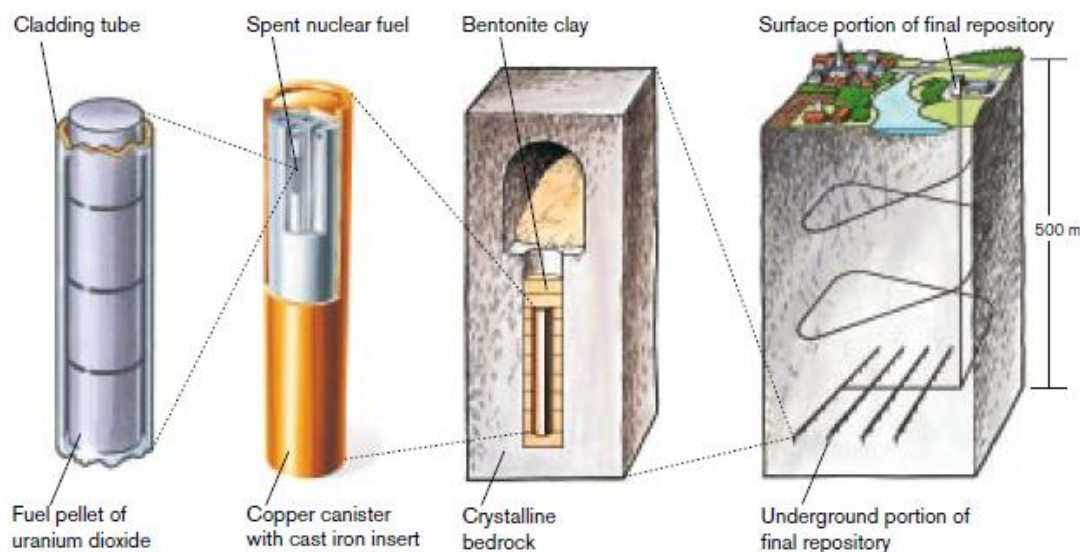


Figure A-1: The KBS-3 concept for disposal of spent nuclear fuel (from [SKB, 2006a, p.11]).

##### *Safety functions, FEPs*

In the SR-Site project, a set of *safety functions* has been defined that the repository system should fulfil over time. The evaluation of the safety functions over time is facilitated by associating every safety function with a *safety function indicator*, i.e. a measurable or calculable property of the repository component in question [SKB, 2011]. In the Swedish Safety Case, two groups of safety functions are distinguished: safety functions and safety functions related to retardation.

A schematic of the safety functions related to *containment* is indicated in Figure A-2 [SKB, 2011; p.290], showing the safety functions (bold), safety function indicators and safety function indicator criteria (SKB, 2011b; p.290). When quantitative criteria could not be given, terms like “high”, “low” and “limited” have been used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions Can1 (red), Can2 (green) or Can3 (blue).

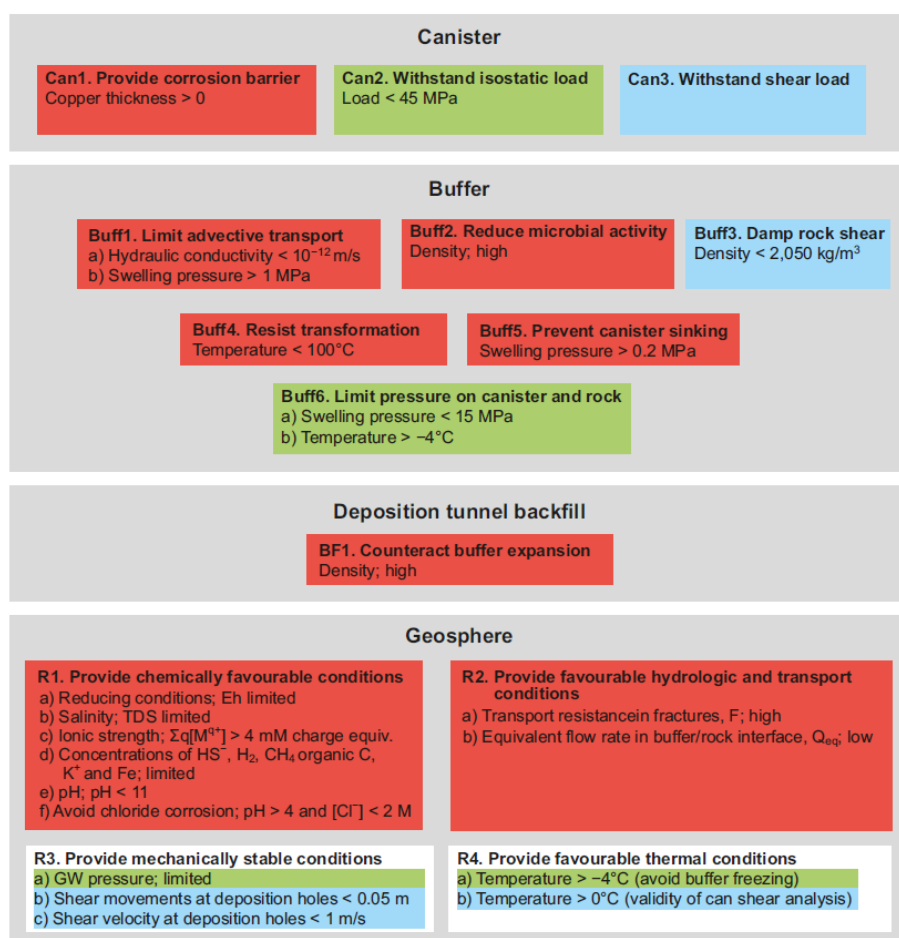


Figure A-2: Safety functions (bold), safety function indicators and safety function indicator criteria related to containment

Figure A-3 shows the safety functions related to *retardation* [SKB, 2011; p.267]. When quantitative criteria could not be given, terms like “high”, “low” and “limited” were used to indicate favourable values of the safety function indicators. Safety functions marked with an asterisk (\*) apply also to containment.

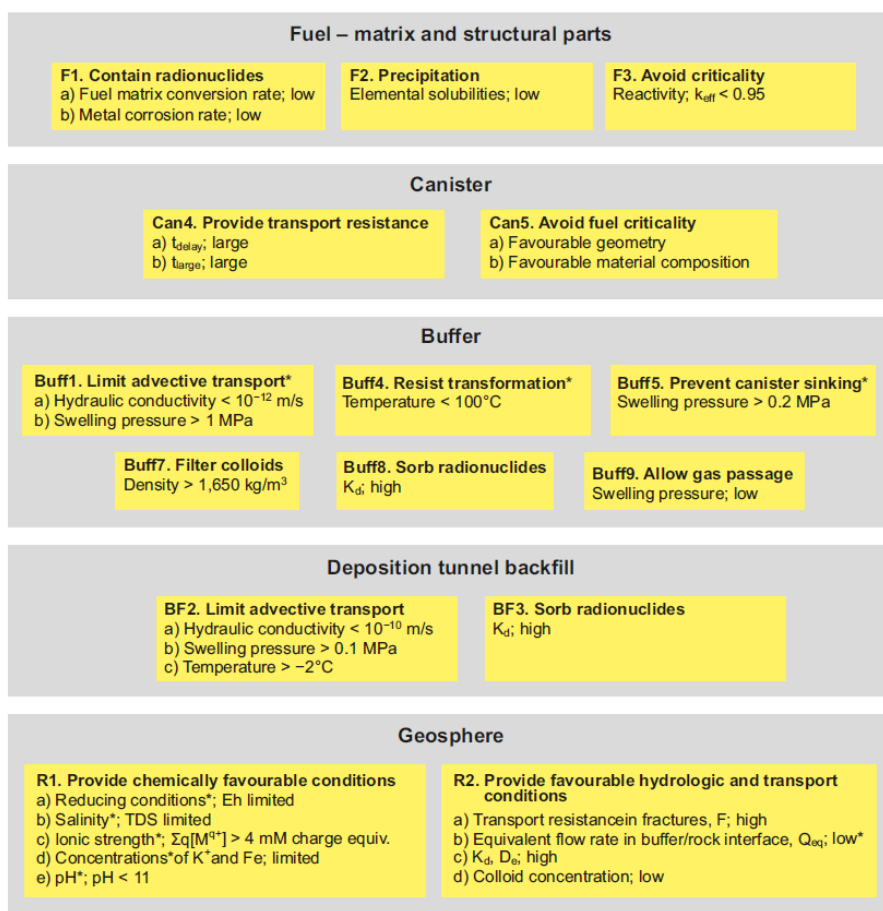


Figure A-3: Safety functions (bold), safety function indicators and safety function indicator criteria related to retardation.

## Scenarios

The assessment of repository safety is broken down into a number of scenarios. Two variants of the reference evolution are analysed [SKB, 2011, Section 10.1]:

- The base variant where it is assumed that the external conditions during the first 120,000 years of the glacial cycle are similar to those experienced during the last glacial cycle. This cycle is repeated seven times to cover the assessment period of one million year.
- The greenhouse variant in which the future climate and, hence, external conditions are assumed to be substantially influenced by anthropogenic greenhouse gas emissions.

Based on an assessment of the potential loss of safety function(s) of the engineered barriers considered in the Swedish concept, scenarios additional to the reference evolution have been identified. The intention of analysing the additional scenarios is to cover uncertainties not addressed in the reference evolution [SKB 2011, Section 11.3]:

- Additional scenarios based on potential loss of safety functions
  - Buffer advection
  - Buffer freezing

- Buffer transformation
- Canister failure due to isostatic load
- Canister failure due to shear movement
- Canister failure due to corrosion
- Scenarios related to future human actions
  - Intrusion by drilling
  - Additional intrusion cases, e.g. nearby rock facility
  - Unsealed repository

### **A.1.2 Indicators & Criteria**

The tunnel end plug is an auxiliary component additional to the engineered barriers. The plug in itself is not meant as a barrier but it is a necessary ingredient to help the backfill in the deposition tunnel to maintain its barrier function [SKB, 2010a, p. 28]. The function of the plug is to 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 [SKB, 2010a, p. 28].

In order for the backfill to withstand conditions, events and processes that may impact its functions, the plug shall [SKB, 2010b, p.24]:

- withstand the hydrostatic pressure at repository depth and the swelling pressure of the backfill until the main tunnel is filled,
- limit water flow past the plug until the adjacent main tunnel is filled and saturated, and
- be durable and maintain its functions in the environment expected in the repository facility and repository until the closure in the main tunnel is saturated.

The plug in deposition tunnels has no long-term safety function in the KBS-3 repository. The plug in deposition tunnels is the construction closing deposition tunnels during the operational phases. The plug shall close the deposition tunnels, keep the backfill in them in place and prevent water flow past the plug until the main tunnel has been filled and saturated. The design premises for the plug are based on that it consists of a concrete plug, a watertight seal and a filter.

In the final repository the plugs can be regarded as residual materials left in the repository when it is backfilled and closed [SKB, 2010b, p. 91]. In the long-term perspective in the final repository, in order for the repository to maintain the multi-barrier principle, the plugs must *not significantly impair the barrier functions of the engineered barriers or rock* [SKB, 2010b, p.24].

Although there are no safety functions attributed to the tunnel end plug (Figure A-2 and Figure A-3), the plug performance can be linked to the safety functions of the *deposition tunnel backfill*, and the *buffer*. Less evident, the plug performance might also be linked to the safety functions of the *canister* and *geosphere*, which is, however, not discussed here. The following safety function of the *deposition tunnel backfill* and the *buffer* can be linked to the plug performance (cf. Figure A-2 and Figure A-3):



- Safety functions of the deposition tunnel backfill
  - Counteract buffer expansion (BF1)
  - Limit advective transport (BF2)
  - Sorb radionuclides (BF3)
- Safety functions of the buffer
  - Limit advective transport (Buff1)
  - Reduce microbial activity (Buff2)
  - Damp rock shear movements (Buff3)
  - Resist transformations (Buff4)
  - Prevent canister sinking (Buff5)
  - Limit pressure on canister and rock (Buff6)
  - Filter colloids (Buff7)
  - Sorb radionuclides (Buff8)
  - Allow gas passage (Buff9)

For each safety function, SKB attempted to define a *safety function indicator*, and an accompanying criterion. For several of these indicators a safety function indicator criterion could be identified such that if the safety function indicator fulfils the criterion, then the safety function corresponding to the indicator in question is upheld. Table A-1 gives an overview of these indicators and their criteria (based on [SKB, 2011; Section 8.4]).

Table A-1: Safety functions, safety function indicators and criteria related to the deposition tunnel backfill and buffer

	Safety function	Safety function indicator	Indicator Criterion
<b>Backfill</b>	Counteract buffer expansion	-	
	Limit advective transport	Backfill hydraulic conductivity	$P_{Backfill, Swell} > 0.1 \text{ MPa}$
		Backfill swelling pressure	$k_{Backfill} < 10^{-10} \text{ m/s}$
		Backfill temperature	$T_{Backfill} > -2^\circ\text{C}$
Sorb radionuclides	Sorption coefficient	$K_{d, Backfill, i}$	
<b>Buffer</b>	Limit advective transport	Buffer hydraulic conductivity	$k_{Buffer} < 10^{-12} \text{ m/s}$
		Buffer swelling pressure	$P_{Buffer, Swell} > 1 \text{ MPa}$
	Reduce microbial activity	-	
	Damp rock shear movements	Maximum buffer density	$\rho_{Buffer, Bulk} < 2,050 \text{ kg/m}^3$
	Resist transformations	Buffer maximum temperature	$T_{Buffer} < 100^\circ\text{C}$
	Prevent canister sinking	Buffer minimum swelling pressure	$P_{Buffer, Swell} > 0.2 \text{ MPa}$
	Limit pressure on canister and rock	Buffer maximum swelling pressure	$P_{Swell} < 15 \text{ MPa}$
		Buffer freezing temperature	$T_{Buffer} > -4^\circ\text{C}$
	Filter colloids	Minimum buffer density	$\rho_{Buffer, Wet} > 1,650 \text{ kg/m}^3$
	Sorb radionuclides	Element specific diffusion coefficient	$D_{e, Buffer, i}$
		Element specific sorption coefficient	$K_{d, Buffer, i}$
	Allow gas passage	-*	

\* at this stage

It must be stressed that in the Swedish concept, the safety function indicators are regarded as measurable or calculable properties of a repository component that indicate the extent to which a safety function is fulfilled [SKB, 2011; p.891]. Taking into account that a safety function is considered to be a role through which a repository component contributes to safety, the safety function indicators would provide an indication about the status of elements contributing to the overall safety of the repository system. The question is to what extent the safety function indicators provide an indication of the overall safety of the repository system, and whether they are measurable in practice.

### **A.1.3 Demonstrator & Monitoring system**

#### ***General description***

As part of the DOPAS project, SKB performs a full-scale *deposition tunnel end plug* (a hydro-mechanical plug) for the KBS-3 concept in crystalline rock (SKB dome plug *DOMPLU* demonstration experiment). The main goal of the *DOMPLU* full-scale test, executed at the Äspö Hard Rock Laboratory (HRL), is to simulate the KBS-3V reference conceptual plug design and to demonstrate that the requirements related to the design and construction phases can be fulfilled. *DOMPLU* also tests the initial operation and performance of the plug under the full hydrostatic pressure and the backfill swelling pressure.

The main requirements for the *deposition tunnel end plug* are [SKB, 2010a; p.28]:

- 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 has 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 plug shall not significantly impair the barrier function of the other barriers.
- The movement of the plug due to pressure shall be sufficiently small to avoid a drop in backfill density in the vicinity of the plug.

In order to verify the above-mentioned requirements, the *DOMPLU* experiment aims to determine leakage through the plug (and the contact surfaces between the rock and the concrete) at the design pressure of 7 MPa. Furthermore, a load-test of the plug up to 10 MPa will be performed within the frame of DOPAS WP4. The leakage through the plug will be determined by frequent measuring in a sealed atmosphere just outside the concrete dome. Data from sensors in the full-scale test will be evaluated continuously. The design of the Swedish full-scale deposition tunnel end plug test was completed during 2011, see Figure A-4 [SKB, 2010b; p.77]. In 2012 detailed activity plans were compiled to be able to install the plug in a controlled manner.

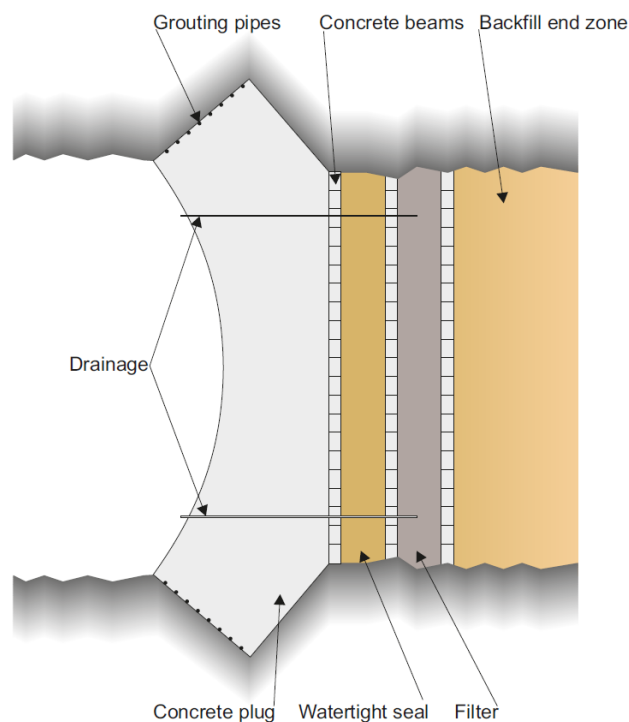


Figure A-4: Principle layout of the reference design of the plug system from SKB [SKB, 2010b]

The tunnel end plug has no long-term safety function but is a necessary ingredient to help the backfill in the deposition tunnel to maintain its barrier function [SKB, 2010b; p.78]. There are five different components that constitute the tunnel end plug, each having its own function (Figure A-4). These are (from the inside of the tunnel and outwards):

- The *drainage material* (crushed rock filter) shall drain the water collected in the filter and transport it out from the deposition tunnel to prevent water pressure to be applied on the concrete plug before it has gained full strength. Thereafter, it has no function.
- The *watertight seal* (bentonite) shall prevent leakage past the plug after closing the drainage system until full water pressure is reached on both sides.
- Two *walls* made of concrete beams are only required to separate the materials during construction.
- The *concrete plug* shall mechanically withstand the water and swelling pressure inside the plug until full water pressure is reached on both sides.
- The *drainage system* shall keep the water pressure low in the drainage material.

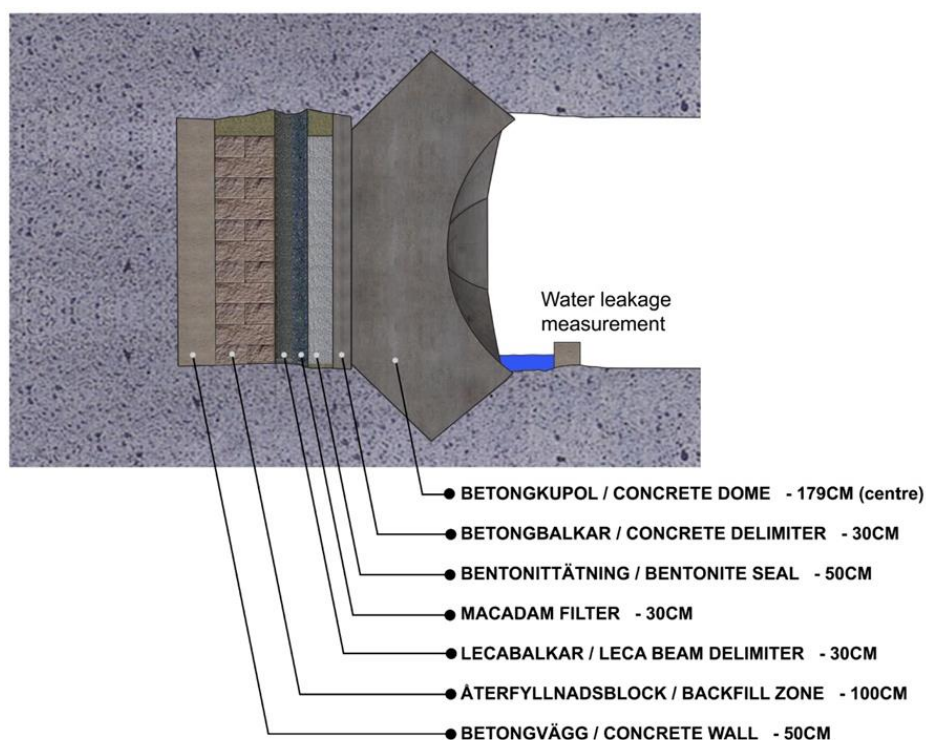


Figure A-5: Schematic section of the *DOMPLU* full-scale test [Grahm *et al.*, 2015].

From the upstream side to the downstream side (i.e. from the left to right in Figure A-5) the components of the *DOMPLU* full scale test are [Grahm *et al.*, 2015]:

- Concrete back-wall
- Bentonite backfill transition zone
- Delimiter/Filter part (LECA beams)
- Filter gravel (fraction 2-4 mm)
- Delimiter (Geotextile)
- Bentonite seal
- Delimiter (Concrete beams)
- Concrete dome (to be cast in the excavated slot)
- Weir for leakage control

In *DOMPLU*, the backfill end zone is redefined as a backfill transition zone where the swelling pressure from the tunnel backfill is reduced to a level that is similar to the sought swelling pressure of the bentonite seal (about 2 MPa) [Grahm *et al.*, 2015]. More information on this modification is given in Section 2.2 in [Grahm *et al.*, 2015].

The lifetime of the plug can be divided into three phases with different requirements [SKB, 2010b; p.81]:

1. Installation phase.
2. Sealing phase.
3. Degradation (post-closure) phase.

For each phase the conformity of the reference plug to the design requirements is to be verified: the design requirements related to the production shall be verified for the curing (installation) phase, the design requirements from the engineered barriers shall be verified for the sealing phase, and the design requirements to the properties in the KBS-3 repository shall be verified for the post closure phase. Additional explanation about the methodology for accomplishing these objectives is given in [SKB, 2010b; Chapter 8].

### ***Monitoring system***

In the *DOMPLU* demonstrator, extensive monitoring is performed. The parameters measured in this demonstrator give an indication about the saturation of the bentonite seal and the backfill as a function of time as well as their swelling at the end of the saturation process. In case the hydraulic conductivity and/or the swelling pressure measured after complete saturation will not meet the assigned safety function indicators criteria (see Section A.1.2), it should be evaluated whether advection of water could be of importance to the system. In that case, advective transport must be included in the calculations for evaluating the effects of corrosion and the influence on radionuclide transport. Three monitoring systems can be distinguished and will be summarized section-wise below:

- Monitoring of the concrete dome
- Monitoring of the bentonite seal, filter and backfill
- Monitoring of the leakage

### ***Monitoring of the concrete dome***

Two types of measurements were carried out within *DOMPLU*:

- Short-term (temporary) measurements and
- Long-term (permanent) concrete measurements.

The short-term monitoring encompasses the measurement of the pressure caused by concrete on the work wear at the time of casting of the concrete wall and during its initial curing. The long-term concrete measurements include the following monitored parameters (Figure A-6 for more information on the placement of the sensors; [Grahm *et al.*, 2015]):

- Gap between concrete dome and host rock
- Deformations
- Strain
- Temperature

The gap to rock measures whether the concrete dome releases from the rock due to shrinkage during curing. The deformation and strain sensors measure the response of the concrete dome, from the point of casting the concrete up to the point where it is subjected to high loads due to water pressure. The strain is measured to have an indication on whether the concrete dome is released

from the rock or not. The temperature measurements give an indication about the heat-up and cooling of the concrete dome. A variation in measured strain that is dependent on the variation in temperature would indicate a (at least partial) release of the concrete dome from the rock. In case of complete adhesion of the concrete dome to the surrounding rock only small variations in strain due to the cooling should be observed. Combined, the monitoring results are used to verify whether the measured behaviour corresponds to the predicted behaviour.

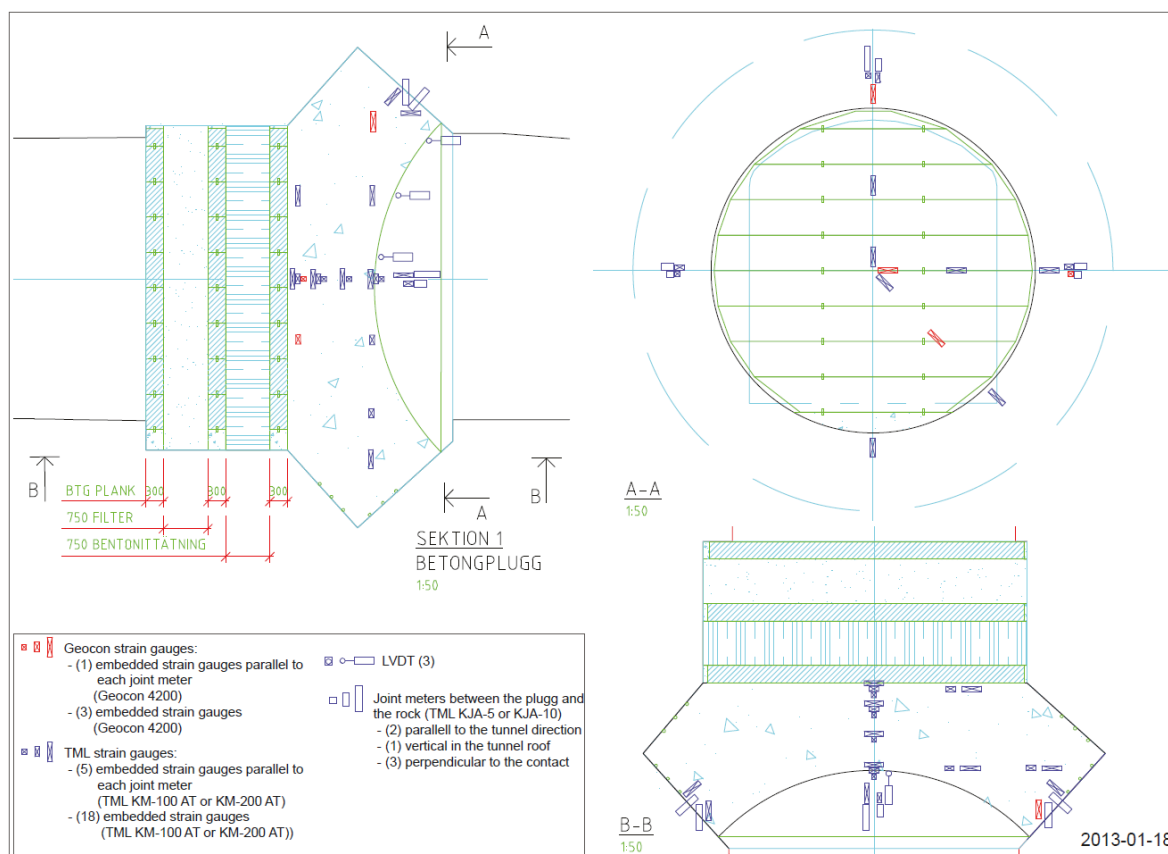


Figure A-6: Placement of sensors in the concrete dome in the DOMPLU demonstrator [Grahm *et al.*, 2015].

The design criterion of SKB's Dome Plug with respect to mechanical properties of the concrete dome is to endure 9 MPa total pressure (5 MPa water pressure, 2 MPa expected swelling pressure, 2 MPa design safety factor). The original plan of the *DOMPLU* experiment was to pressurize the plug to 7 MPa (5 MPa water pressure + 2 MPa swelling pressure). To verify the ultimate limit pressure for the dome shaped concrete plug it was planned to raise the total pressure to 10 MPa including both water and bentonite swelling pressure. During the DOPAS project, the planned 5 MPa water pressure could not be reached, therefore the operational limit for water pressure was 4 MPa.

### ***Monitoring of the bentonite seal, filter and backfill***

In order to analyse the behaviour of the bentonite seal, filter and backfill, the following parameters were monitored (see Figure A-7 for more detail on the position of these sensors):

- Total pressure
- Pore pressure
- Relative humidity
- Displacement

The measurement of the relative humidity (RH) follows the saturation process and permits the estimation of the water content and the degree of saturation of a material. The total pressure gives an indication of the development and distribution of swelling pressure (seal and backfill). The displacements between different zones of the plug are detected as result of displacement measurements.

The monitoring of the bentonite seal and backfill evaluate the sealing function of the plug.

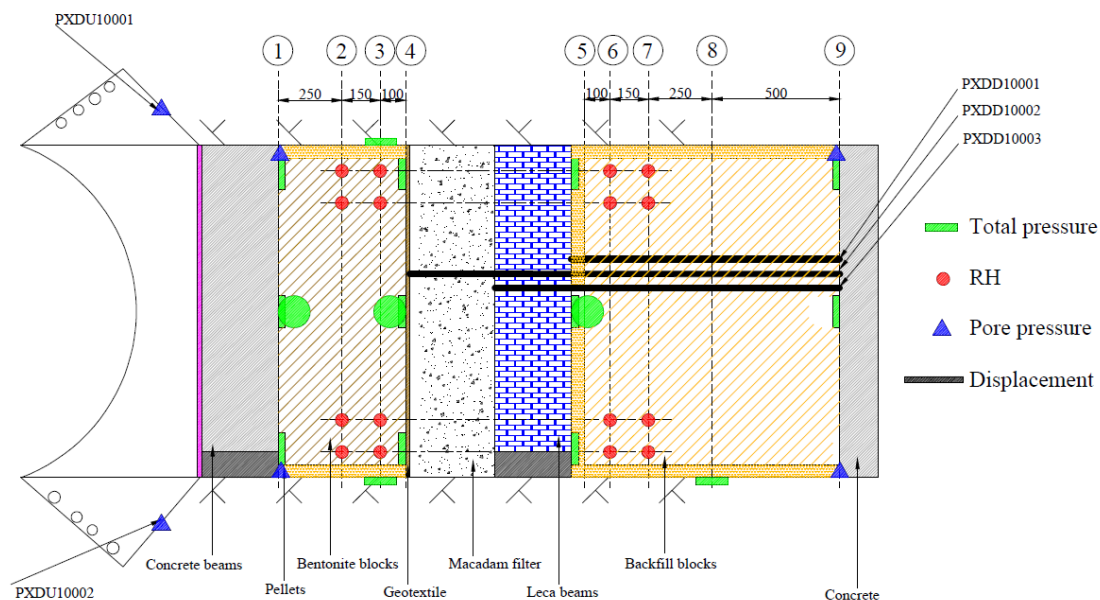


Figure A-7: Monitoring of the bentonite seal, filter and backfill in the *DOMPLU* demonstrator [Grahm *et al.*, 2015]

### ***Monitoring of leakage***

All leakage water passing the plug is collected in a watertight weir [Grahm *et al.*, 2015]. The water in the weir is transported via a steel pipe and then collected into a basin, where the water is automatically weighed, providing an on-line record of the leakage rate. A metal filter was installed in the weir to prevent particles from being transported to the basin and to avoid the blocking of the outlet. A plastic cover was installed on the downstream side of the concrete dome in order to seal the atmosphere in order to prevent evaporation and to allow condensation to drip into the weir.

In addition to the leakage measurement described above, two manual measurement locations were introduced since experiment-related leakages started to occur at high pressure: one water escape

route was via the cable bundle from sensors within the concrete dome and the other involved water escape via a rock fracture [Grahm *et al.*, 2015]. These experiment-related water escapes were recorded separately and were not included in the monitoring of leakage past the plug collected in the weir. The composition the water in the weir was established by laser scattering and XRF. The design criteria of SKB’s Dome Plug is a maximum leakage of <math>150\text{ m}^3</math> over 100 years (2.5 to 50 ml/min) to prevent bentonite erosion.

#### A.1.4 Relevance of monitored processes for the long-term safety

Based on the considerations described in the previous paragraphs the links between the safety functions of the buffer and backfill and the related safety function indicators were established and summarized in Table A-2. The next step is to see whether the indicated parameters are measurable, either in the short term, in the long term, or both.

Table A-2: Safety function indicators linked to safety functions of the deposition tunnel backfill and buffer.

Safety function		Density	Swelling pressure	Hydraulic conductivity	Temperature	Sorption coefficient	Diffusion coefficient
Backfill	Counteract buffer expansion	+					
	Limit advective transport		+	+	+		
	Sorb radionuclides					+	
Buffer	Limit advective transport		+	+			
	Reduce microbial activity	+					
	Damp rock shear movements	+					
	Resist transformations				+		
	Prevent canister sinking		+				
	Limit pressure on canister and rock	+	+				
	Filter colloids	+					
	Sorb radionuclides					+	+
	Allow gas passage		+				

\* at this stage

#### Derivation of parameter & monitoring options

The safety function indicators for the backfill (see Table A-2) are assessed regarding their compliance the criteria on monitorability and relevance for PA. The safety function indicators for the tunnel backfill which are directly or indirectly measured in the *DOMPLU* demonstrators are:

- Backfill density (indirectly measurable)
- Backfill hydraulic conductivity (indirectly measurable)
- Backfill swelling pressure (directly measurable)



These three safety function indicators are related to the safety functions summarized in Table A-3:

Table A-3: Selection of relevant indicators for Safety function indicators for deposition tunnel backfill

Safety function	Parameter	Directly measurable in demonstrators	Indirectly measurable in demonstrators	Overall safety of the system
<i>Limit advective transport</i>	Backfill temperature	-	-	-
	Backfill swelling pressure	+	+	-
	Backfill hydraulic conductivity	-	+	-
<i>Sorb radionuclides</i>	Backfill $K_d$	-	-	-
<i>Counteract buffer expansion</i>	Backfill density	-	+	-

The three identified, measurable safety function indicators are related to each other by coupled hydro-mechanical processes. The monitoring of these parameters during the saturation phase gives an indication about the evolution of the saturation process but does not provide information about the long-term safety of the system nor about the fulfilment of the corresponding safety functions. For example at equilibrium and full water saturation the pressure in a confined volume is closely related to the water ratio (mass of water/ mass of solid) in the bentonite, which is related to the density of the bentonite-water system.

After swelling, the backfill should have a certain swelling pressure to assure its tightness and homogeneity and a limited hydraulic conductivity. The quantitative criteria related to the identified indicators are the following [SKB, 2011; Section 8.4]:

- $P_{\text{Swell, Backfill}} > 0.1 \text{ MPa}$
- $k_{\text{Backfill}} < 10^{-10} \text{ m/s}$
- $K_d$  : high

Sorption of radionuclides in the deposition tunnel backfill may provide a limitation on the outward transport of radionuclides. The sorption coefficients ( $K_d$ ) are suitable indicators for this safety function. However, these are not monitored as part of the *DOMPLU* demonstrator, but must be evaluated either in separate experiments or by means of dedicated simulations. The temperature and the  $K_d$  of the backfill are not monitored in the analysed demonstrators.

## A.2 Shaft seal of the German disposal concept in rock salt: ELSA

### A.2.1 Disposal design, Safety Functions, FEP's & Scenario's

#### Disposal concept

As part of DOPAS, a conceptual shaft sealing (ELSA<sup>11</sup>) for a disposal concept in rock salt, based on local condition as present in Gorleben has been evaluated. Since 1977, the salt dome at Gorleben in lower Saxony is investigated as potential site for a repository for high-level waste in Germany. A repository layout and a sealing concept for the Gorleben site were developed within the VSG project [Bollingerfehr *et al.*, 2011]. Both layout and sealing concept were adapted to the site-specific geologic boundary conditions, see Figure A-8 (adapted from [Bollingerfehr *et al.*, 2012; p.21]).

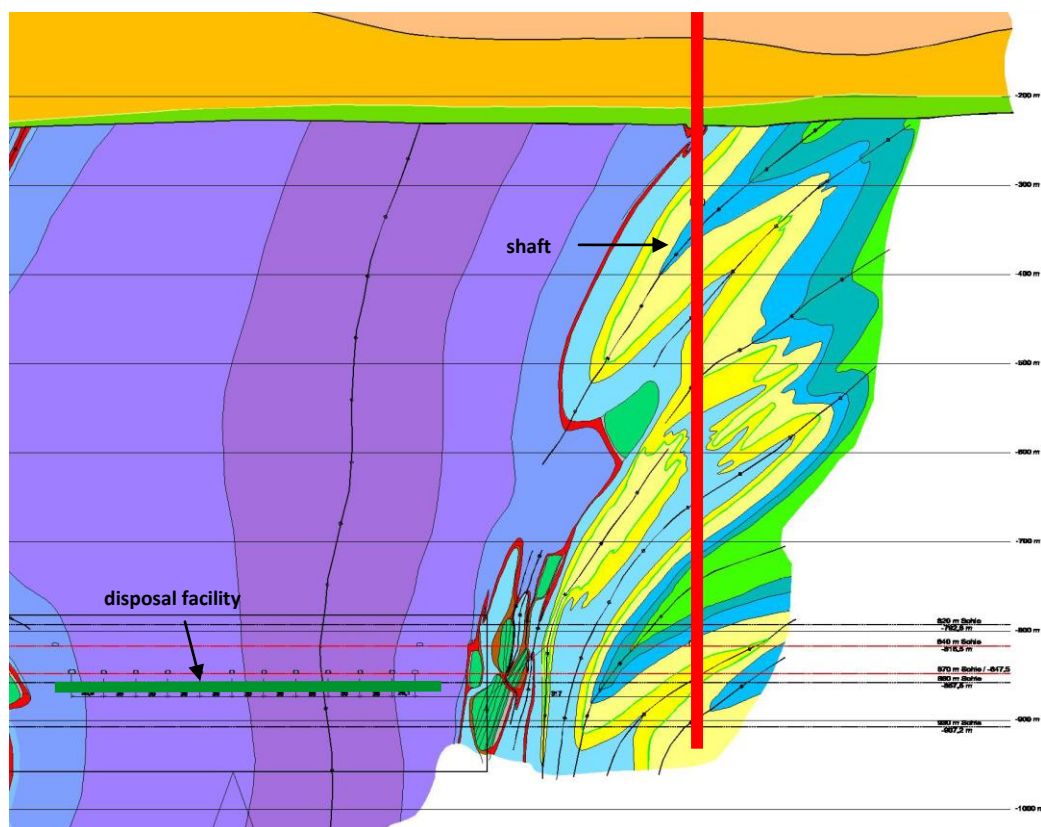


Figure A-8: Cross section of the shaft and disposal facility for the generic disposal concept in Gorleben. The purple colour represents the main salt of the Zechstein series, green colours anhydrites.

The VSG concept considers two waste types: HLW (spent fuel and vitrified high level waste) and ILW. There are two emplacement concepts considered for the repository in a salt dome: drift disposal or vertical borehole emplacement of the containers. More detail on these two emplacement

<sup>11</sup> ELSA: Schachtverschlüsse für Endlager für hochradioaktive Abfälle

concepts can be found in DOPAS Deliverable D5.6, Ch. 2. The backfilling and sealing of the drifts and shafts and the backfilling of the infrastructure area are comparable for both concepts. The locations and the layout of the drift and shaft seals are also the same.

The geotechnical barrier comprises of individual consecutive barriers: containers, borehole seal, drift seal, and shaft seal. These geotechnical barriers must be placed and – with regard to their hydraulic resistance and long-term stability – designed in such a way that (1) brine intrusion to the waste via the shaft and the backfilled drifts are prevented to the greatest extent, and (2) a subsequent forced outflow of contaminated solutions, via the same pathway as a result of decreasing convergence, need to be minimized in the case of undisturbed repository evolution. The long-term stability and the hydraulic resistance of the geotechnical barriers are chosen in such a way that the waste disposal is fully sealed from the biosphere. In the *ELSA*-experiment, the shaft seal is investigated [Schreiter, 2013].

### Safety functions

In Germany a concept for the demonstration of the safety of a final disposal of HLW was developed [Bollingerfehr *et al.*, 2008]. That concept is based on a systematic demonstration of the safe long-term confinement of the waste and has two main key components: (1) demonstration of the integrity of the relevant geotechnical barriers and (2) demonstration of the integrity of the main geological barrier system. Scenario analysis permits the evaluation of altered evolutions of the system.

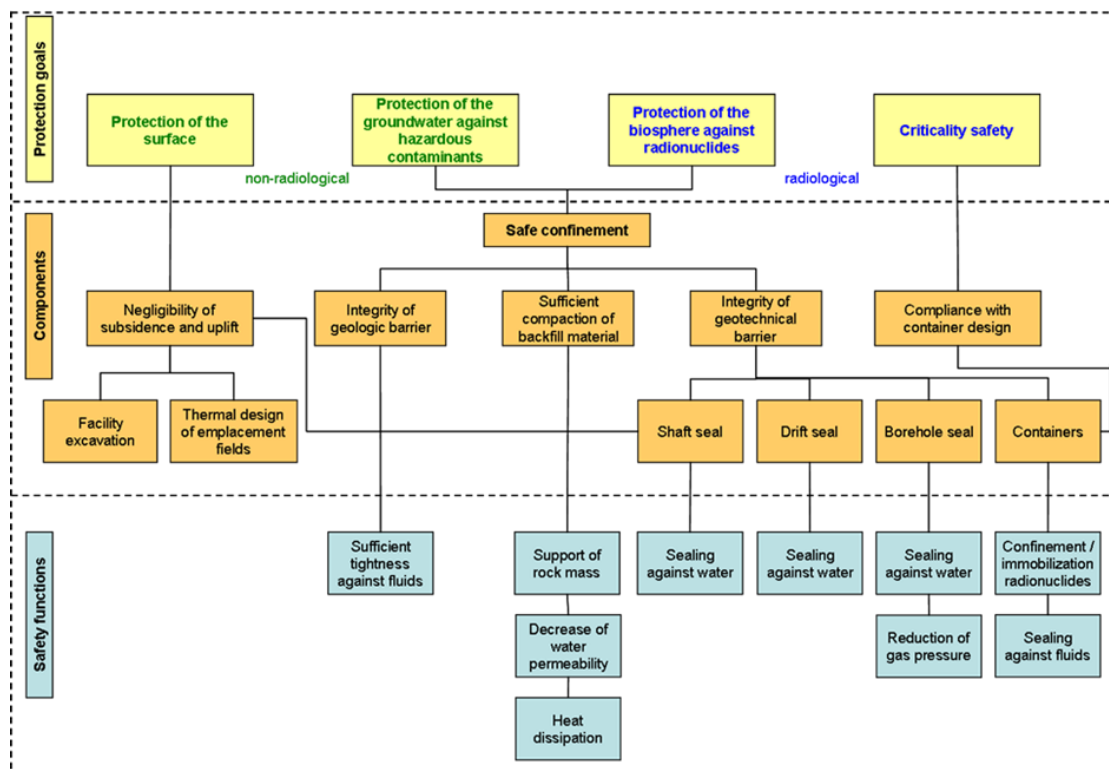


Figure A-9: Link between protection goals, safety assessment components, and safety functions [MoDeRn, 2013b].

The links between protection goals, safety assessment components, and safety functions is given in Figure A-9 [MoDeRn, 2013b].

The core element "*safe confinement*" comprises the components "*integrity of the geologic barrier*", "*sufficient compaction of the backfill material*", and "*integrity of the geotechnical barrier*". The latter comprises the individual barriers shaft seal, drift seal, borehole seal, and containers. The safety functions allocated to the individual barriers are listed as well, in blue. While most of the safety components support the isolation of the waste, the component "*sufficient compaction of the backfill material*" is linked to three different safety functions representing the involved physical processes. In addition to a decrease of the hydraulic permeability, the support of the rock mass (mechanical) as well as the dissipation of the container heat (thermal) has to be provided.

### **FEPs**

The design of the shaft seal needs to take into account those FEPs that could lead to an impairment of its effectiveness [Jobmann, 2013]. The FEP analysis alone is not sufficient. Only the scenario analysis, which is based on the relevant FEPs, allows drawing conclusions on possible impairments and, thus, on possible changes in the draft design and the dimensions. The FEPs that may affect the components of a shaft seal in rock salt were identified in [Wolf *et al.*, 2012] and allocated to scenarios in [Beuth *et al.*, 2012]. The tables below list the likely (primary FEPs) and the less likely FEPs that may lead to the impairment of the effectiveness of the shaft seal [Jobmann, 2013; p.7].

Table A-4: Primary FEPs (left) and less likely FEPs (right) that may affect the shaft seal in rock salt [Jobmann, 2013]

FEP No.	FEP name	FEP No.	FEP name
1.2.03.01	Earthquake	2.1.07.05	Premature failure of a shaft seal
1.2.09.01	Diapirism	2.1.08.05	Channel formation in sealing elements
1.2.09.02	Subrosion		
1.3.05.03	Formation of glacial channels		
2.1.05.04	Alteration of seals		
2.1.07.01	Convergence		
2.1.07.02	Fluid pressure changes		
2.1.07.04	Volume changes in materials, not temperature induced		
2.1.07.07	Displacement of sealing elements		
2.1.08.08	Swelling of bentonite		
2.1.09.02	Dissolution and precipitation		
2.1.09.06	Corrosion of materials		
2.2.01.01	Excavation damaged zone		
2.2.06.01	Change in stress state and stress redistribution		

## Scenarios

The safety assessment methodology in Germany, more specifically the development of scenarios, was evolved in two projects. Initially, in an early phase of the R&D project ISIBEL [Buhmann *et al.* 2010], the methodology was deduced and tested for reference scenarios. The methodology was then expanded in the course of the VSG project for the development of alternative scenarios [Beuth, 2012].

The methodology aims at deriving, in a systematic manner, a limited number of plausible scenarios' specifically one reference scenario and a number of alternative scenarios. Overall, the scenarios should comprehensively represent the reasonable range of repository system evolutions. The methodology allows direct assignment of probability classes to the scenarios in accordance with the safety requirements and is depicted schematically in Figure A-10 [Beuth, 2012a; Abb.3.1].

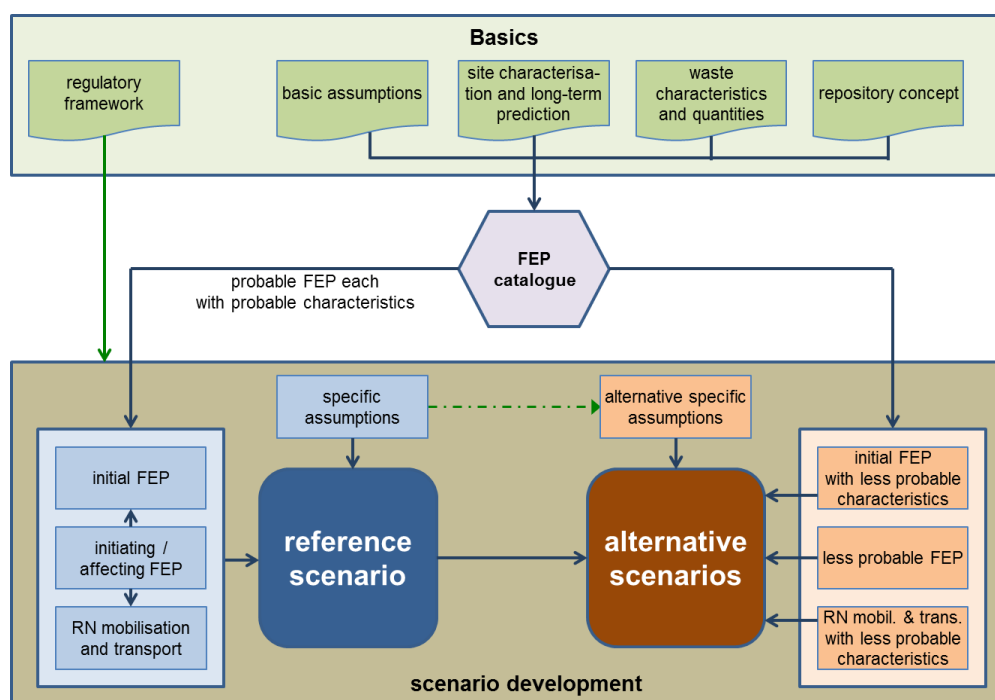


Figure A-10: Methodology for the development of scenarios applied in R&D project VSG.

Taking specific assumptions into account, the *reference scenario* was developed by considering all probable FEPs that:

- may impair the functionality of the initial barriers (Initial FEPs), and
- determine the mobilization of radionuclides from the waste and their subsequent transport, both in the gas phase and in the liquid phase.

*Alternative scenarios* are evolutions which differ in exactly one aspect from the reference scenario and are developed from e.g. considerations regarding alternative assumptions, or less probable characteristics of FEPs adversely affecting a barrier of the system (Figure A-10).

In VSG, 17 alternative scenarios were developed for the drift emplacement disposal concept and described in detail [Beuth, 2012]. The alternative scenarios cover aspects like divergent glacial impacts, misinterpreted and undetected geological properties, or new pathways between exploration and emplacement level. By assuming less probable characteristics of primary FEPs (e.g. enhanced corrosion, convergence, brine intrusion) and the FEP *Radionuclide Mobilisation and Radionuclide Transport*, 9 additional alternative scenarios were defined. A tabulated overview of all scenarios is provided in Table 7.1 of [Beuth, 2012].

### **A.2.2 Indicators & Criteria**

According to the German Safety Requirements, the following two radiological safety indicators are acknowledged [BMU, 2010; Section 6]:

- the effective dose in the biosphere, and
- a radiological indicator, which is based on the release of radionuclides from the “containment-providing rock zone” (CRZ).

The calculation of effective dose has been applied for many years and the application scheme is straightforward. Criteria for the additional effective dose are specified in the German Safety Requirements [BMU, 2010; Section 6].

To implement the specifications in the Safety Requirements for a radiological indicator, the RGI (“Radiologischer Geringfügigkeits-Index”; index of marginal radiological impact) was developed in the *ISIBEL* project [Mönig, 2012; Section 4.6.1].

If radionuclides are released from the CRZ, safe containment has to be demonstrated. For this purpose the RGI is applied, for which the calculation scheme is elucidated in [Bollingerfehr, 2013; Section 5.9.1], see also Figure A-11.

The parameter RGI can be regarded as a quantitative measure of the safety function “containment” in the CRZ. If the RGI is below 1, a safe containment of the radionuclides within the CRZ is demonstrated (stage 2). If the RGI is above 1, the radionuclide release from CRZ is not insignificant (stage 3). This does not mean that the repository system is not safe, but an additional assessment, especially the calculation of the effective dose in the biosphere, is required in order to identify whether the consequences of the analysed scenario can be considered to meet the criteria of the Safety Requirements. If not (stage 4), the disposal system is not suitable.

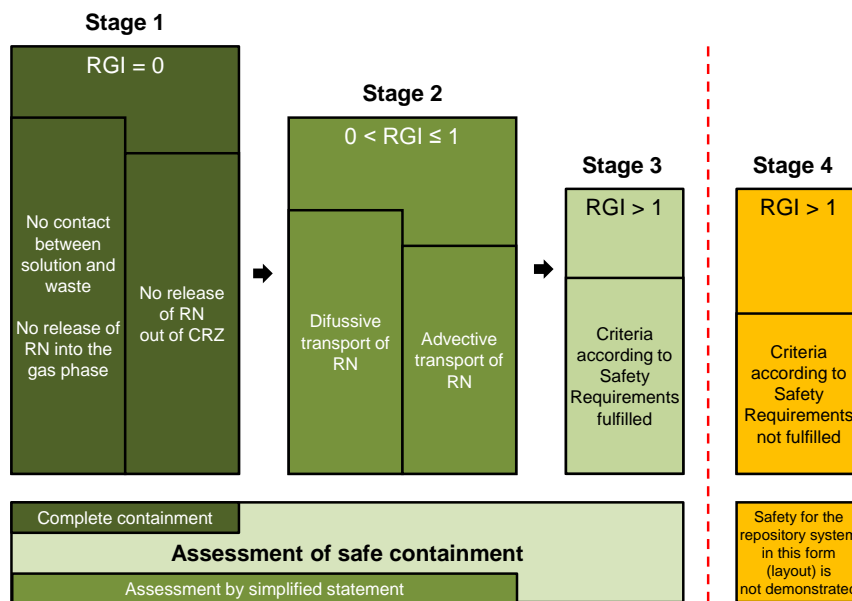


Figure A-11: Methodology Staged approach for the long-term safety assessment.

### A.2.3 Demonstrator & Monitoring system

#### General description

The *ELSA*-experiment represents the last phase of the *ELSA* programme of laboratory and *in-situ* experiments aiming to develop further the existing reference shaft seal concept for the German disposal concept for a repository in rock salt. The current design of the shaft seal is developed during the *VSG* project and is presented in Figure A-12.

According to the design above, the shaft seal consists of three sealing elements designed, one long-term sealing element made of crushed salt, and multiple additional elements. The sealing elements designed for short-term maintain their functionality until the compaction of the backfill in the mine galleries is finished. The first short-term sealing element is made of bentonite; the second is made of salt concrete the third one is of sorel concrete. The long-term sealing element is designed to be made of crushed salt and located between the two concrete sealing elements. After compaction, this crushed salt layer reaches a permeability similar to the permeability of the host rock. The position of each element is related to the geologic structures (see Figure A-8) which means that for the *ELSA* demonstration test the current design will be adapted to the geology and geometric characteristics of the actual testing site, which has not yet been selected [DOPAS Newsletter 2, 9.06.2014].

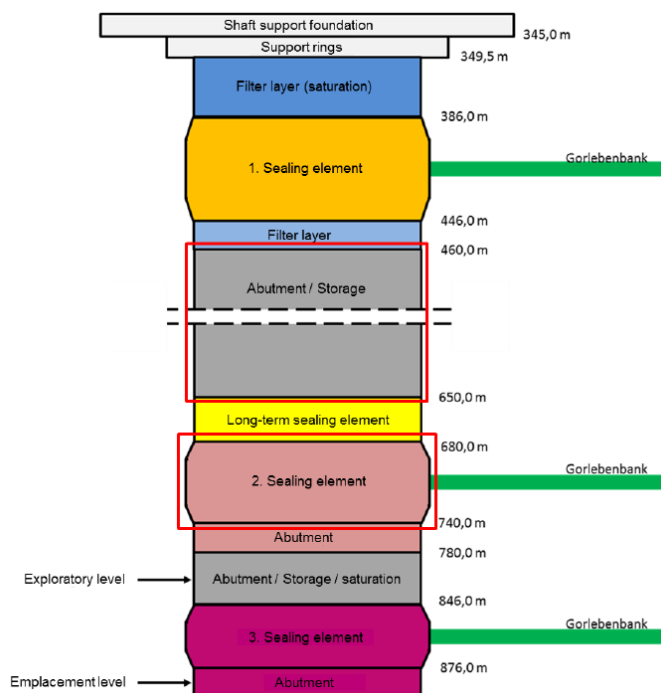


Figure A-12: Schematic of the shaft seal according to VSG (1<sup>st</sup> draft). The elements considered in the exemplary safety assessment are framed in red [Müller-Hoeppe *et al.*, 2013]

### Monitoring system

No information on the planned monitoring activities is available yet.

#### A.2.4 Relevance of monitored processes for the long-term safety

The main function of the shaft seal is to prevent or at least significantly slow down the inflow of water or brine from the overburden into the repository after its closure. Furthermore, in the event that radioactive nuclides are mobilised during the post-closure phase, the sealing function of the shaft seal is to retain these radionuclides in the repository. The sealing functions in both directions, i.e. against potential inflow of fluids from the surface and against potential outflow from the repository, ensures compliance with the conventional safety objective "*protection of the groundwater against hazardous contaminants*" as well as with the radiological protection goal "*protection of the biosphere against radionuclides*".

The processes that influence a sealing construction in a shaft and that are relevant regarding the safety assessment concept are:

- the convergence of the shaft,
- the hydraulic load development on one or on both sides (top and bottom) of the sealing elements of the shaft seal,
- the inflow of potentially corrosive fluids, and



- the subsidence of the entire sealing construction.

In the *MoDeRn* project, a subset of processes and parameters that might be a subject of monitoring is given [Jobmann, 2013]. The parameters characterising these processes and considered in *MoDeRn* are:

- the subsidence of the sealing construction or of individual components
- the convergence in the vicinity of the sealing elements
- the rock displacements in the vicinity of the sealing elements
- the pore pressure above and below the sealing elements
- the humidity above and below the sealing elements
- the pH-value of the water/brine
- the electric conductivity of the water/brine

The most relevant parameters to be monitored are the pore pressure and the total pressure since both of them give indications of fluid movement.

Based on the information above the Safety functions and relevant parameters corresponding to the shaft seal can be summarized as follows:

Table A-5: Safety functions, relevant processes and parameters linked to the shaft seal

Relevant disposal component	Safety function of the component	Relevant processes (FEPs)	Relevant parameters
Shaft seal	Sealing against brine inflow	<ul style="list-style-type: none"> <li>• Rock convergence</li> <li>• Fluid pressure build up on both sides</li> <li>• Infiltration of corrosive fluids</li> <li>• Subsidence of the entire sealing system</li> </ul>	<ul style="list-style-type: none"> <li>• Shaft convergence</li> <li>• Hydraulic pressure at seal top</li> <li>• Pore pressure at seal bottom</li> <li>• pH-value of water/brine</li> <li>• electric conductivity of water/brine</li> <li>• Subsidence of plug components</li> </ul>

## A.3 Drift and ILW disposal vault seal of the French disposal concept in clay: FSS

### A.3.1 Disposal design, Safety Functions, FEP's & Scenario's

#### *Disposal concept*

In France, the repository host rock is a Callovo-Oxfordian clay formation in the east of the Parisian Basin. The reference repository is located in the middle of an argillaceous formation with a thickness of 250 m situated at 500-600 m depth. The repository project is referred to as *Cigéo*. The wastes to be disposed include long-lived Intermediate-level waste (ILW) from nuclear facilities and HLW from spent fuel reprocessing and will be disposed of in two separated disposal zones: one for ILW and one for HLW. The wastes are disposed in horizontal disposal drifts.

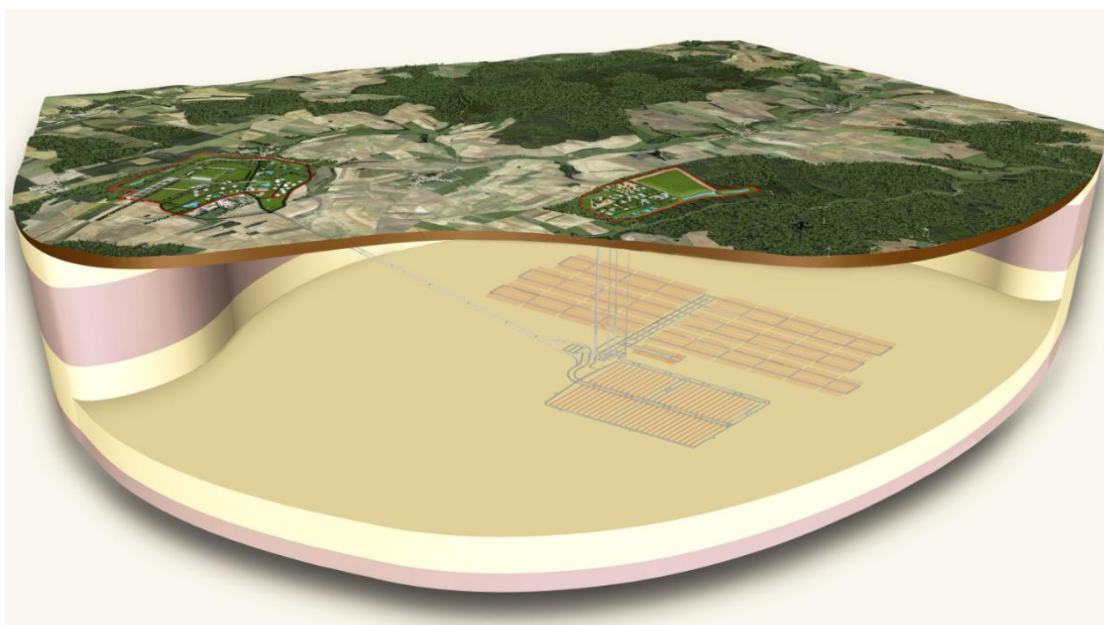


Figure A-13: Artist impression of the facilities at *Cigéo* ([www.andra.fr](http://www.andra.fr)).

#### *Safety functions*

One of the key functions of the repository is to limit transfer of disposed radioactive substances of to the biosphere by means of water [MoDeRn, 2013b, p. 28]. In the French concept safety functions are organised in a multi-level breakdown structure (starting from general ones to more detailed ones). A distinction is made between the safety functions during the operational and the post closure phases of the repository.

In the post closure phase, the three *primary functions* (also called *objectives*) of the repository with respect to the long-term safety are [Marivoet *et al.*, 2008]:

- Isolating waste from surface phenomena and human intrusion,

- Preserving the repository record,
- Protecting the human being and the environment against hazards associated with the dissemination of radioactive substances.

The accomplishment of these objectives relies on the favourable properties of the host formation in combination with the performance of the engineered barriers. The primary function '*Protecting the human being and the environment against hazards associated with the dissemination of radioactive substances*' can be broken down to three high-level safety functions, that are at the core of the long-term safety assessment. These functions are broken down further according to timescales (see Figure A-14) and physical extent (see Figure A-15 ) into *sub-functions* accomplished by specific repository components [MoDeRn, 2013b]:

- *Counter water circulation*<sup>12</sup>:
  - Limit water flux from overlying rock formations (through shafts and/or ramps, during the transient post-closure re-saturation phase)
  - Limit water flux from the host (clay) formation to the closed repository (during permanent post-closure hydraulic conditions)
  - Limit water flux through the repository structures (to avoid transfer bypass of host formation during permanent, post-closure conditions)
  - Limit water flux in HLW and ILW disposal cells
- *Limit release of radionuclide elements to immobilize them in the repository*:
  - Protect waste and waste forms from alteration by water
  - Limit solubility of radionuclides
  - Limit mobility of radionuclides
- *Reduce concentration and delay radionuclide migration outside of the disposal cells*:
  - Delay and reduce radionuclide flux along infrastructure
  - Delay and reduce radionuclide migration through the host formation
  - Preserve natural diffusion and dispersion potential of surrounding formations

The safety functions are broken down to a level of detail that allowing the definition of requirements for each component of the disposal system. This way, each safety function can be characterised by a performance level, a period during which the function has to be available, one or more components that have to fulfil the function and the physical phenomenon or phenomena that enable these components to fulfil it [Marivoet *et al.*, 2008, p. 29-30].

<sup>12</sup> also called *Resisting the circulation of water* in Dossier Argile [Andra, 2005].

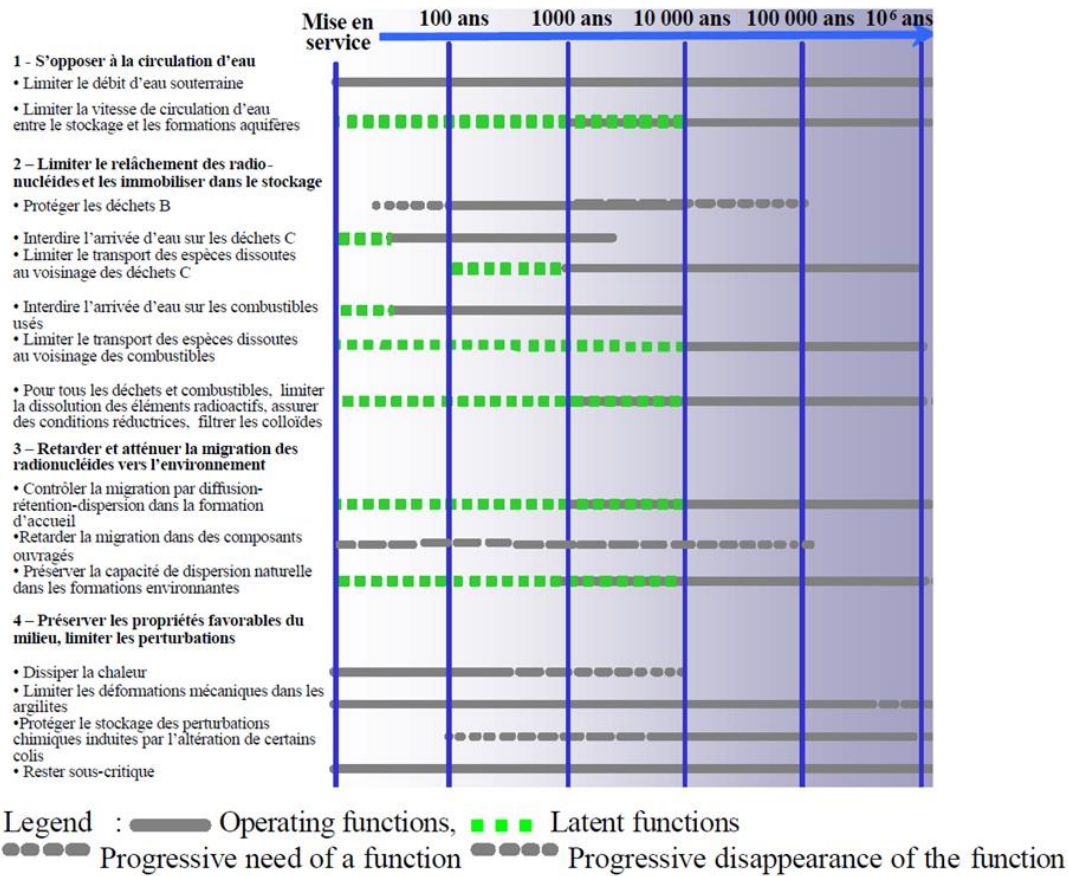


Figure A-14: Safety functions over time [Marivoet *et al.*, 2008]

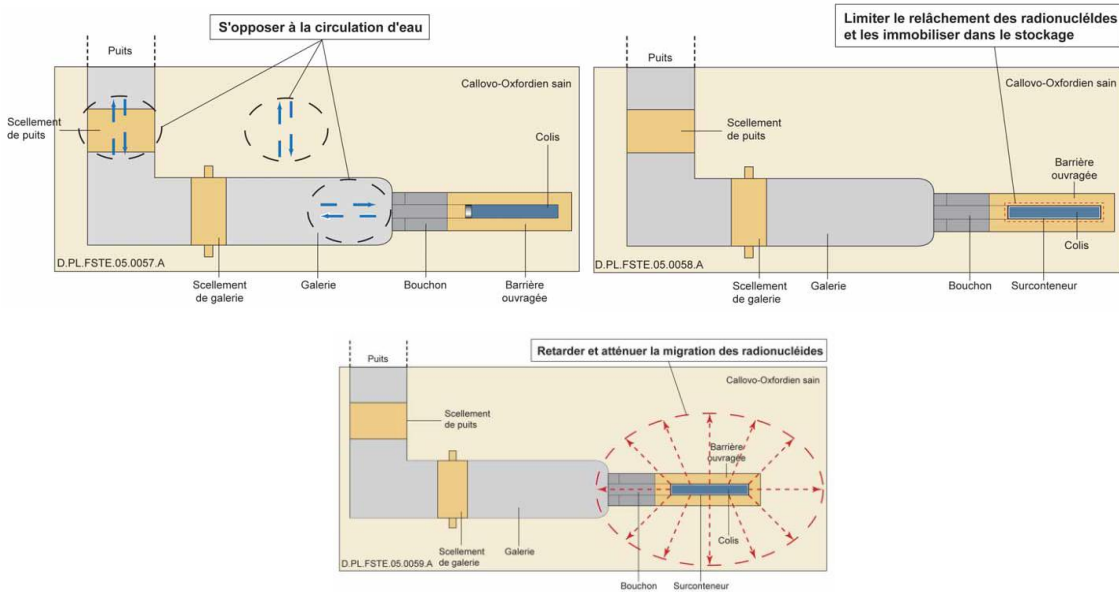


Figure A-15: Graphical representation of the high-level safety functions *Counter water circulation, Limit release of radionuclide elements immobilize them in the repository, and Reduce concentration and delay radionuclide migration outside of the disposal cells* and corresponding components (adapted from [Andra, 2005])

There are three categories of engineered repository components with a specific contribution to safety [MoDeRn, 2013b]:

- *Seals* of the disposal galleries, and/or transport galleries
- *Waste disposal packages*
- *Other engineered components* contributing to the protection of the waste disposal packages (e.g. backfill)

In the French concept following types of seals or plugs can be distinguished (MoDeRn, 2013b, Section 5):

- Seals of surface to depth infrastructure (shafts, ramps),
- Seals within repository gallery (drift seals),
- Seals at the edges of ILW disposal cells (Figure A-16),
- Plugs at the end of HLW disposal cells.

Seal properties are specific to different types of seals:

- The design specifications of the *shaft and ramps seals* require a core of swelling clay ensuring permeability in the order of  $10^{-11}$  m/s. The dry density upon emplacement should correspond to a saturated swelling pressure between 1 and 7 MPa. The seal will be surrounded by support structures low-pH concrete (pH<11), to provide a long term mechanical stability of the seal.
- The design requirements for the *gallery (drift) seals* and *ILW disposal cell seals* include similar core material as for the shaft/ramp seals, and a total length of approximately 40 m.
- The requirements for the HLW disposal cell plugs include a 3 m long swelling clay plug, emplaced inside the metal cell liner. The required performance for the plug is to provide a permeability  $<10^{-10}$  m/s.

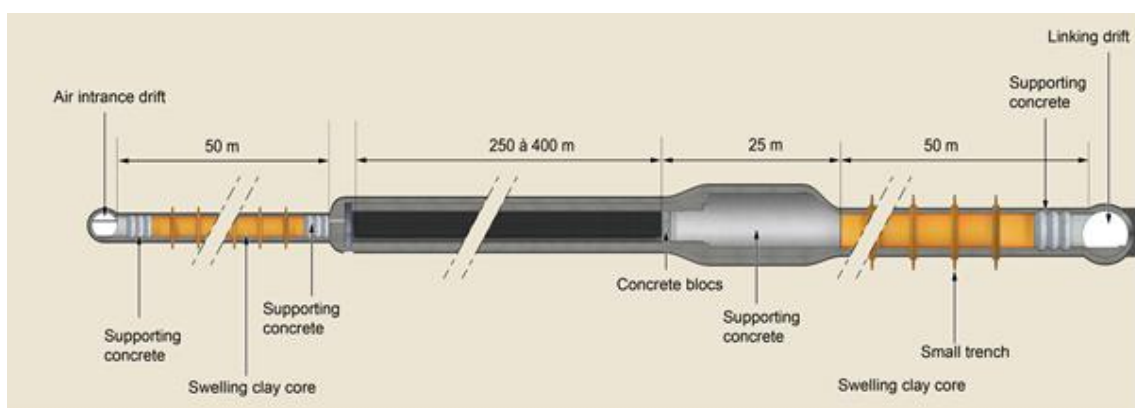


Figure A-16: Seals emplaced upon closure of an ILW disposal cell

The object of the *FSS* experiment are the drift seals and ILW disposal vault seal, only this type of seals will be considered in the remaining part of this section. The design features of the *drift (gallery) seals* and *ILW disposal vault seal* and their contribution to the long-term safety functions are summarized in Table A-6.

Table A-6: Design features of the seals within repository galleries and the ILW disposal vault seals related to the long-term safety functions (from [MoDeRn, 2013b] Tab. 5-1, 5-3, 5-5).

Safety function	Design features
<b><i>Counter water circulation</i></b>	
Limit water flux through the repository structures (to avoid transfer bypass of host formation during permanent, post-closure conditions)	Seals within repository galleries
Limit water flux within the disposal cells	Seals around ILW disposal cells
<b><i>Limit release and immobilize in repository</i></b>	
Limit solubility of radionuclides	Imported construction materials: Prevent risk of complexing agents enhancing solubility
Limit mobility of radionuclides	Imported construction materials: Prevent risk of complexing agents enhancing mobility
<b><i>Delay and reduce concentration of radionuclide migration</i></b>	
-	-
-	-

The drift seals and ILW vault seals contribute mainly to the high-level safety function *Counter water circulation* by limiting the water flux through repository structures.

The safety function *Limit release and immobilize in repository* is concerned with the source term and relies on:

- The chemical environment in the disposal cell, including favourable site properties influencing this environment (release; transfer properties through the cell)
- The absence of complexing agents or good understanding of their influence on transport (transfer properties through the cell)

The contribution of the seals to this function reduces mainly to preventing the presence of complexing agents enhancing the solubility and mobility of radionuclides. Imported complexing agents are identified prior to emplacement so that this design feature does not require further analysis in relation to the long-term safety of the system.

The third safety function *Delay and reduce concentration of radionuclide migration outside of disposal cells* is based on three major contributions: repository design, repository siting and layout, unperturbed long-term properties of surrounding formations. This safety relies on [MoDeRn, 2013b, p. 42]:

- Favourable flow and transport properties in host formation

- Specific cell, disposal unit and overall repository layout features
- Transport conditions from disposal cell to access shafts/ramps
- Unperturbed, natural flow and transport properties of surrounding formations.

The drift seal is not a key component for this safety function.

### **Scenarios**

The performance assessment of the repository is based on a normal evolution scenario and a set of altered scenarios [Marivoet *et al.*, 2008, p. 132]. The definition of the altered scenarios is based on a breakdown by safety function [Andra, 2005, Ch. 7.1.1]:

- For the safety function *Counter water circulation* a *seal failure scenario* covering a failure of combinations of seals was developed;
- For the safety function of *Limit release and immobilize in repository* a scenario involving *failure of thermal waste containers* was chosen; and
- For the safety function *Delay and reduce concentration of radionuclide migration* an *intrusive borehole* intercepting the geological formations and the repository at various points is considered in a way that short-circuit all barriers.

The first three altered scenarios test the degree of redundancy between the safety functions. An additional scenario - *severely degraded evolution* - that considers a generalised failure of all safety functions was defined to complement the altered scenarios defined above. This scenario assesses the complementary nature of these functions [Andra, 2005, Ch. 7.1.1]. By comparing the results of the *severely degraded evolution scenario* with the results of the *normal evolution scenario*, it can be seen whether minimal performance levels complement each other sufficiently well to control the impact.

For the purpose of DOPAS, the *seal failure scenario* is of interest. This scenario is intended to consider a failure in all or part of the seals so as to assess the robustness of the repository system with respect to various combinations of such defects in repository components (shafts, drifts, module separation) or cell plugs. More information on this scenario can be found in [Andra, 2005, Ch.7.2.1].

### **A.3.2 Indicators & Criteria**

The main safety indicator is the committed individual effective dose [Marivoet *et al.*, 2008, p. 358]. Other indicators than dose (complementary indicators) were used in the safety analysis carried out in in the *Dossier 2005 Argile* [Andra, 2005]. The complementary indicators are linked to the three main safety functions. The safety function *Resisting water circulation* is assessed/quantified by following complementary indicators [Marivoet *et al.*, 2008, p.361-362]:

1. The Péclet number, characterising the comparison of diffusive and advective transfer kinetics;
2. Advective and diffusive flow indicators, providing a comparison of these two flows leaving the host rock (argillite);
3. Distribution of radionuclides over different compartment.

The safety function *Limiting the release of radionuclides and immobilizing them in the repository* can be assessed/quantified by following complementary indicators [Marivoet *et al.*, 2008]:

1. Attenuation functions
2. Péclet number
3. Radionuclides outside the disposal cell relative to the total amount of radionuclides released from the waste matrix

The *Delaying and reducing the migration of radionuclides* is quantified by three values associated with the molar flow [Marivoet *et al.*, 2008, p. 363]:

1. Maximum molar flow
2. Integrated molar flow
3. Occurrence time of the maximum molar flow

The expected performances and indicators of key components of the repository system are given in [MoDeRn, 2013b; Tables 5-2, 5-4, 5-6 & 5-8]. Expected performances and/or indicators related to the seals within the repository galleries and the seals around ILW disposal cell are summarized in Table A-7.

Table A-7: Performances, indicators and criteria expected from the seals within the galleries in relation to the long-term safety functions [MoDeRn, 2013b]

Relevant disposal component	Safety function of the component	Features and/or expected performances and indicators as basis for the safety
Seals within repository galleries	Limit water flux through the repository structure	Performance of gallery seal close to source: <ul style="list-style-type: none"> <li>• Permeability <math>10^{-11}</math> m/s</li> <li>• Dry density related to swelling pressure</li> <li>• Swelling pressure between 1 and 7 MPa</li> </ul>
Seals around ILW disposal cells	Limit water flux within disposal cell	Cf. gallery seal

### **A.3.3 Demonstrator & Monitoring system**

#### **General description**

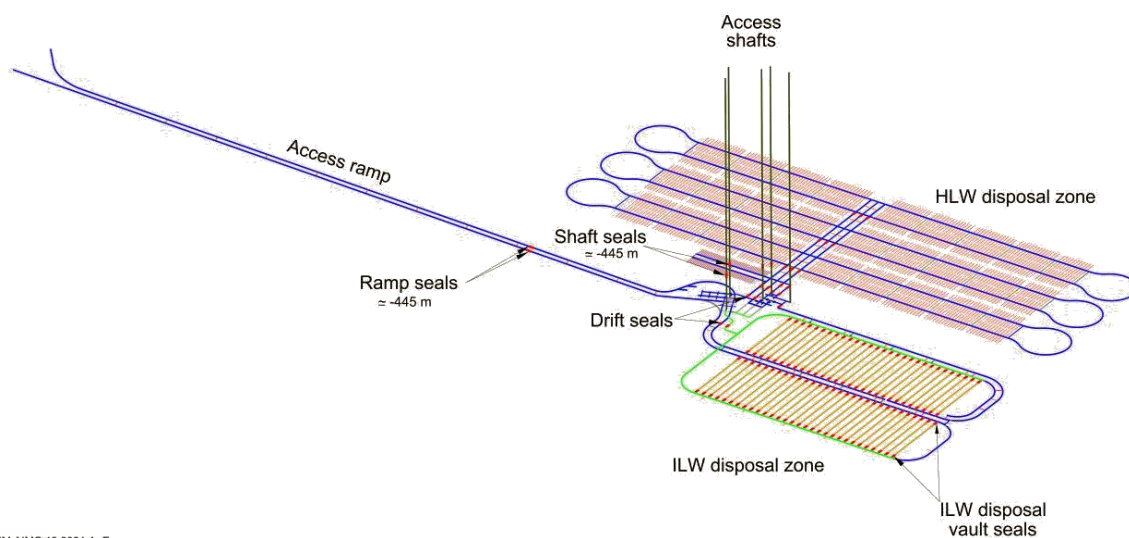
*FSS* is a full-scale demonstrator of the reference drift and intermediate-level waste (ILW) disposal vault seal for the French Cigéo repository concept (Figure A-13 and Figure A-17). The main objective of the *FSS* experiment is to develop confidence in, and to demonstrate, the technical



feasibility of constructing a full-scale drift or ILW disposal vault seal. The experiment is focused on the construction of the seal, and the materials will not be saturated or otherwise pressurised. In the French concept, *seals* are defined as hydraulic components for closure of large diameter underground installations and infrastructure components such as shafts, ramps, drifts and ILW disposal vaults. Each seal consists of a swelling clay core (EBS) and concrete containment walls. Figure A-17 indicated the location of the drift seals and ILW disposal vault seals.

The design basis for *FSS* is derived from a functional analysis of the safety functions specified for the structures, with the *FSS* design basis defined in the technical specification produced by Andra and justified in DOPAS [DOPAS, 2016a]. The design basis contains requirements on each component of the experiment, on monitoring, and on procedures to be applied during implementation of the experiment.

In the French concept the horizontal drift seal is composed of swelling clay core (Bentonite) with two low pH concrete containment plugs, one at each end (Figure A-18). The *FSS* test box has an internal diameter of about 7.6 m and is 36 m long. Representative underground ambient conditions are maintained within the test box. 5 m long containment walls close the volume of the swelling



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Figure A-17: Location of the drift seals and ILW disposal vault seals in the French repository concept [DOPAS, 2014]. Drifts are horizontal tunnels, whereas ramps are inclined tunnels.

The conceptual design of both drift and ILW disposal vault seals are the same. The bentonite swelling core is about 14 m long. *FSS* is being developed in a specially constructed concrete box located in a warehouse. The main difference between the *Cigéo* reference concept and the *FSS* design is the smaller length of the seal. The box can be closed at each end to allow environmental conditions (temperature and relative humidity) representative of those of the underground. The seal itself consists of a cast concrete containment wall, a swelling clay core and a shotcrete containment plug. The design also includes recesses that represent breakouts generated by the removal of the concrete lining used to support drifts and vaults during operations; the linings are removed to ensure that the seal meets hydraulic requirements.

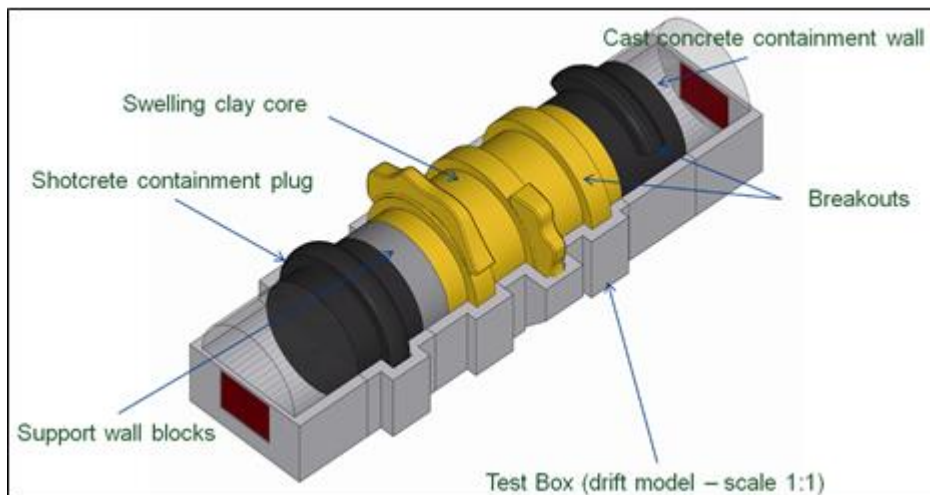


Figure A-18: 3D view of the *FSS* test box with the breakouts (recesses) in the argillite formation [DOPAS, 2016b].

There are two alternative designs of the seals of the horizontal drifts:

- In the *reference design*, the seal is installed in a section of the drift where the concrete liner is partially dismantled, allowing a direct contact between the argillite formation and the bentonite core. The swelling pressure of the bentonite core should be as close as possible to 7 MPa.
- The *alternative design* is based on the excavation of a thin groove at the outer boundaries of the drift liner and filled with bentonite at direct contact with the argillites, providing an EDZ cut-off. The bentonite swelling pressure in the groove should be between 3 to 5 MPa.

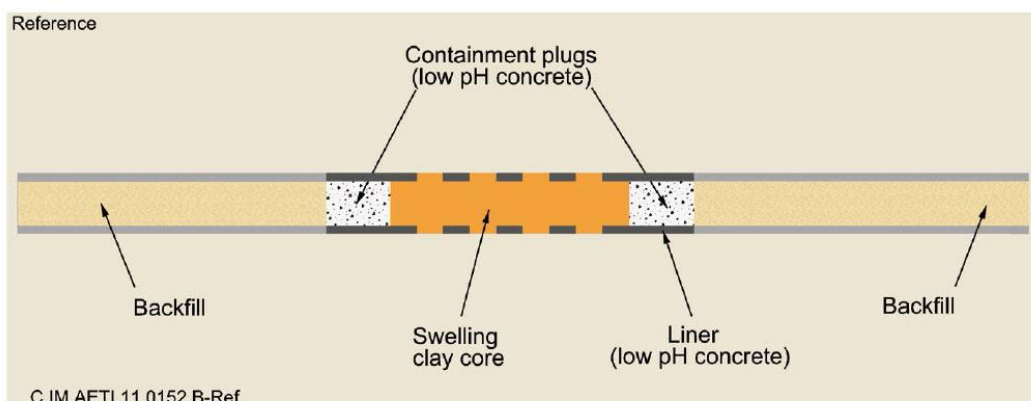


Figure A-19: Reference design of a horizontal drift seal [DOPAS, 2016b]

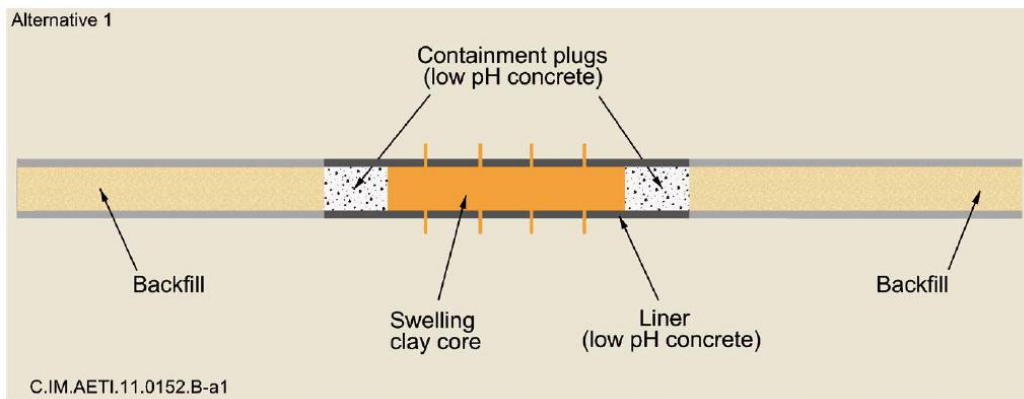


Figure A-20: Alternative design of a horizontal drift seal [DOPAS, 2016b]

The *FSS* experiment is a full scale test of the *reference design* of the seal (Figure A-19). Figure A-21 provides longitudinal section views of the *FSS* experiment:

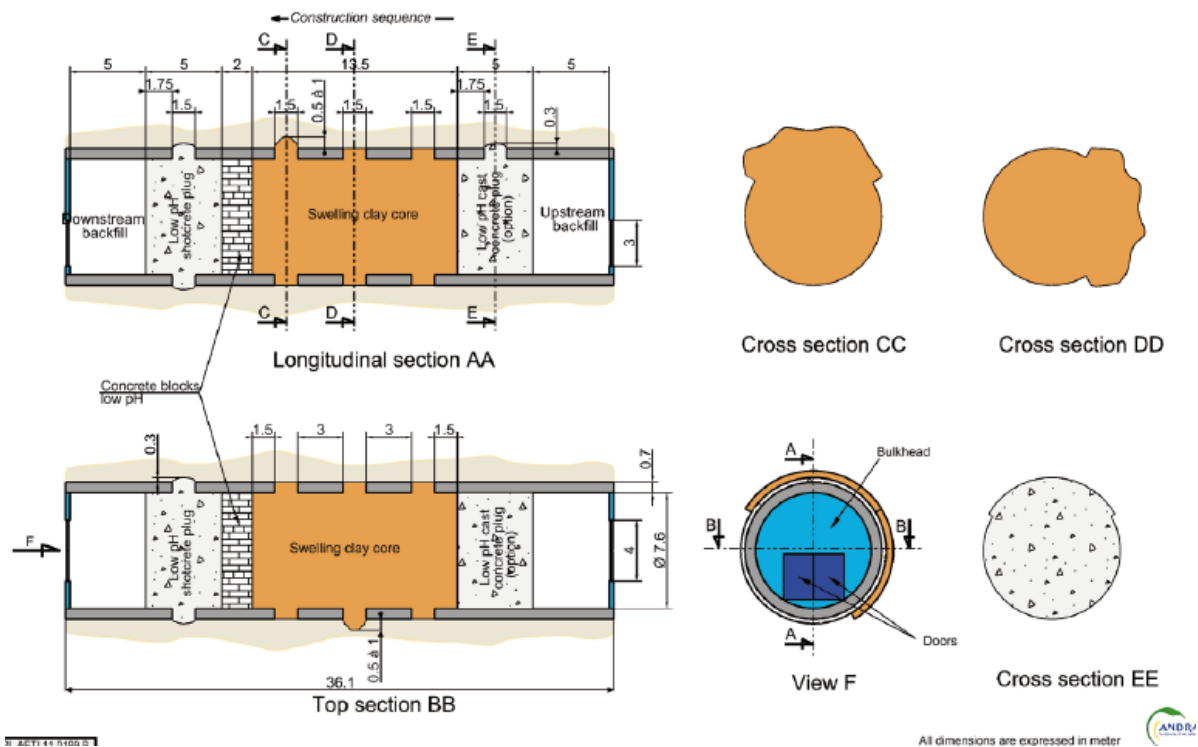


Figure A-21: Longitudinal section view of the *FSS* experiment [Lebon *et al.*, 2013]

The first concrete containment wall made of low pH concrete is followed by a swelling clay core, a supporting wall made of concrete blocks and, at last, by the second containment wall made of low pH shotcrete.



### ***Monitoring system***

The scope of the *FSS* demonstrator is to prove the technical feasibility of constructing a seal at full scale. *FSS* was built at representative underground ambient conditions and was not saturated. The parameters monitored in the *FSS* experiment were [DOPAS 2016b]:

- Environmental monitoring:
  - Ambient temperature
  - Humidity
  - Dust in the air
- Test-box monitoring:
  - Subsidence
  - Tilting
  - Pitch
  - Deformation
- Containment wall monitoring:
  - Curing temperature
  - Shrinkage
- Bentonite core monitoring:
  - 3D scan for evaluation of the backfilled volumes

The saturation and swelling of the bentonite core were examined in an additional bentonite saturation test (*REM*) carried out within DOPAS WP4. The parameters measured in the bentonite saturation test *REM* [Conil *et al.*, 2015] are:

- Climate conditions
- Hydration water
- Relative humidity
- Temperature
- Total pressure
- Pore pressure
- Airflow

## A.4 Pressure and sealing plug of the Czech disposal concept in granite: EPSP

### A.4.1 Disposal design, Safety Functions, FEP's & Scenario's

#### *Disposal concept*

The Czech reference concept considers a deep geological repository to be built in crystalline rock at a depth of around 500 m where a system of deposition galleries will be built. It is assumed that one central Czech disposal will be build were all high-level waste (HLW) and other long-lived radioactive waste is disposed of. The disposal is presently in a preparatory phase, with ongoing research studies performed in all connected areas (geological, civil engineering, radionuclides transport, monitoring, etc.). The first assessment of disposal of spent fuel and HLW in the Czech Republic considered a generic reference concept based on the Swedish vertical disposal concept, KBS-3V. Presently, a horizontal disposal concept (KBS-3H) is regarded as the reference concept.

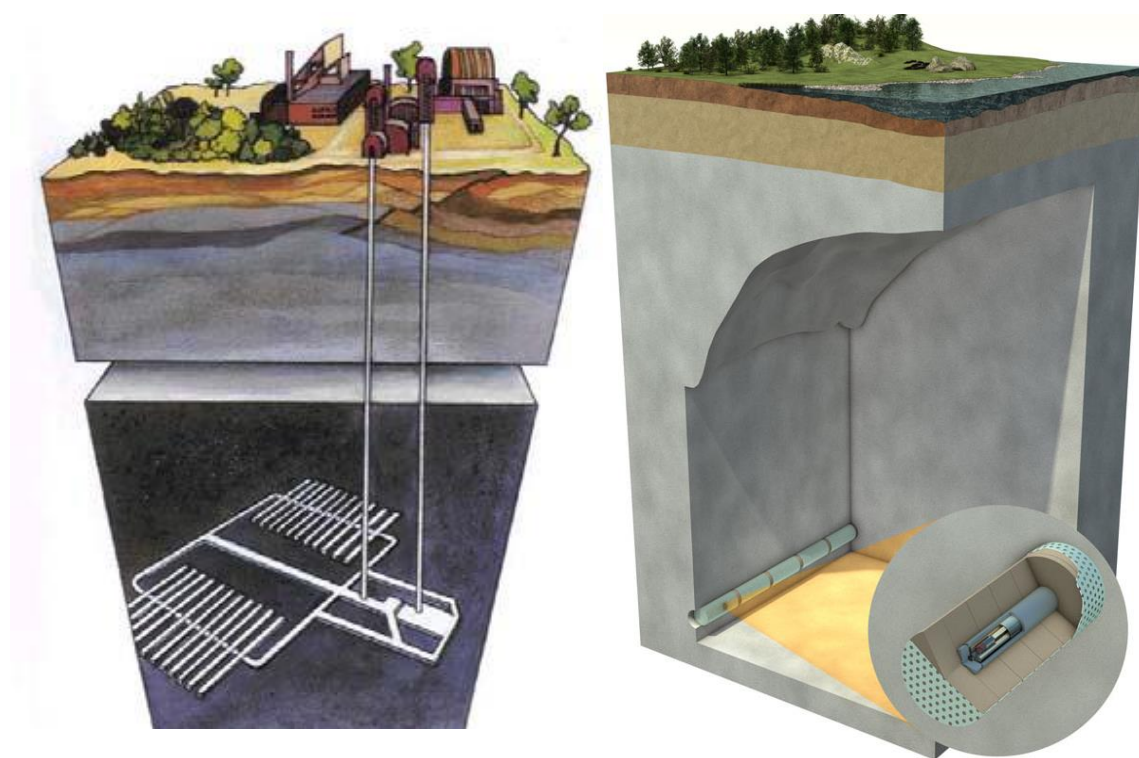


Figure A-22: Artist impressions of the planned Czech deep repository [www.rawra.cz]

In the present Czech reference concept, a plug is defined as a structure for closure of tunnels in the repository and the seals are defined as hydraulic components for closure of large-diameter (several meters) underground installations and infrastructure components, including shafts, ramps and drifts [DOPAS, 2016a].

### ***Safety functions***

A system of safety functions was developed, that can be divided into subgroups [Marivoet *et al.*, 2008, p.87]. The following functions are of interest for DOPAS:

- **Disposal system safety functions:**
  - To ensure the compliance with individual dose limits through isolation, retention and dilution.
  - To show stable long-term properties.
  - To substantiate the robustness of the system with regard to potential adverse initial events and uncertainties.
- **Near field safety functions:**
  - The *container* will provide physical containment to the final waste form and will prevent radionuclide release and/or retard it in the period after repository resaturation.
  - The *waste form* has to provide physical containment for the waste in the periods of interim storage and to immobilize the waste in the first period after disposal.
  - The *backfill* (including sealing) has to provide a barrier function after the failure of the isolation of the waste form and the container, by retarding the radionuclide migration and delaying their release to the hydrological environment.
  - The *EBS* will provide isolation and retention of radionuclides in the near field for a period that has to be evaluated. The EBS shall ensure that the diffusion transport is the principal process in the near field.

In a more systematic approach for safety functions development the following set of functions is defined for *materials surrounding systems* [Marivoet *et al.*, 2008, p. 91- 93]:

- To conduct heat from waste packages (Thermal effect)
- To limit water flux to and from waste packages (Hydrological effect)
- To prevent mechanical stress on waste packages (Mechanical effect)
- To provide favourable chemical and microbiological conditions (Chemical effect)
- Minimise release of radionuclides after waste packages failure from near field by:
  - Low degradation rates of waste form;
  - Low solubility of radionuclides;
  - Low permeability of surrounding materials;
  - High sorption of radionuclides on EBS materials;
  - Limited contact of waste form with water;
  - Limited degradation rates of waste form;
  - Limited solubility of radionuclides in near field;
  - Retarded migration of radionuclides by sorption.

In the framework of the *PAMINA* project and other projects supported by RAWRA it was proposed to start a systematic top-down approach starting from a top function for the whole disposal system

based on so-called “FRAT” (Function, Requirements, Answers, Test) system (see [Marivoet *et al.*, 2008, p.93] for more information).

### **Scenarios**

The following scenarios were selected and accepted within the Czech programme on HLW repository in granite [Marivoet *et al.*, 2008, p.208-210]:

- **Normal evolution scenario**
- **Altered scenarios initiated by unfavourable initial conditions:**
  - Premature container defect;
  - Damaged backfill;
  - Wrong container emplacement;
  - Stray construction materials left in the repository;
  - Presence of higher amounts of microbes;
  - Induced stress in disposal facility or generation of fractures.
- **Altered scenarios initiated by climatic changes:**
  - Glaciation;
  - Permafrost;
  - Seismic changes;
  - Global warming;
- **Human induced scenarios:**
  - Human intrusion;
  - Drilling of borehole in a repository;
  - Drilling through disposal units and taking of samples to the surface;
  - Major changes in groundwater flux
  - Change of chemistry at the site

#### **A.4.2 Indicators & Criteria**

The work of the Nuclear Research Institute (NRI) focused primarily on safety indicators based on analysis of available measurements of natural activity in the Czech Republic. A deep geological repository will also be assessed according to Environmental Impact Statement (EIA) regulations. The impact of the disposal on the state of the environment can be described using so called Environmental Indicators [Marivoet *et al.*, 2008, p.444].

Performance indicators in the sense of the *SPIN* project have not been considered in the Czech Republic in formal assessments of proposed repository designs, but the calculations of values of activity fluxes coming from different repository compartments (canister, near field) are commonly part of the analyses [Marivoet *et al.*, 2008, p.448].

### A.4.3 Demonstrator & Monitoring system

#### General description

The aims of the *EPSP* experiment are to develop, monitor and verify the functionality of a sealing plug and to determine a detailed characterisation of the materials from which the plug is constructed. *EPSP* is not a specific plug or seal; rather it is being built at a similar scale to a disposal tunnel plug and will contribute to the development of a reference design for such structures [DOPAS, 2016b]. It is expected that such a plug will be functional during the operational phase of the repository (150 years) and will resist a total pressure of 7 MPa [DOPAS, 2016b].

The main components of *EPSP* include (from outside to the inside, see Figure A-23):

- Outer concrete plug holding the other components of *EPSP* in place,
- Filter collecting any water that is not retained by the bentonite,
- Bentonite pellets to seal and absorb any water leaking across the inner concrete plug,
- Inner concrete plug,
- Concrete walls to facilitate the construction,
- Pressure chamber used to pressurise the inner plug.

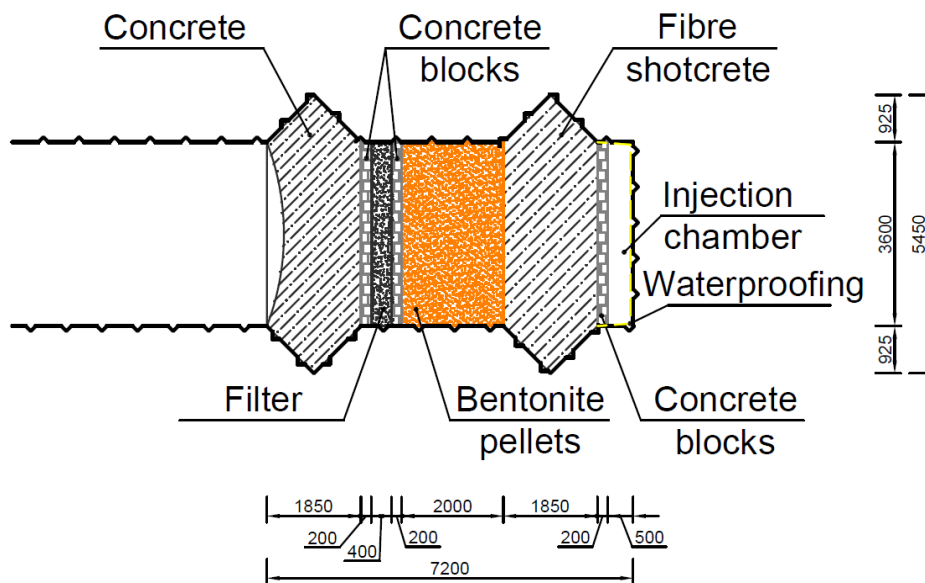


Figure A-23: Scheme of *EPSP* [DOPAS, 2016a]

The concrete blocks and the sealing element between them are the main structural elements of the plug.



### ***Monitoring activities***

Monitoring focuses on water movement inside the experiment and the experiment's response to pressurization (especially the deformation of the plugs). Water movement inside the experiment will be monitored in terms of water in/out-flow, water content distribution within the bentonite seal (RH & TDR sensors) and water (pore) pressure distribution (VW piezometers). The mechanical response of the plug is being monitored by means of VW strain gauges installed at key locations in the concrete plugs and instrumented rock bolts positioned within the rock. Moreover, contact stress measurements are deployed between the rock and the plug (VW pressure cells). Temperature distribution is being monitored since it is important not only during the construction stage (hydration heat) but also during the loading of the experiment as a reference base for sensor compensation. More information on the monitoring of the *EPSP* will be documented in the DOPAS Deliverable D3.18 "Testing plan for *EPSP* instrumentation and monitoring" which is not yet available. Information on the progress of monitoring activity within *EPSP* is given in [Grahm *et al.*, 2015]:

- The primary aim of monitoring of *EPSP* is to investigate the various processes developing inside each plug component, to verify component behaviour and to assist in assessing their performance in order to build a knowledge base for the construction of a future repository plug.
- The key processes and locations inside *EPSP* have been identified and sensors have been specially selected in order to capture them. Monitoring of *EPSP* focuses on water movement inside the experiment and the experiment's response to pressurisation.
- Water movement inside the experiment is monitored in terms of water inflow, water content distribution within the bentonite seal and water (pore) pressure distribution.
- The mechanical response of the plug is monitored by means of strain gauges installed at key locations in the concrete plugs and instrumented rock bolts positioned within the rock. Moreover, contact stress measurement is deployed between the rock and the plug.
- Temperature distribution is monitored since it is important not only to understand the hydration heat generated through curing, but it is also used as a reference base for sensor reading compensation during the loading of the experiment.
- Several measures were taken in order to ensure the provision of reliable data such as cross validation (sensors working on different principles are used to measure similar phenomena) and redundancy. Only pretested/calibrated/verified sensors were used in the experiment.
- An integral element of the monitoring process consisted of the presentation of the measured data for further analysis; therefore the data were instantly available online to end-users via a simple web interface.

## A.5 Deposition tunnel end plug of the Finish disposal concept in granite: POPLU

### A.5.1 Disposal design, Safety Functions, FEP's & Scenario's

#### Disposal design

In the current repository design from Posiva (KBS-3 method), spent nuclear fuel is emplaced in a geological repository located at a minimum depth of 400 m in granitic bedrock. The spent fuel is encapsulated in water-tight and gas-tight sealed copper canisters with a mechanical-load-bearing insert. The reference design is based on vertical emplacement of the spent nuclear fuel canisters (KBS-3V; Figure A-24) and is comparable to the Swedish concept (Appendix A.1). The alternative design (KBS-3H; Figure A-25 ) considers horizontal emplacement of the canisters.

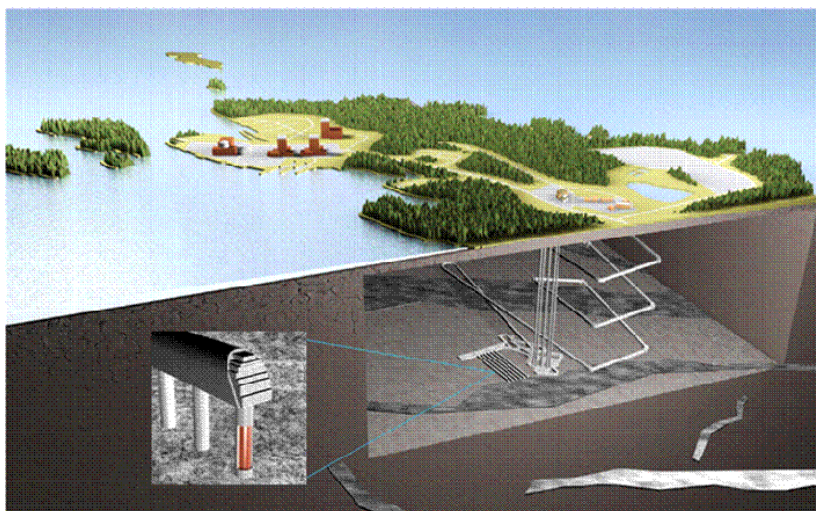


Figure A-24: Schematic presentation of the KBS-3V design (from [Posiva 2012a]).

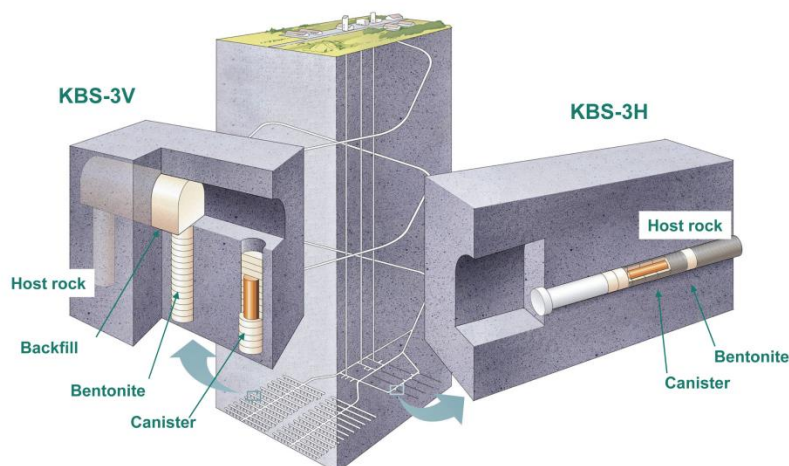


Figure A-25: The two alternative disposal methods: KBS-3V (on the left) and KBS-3H (on the right) [www.posiva.fi].

### Safety functions

The safety concept for a KBS-3 type of repository (Figure A-26) shows the primary roles of and relationship between the different technical components of the disposal system.

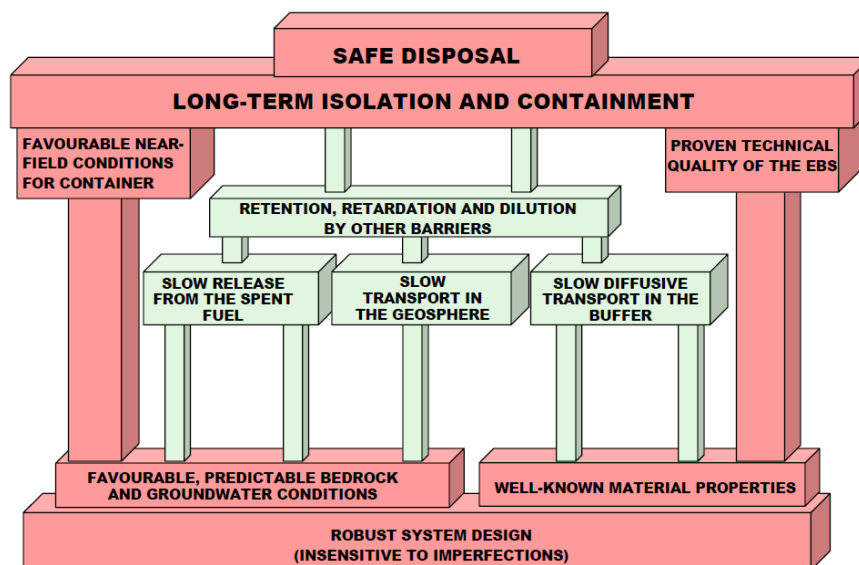


Figure A-26: Outline of the safety concept for a KBS-3 type repository for spent fuel in crystalline bedrock. Red pillars link characteristics of the disposal system to other characteristics on which they primarily depend. Green boxes and pillars indicate secondary characteristics and dependencies (from [Posiva, 2005, p.8]).

The engineered barrier system consists of [Posiva 2012a, p. 15]:

- canisters,
- buffer between the canisters and the host rock,
- deposition tunnel backfill and plugs, and
- the shaft & ramp closure.

Performance objectives are defined for each barrier of the disposal system. The performance objectives are expressed as performance targets in the case of the engineered barriers and target properties in the case of natural barriers. Based on the performance objectives, a set of technical design requirements of the repository system is defined. The technical design requirements can be tested or otherwise proven at the stage of implementation through observations and measurements [Posiva, 2013b].

The performance targets of the *backfill in the access tunnels* to the disposal boreholes are to [Posiva, 2013b, Table 2-1]:

- limit advective flow along the deposition tunnels,
- keep the buffer in place,
- contribute to the mechanical stability of the deposition tunnels,
- contribute to preventing the uplifting of the canister in the disposal borehole.



The performance targets of the *plugs* are [Posiva, 2013b, Table 2-2]:

- hydraulically isolate the deposition tunnels during the operational phase of the repository,
- keep the backfill in place during the operational phase.

In addition, all components of the repository (also deposition tunnel backfill and plug materials) are required to be compatible with each other so that their compositions shall not jeopardise the performance of each other or endanger the favourable conditions. Based on the safety functions, performance targets and design requirements, design specifications are derived:

Table A-8: Design specifications for backfill and deposition tunnel end plug (Table 2-3 from [Posiva, 2013b],)

<b>1 PERFORMANCE</b>
<b>1.1 BACKFILL</b>
<i>Montmorillonite content:</i>
The montmorillonite content of Friedland clay blocks shall be 30-38%.
The foundation layer and pellets shall consist of bentonite with montmorillonite content between 75-90%
<i>Dry density:</i>
The dry density of Friedland clay blocks shall be within the range of 1990-2070 kg/m <sup>3</sup> .
The dry density of the foundation layer shall be within the range of 1150-1350 kg/m <sup>3</sup> .
The dry density of the pellet fill shall be within the range of 900-1100 kg/m <sup>3</sup>
<i>Geometry:</i>
The backfill blocks shall have following dimensions: 550 x 470 x 330 mm. The manufacturing tolerance shall be -1 mm / +2 mm.
The block filling degree (from the theoretical/nominal cross-section) shall be >80%.
The gap width between the blocks and the theoretical tunnel wall/roof shall be 100 mm. The pellet fill shall fill the remaining open gap between the blocks and rock.
The thickness of the foundation bed shall be maximum +150 mm above the theoretical floor layer. Considering excavation tolerance of +400 mm, the maximum thickness of the foundation layer is 550 mm.
<b>1.2 PLUG</b>
The plug shall consist of a concrete dome, bentonite seal and a filter layer. The thickness of the sealing and filter layers is 750 mm. The thickness of the concrete dome is 1500 mm measured from the centre of the plug.
The concrete shall be watertight after installation. The hydraulic conductivity of the concrete mass shall be <1x10 <sup>-11</sup> m/s.
The bentonite seal shall consist of bentonite with montmorillonite content of 75-90%. In order to ensure sufficient sealing capacity the dry density shall be >1400 kg/m <sup>3</sup> . The sealing layer shall be pre-saturated to ensure water tightness after installation of the plug.
The filter layer shall consist of sand or crushed rock with grain size distribution optimised for filtering.
The plug shall maintain its hydraulic isolation capacity for at least 100 years.
<b>2 CHEMICAL PROPERTIES</b>
<b>2.1 BACKFILL</b>
The organics content in the backfill shall be lower than 1 wt-%.
The total sulphur content in the backfill shall be less than 1 wt-%, with sulphides making, at most, half of this.
<b>2.2 PLUG</b>
The cementitious materials that are used in plugs shall have a calcium to silica mass ratio less than 1:6.
The organics content in the plug shall be lower than 1 wt-%.
The total sulphur content in the plug shall be less than 1 wt-%, with sulphides making, at most, half of this.
<b>3 SUPPORT OF OTHER COMPONENTS OF THE DISPOSAL SYSTEM/MECHANICAL PROPERTIES</b>
<b>3.1 PLUG</b>
The mechanical strength of the plugs shall correspond to a pressure load of at least 7.5 MPa including the ambient hydrostatic pressure.
The main material component in the plug shall be quartz sand or crushed rock.

### **FEPs**

Table A-9 and Table A-10 summarize respectively processes related to the evolution of the engineered barrier system, and to the migration of substances within it [Posiva, 2012a].

Table A-9: Processes of significance to the long-term safety and related to the evolution of the engineered barrier system (from [Posiva 2012a] Table 2-1)

<b>Buffer and backfill evolution</b>
<i>Heat transfer</i> (see for more information [Posiva 2012a, Sections 5.2.1, 6.2.1])
<i>Water uptake and swelling</i> (see for more information [Posiva 2012a, Sections 5.2.2, 6.2.2])
<i>Piping and erosion</i> (see for more information [Posiva 2012a, Sections 5.2.3, 6.2.3])
<i>Chemical erosion</i> (see for more information [Posiva 2012a, Sections 5.2.4, 6.2.4])
<i>Radiolysis of porewater</i> (see for more information [Posiva 2012a, Section 5.2.5])
<i>Montmorillonite transformation</i> (see for more information [Posiva 2012a, Sections 5.2.6, 6.2.5])
<i>Alteration of accessory minerals</i> (see for more information [Posiva 2012a, Sections 5.2.7, 6.2.6])
<i>Microbial activity</i> (see for more information [Posiva 2012a, Sections 5.2.8, 6.2.7])
<i>Freezing and thawing</i> (see for more information [Posiva 2012a, Sections 6.2.8])
<b>Auxiliary components evolution</b>
<i>Chemical degradation</i> (see for more information [Posiva 2012a, Section 7.2.1])
<i>Physical degradation</i> (see for more information [Posiva 2012a, Section 7.2.2])
<i>Freezing and thawing</i> (see for more information [Posiva 2012a, Section 7.2.3])

Table A-10: Processes (and feature) related to migration within the EBS (from [Posiva 2012a], Table 2-1)

<b>Migration within EBS</b>
<i>Aqueous solubility and speciation</i> [Posiva 2012a, Section 6.3.1 (backfill) and 7.3.1 (auxiliary)]
<i>Precipitation and co-precipitation</i> [Posiva 2012a, Section 6.3.2 (backfill) and 7.3.1 (auxiliary)]
<i>Sorption</i> [Posiva 2012a, Section 6.3.3]
<i>Diffusion</i> [Posiva 2012a, Section 6.3.4 (backfill) and 7.3.1 (auxiliary)]
<i>Advection</i> [Posiva 2012a, Section 6.3.5 (backfill) and 7.3.1 (auxiliary)]
<i>Colloid transport</i> [Posiva 2012a, Section 6.3.6 (backfill) and 7.3.1 (auxiliary)]
<i>Gas transport</i> [Posiva 2012a, Section 6.3.7 (backfill) and 7.3.1 (auxiliary)]

### **Scenarios**

Three “top level” types of repository evolution scenarios are considered: a base scenario, variant scenarios, and disturbance scenarios (see Figure A-27). Surface environment scenarios are formulated independently from those for the repository system and are limited to the time window covering the first ten millennia after emplacement of the first waste canister [Posiva 3013c].

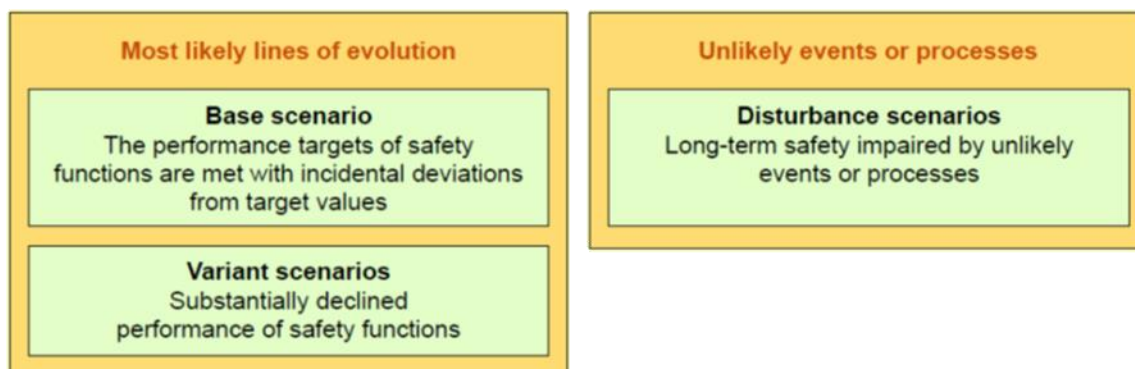


Figure A-27: Scenario classification (from [Posiva, 2013c])

### A.5.2 Indicators & Criteria

The safety indicators in the Posiva Safety Case directly related to the regulatory guidelines are the annual effective dose as *primary safety indicator*, and several additional *complementary safety indicators*, sub-divided in numerical (e.g. radionuclide fluxes) and qualitative (e.g. evidence from natural and anthropogenic analogues) indicators [Marivoet *et al.*, 2008, p.452].

The terminology with performance indicator (PI) and function indicator (FI) has not been adopted in the Posiva Safety Case as such [Marivoet *et al.*, 2008, p.452]. The 'properties' of the disposal system components used in the KBS-3H Safety Case are equivalent to the “*safety function indicator*” used in the SR-Can safety assessment developed in Sweden (see also Appendix A.1). A (quantitative) criterion is given to each property in order to fulfil the requirements. Table A-11 gives an overview of the safety functions of the deposition tunnel end plug and related design specifications (properties and criteria), based on the information given in table A-8.

Table A-11: Design specifications linked to safety functions of the *POPLU* deposition tunnel end plug.

Safety function	Design specifications	
	Property	Criterion
Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for buffer and canisters	Hydraulic conductivity of concrete mass	$< 10^{-11}$ m/s for at least 100 years
	Montmorillonite content of the seal	75-90 %
	Dry density seal	$> 1400$ kg/m <sup>3</sup>
Limit and retard radionuclide releases in the possible event of canister failure	Organics content in the plug	$< 1$ wt-%
	Sulphur content	$< 1$ wt-%
	Calcium to silica ratio of cementitious materials	$< 1:6$
Contribute to mechanical stability of the rock adjacent to the deposition tunnels	Mechanical strength to withstand the sum of the swelling pressure of backfill and hydrostatic pressure of the groundwater	Pressure load of at least 7.5 MPa
	Main material component of the plug	Quartz sand or crushed rock

### A.5.3 Demonstrator & Monitoring system

#### General description of the demonstrator

The *POPLU* wedge-plug is an alternative design of the Posiva's dome-plug reference and could be utilized in certain environmental scenarios within the deposition tunnel (depending on rock suitability and leakage).

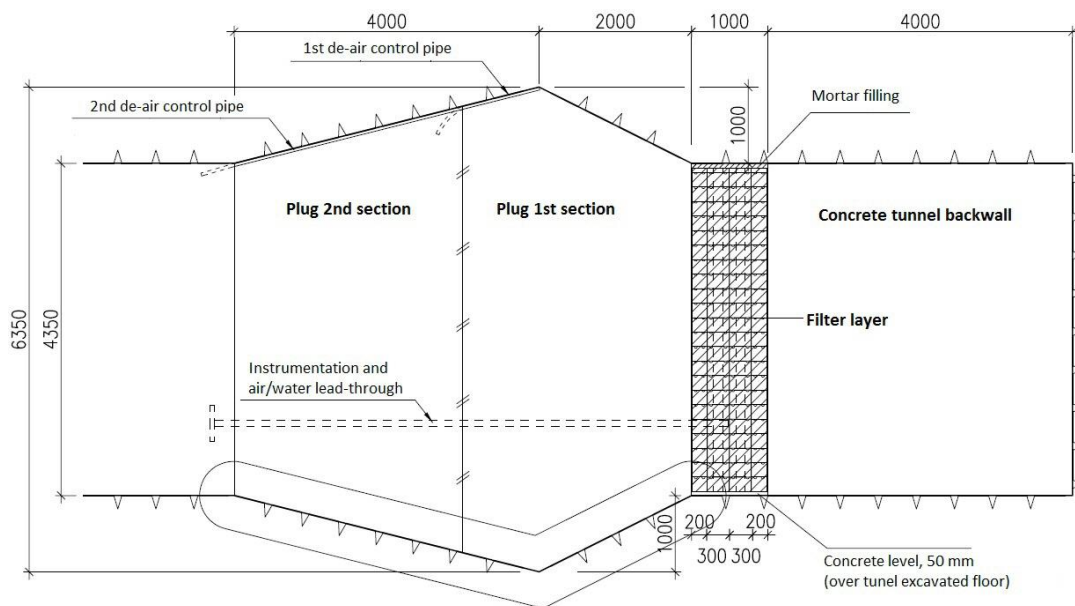


Figure A-28: Vertical section of Posiva's wedge plug [Holt and Koho., 2016, p.29]

The expected loads acting on the plug are:

- water pressure of 4,5 MPa (representing a water column of 450 metres)
- maximum average swelling pressure of 3,0 MPa from the bentonite backfill
- the heat expansion arising through the bedrock from spent nuclear fuel canisters will load the plug at a maximum level of 13 MPa.

In the preliminary design the tunnel behind the plug was planned to be backfilled with clay blocks or similar materials to provide hydraulic isolation. In the final design it was agreed that there would not be any backfill structure but only a filter layer and a concrete back wall to shorten the tunnel if needed. The monitored parameters include temperature, humidity, strain, displacement and pressure.

The details on the performance monitoring systems are reported within the [Holt and Koho, 2016] and briefly described in the following paragraphs.

The concrete plug, the gap between rock and plug and the structure behind the plug are monitored to observe changes in their condition with time and increasing pressure. Following parameters are monitored within *POPLU* [Holt and Koho, 2016]:

- displacement of the plug (mm)
- strain of reinforcement and concrete ( $\mu\text{S}$ )
- relative humidity of concrete and potential backfill (RH %)
- pressure between the rock and the plug (MPa)
- pressure behind the plug (MPa)
- temperature of the concrete (K)
- water leakage through and around the concrete plug ( $\text{dm}^3/\text{hour}$ )

### Monitoring of the concrete plug

The plug is a massive and rigid structure of reinforced concrete with no deformations. Therefore its movement can be calculated according to the front surface displacement. Displacement sensors measure any possible movement of the plug (e.g. during the grouting phase). The sensors measure the relative movement between the rock and plug in three locations at the plug front face [Holt and Koho, 2016].

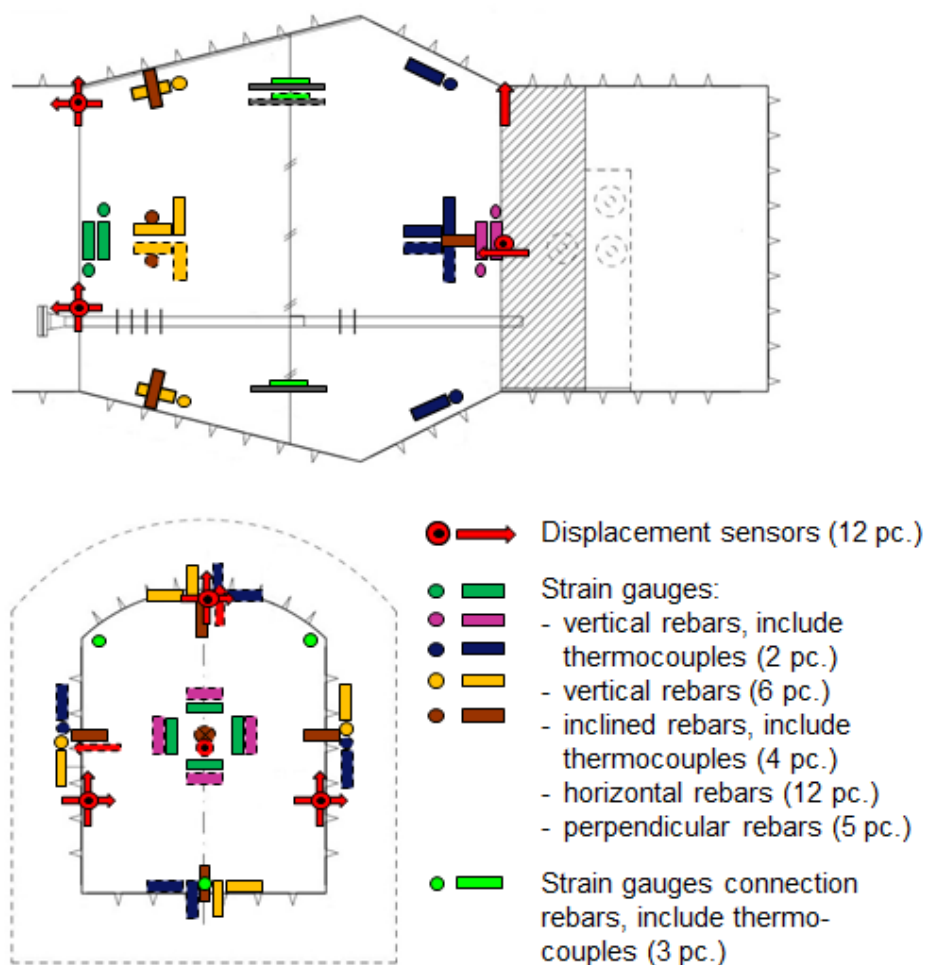


Figure A-29: Designed locations of monitoring system components including displacement sensors at front and back face of the plug [Holt and Koho, 2016].



The strains in the plug are measured by strain gauges fixed on the rebars. The dark green labels in Figure A-29 refer to the strain gauges on the front surface and the violet labels to the gauges on the back face. The yellow labels refer to strain gauges around the front part of plug and blue labels to gauges around the back part of plug. Some strain gauges also include temperature measurement sensors to be able to eliminate strains due to temperature variations.

The pressure, humidity and temperature of the concrete are measured during the casting phase as well as thereafter. The temperature in the demonstration tunnels is quite consistent throughout the year, on average approximately 10 to 12°C. During the concrete casting the temperature of the early age concrete can rise up to 50 °C due to exothermic reactions caused by hydration of the cement and additives in the concrete mix. The concrete temperature will be measured on the front faces of the two plug parts by thermocouples. Those sensors will be removed after removing of the formwork. In addition, some other installed sensors, e.g. strain gauges and relative humidity sensors, will also allow for temperature measurements. These sensors are used for temperature monitoring during the pressurization phase, when slight changes of temperature might occur.

The hardening process of the concrete used for the construction of both parts of the plug will be investigated by means of two relative humidity sensors in both the front and back parts of the concrete plug. The intention of the measurements is to monitor the hydration process of the applied low-pH concrete. The data provided by the relative humidity and temperature sensors will allow for an evaluation of the concrete quality and condition. The critical locations to monitor the relative humidity of the concrete are the centre of the plug parts, where the hydration heat is highest and influences from outside are weakest, and the corner points of the plug parts, where possible changes of the relative humidity might occur after a certain time due to penetration of water into the concrete during the pressurization phase. Two types of pressure sensors will be installed to monitor pore pressure and the total pressure in the gap between the rock and plug during the pressurization phase.

### ***Monitoring of the backfill***

In December 2013 the final design was agreed upon with Posiva and it was decided that there would not be any backfill (including the sealing layer) but only a filter layer and a concrete back wall if needed, for shortening the tunnel [Holt and Koho, 2016]. Bentonite tape rings are still included as sealers directly between the concrete plug circumference and the rock tunnel wall

### ***Monitoring of leakage***

Any leakage water through the plug front face is measured in a first phase from four equal sized sectors on the plug wall. In the second phase the water is collected via a canal on the floor in front of the plug. In the third phase the water will be collected in a small water tank or bottle for further analyses, such as chemical composition and *pH*. The amount of dissolved bentonite in every pressurizing phase indicates the level of sealing achieved.

### ***Monitoring of near-field***

To assess the responses of the near field to the plug during the experiment, a tunnel was excavated next to the plug tunnel to host the instrumentation and pressurization equipment. Additional measurements as water pressure, water leakage, temperature, strains and dislocations of the rock mass are performed there.

#### **A.5.4 Relevance of monitored processes for the long-term safety**

Following the same methodology as in the case of DOMPLU (see A-1), the links between the safety functions of the plug and the related safety function indicators were established and summarized in Table A-2.

Table A-12: Parameters linked to safety functions of the plug.

Safety function	Hydraulic conductivity concrete	Dry density seal	Mechanical strength
Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for buffer and canisters	+	+	
Contribute to mechanical stability of the rock adjacent to the deposition tunnels			+

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## List of tables

Table 1-1: Safety functions, safety function indicators and criteria related to the deposition tunnel backfill and buffer .....	16
Table 3-1: Model parameters for the components of the shaft sealing ( <i>ELSA</i> , <i>GRS</i> ) .....	47
Table 3-2: Model parameters for the components of the shaft sealing ( <i>NRG</i> ) .....	48
Table 3-3: Parameter values of $n$ , $F_{09}$ , $F_{46}$ en $F_{47}$ .....	55
Table 3-4: Model parameters for the convergence/compaction models.....	56
Table 4-1: Parameters monitored in the DOPAS demonstrators <i>DOMPLU</i> (Dome Plug, <i>SKB</i> ), <i>FSS</i> (Full Scale Seal, <i>Andra</i> ), <i>EPSP</i> (Experimental Pressure and Sealing Plug, <i>SURAO</i> ), and <i>POPLU</i> ( <i>POsiva PLUg</i> , <i>Posiva</i> ).....	65
Table 4-2: Safety function indicators linked to safety functions of the deposition tunnel backfill. ....	68
Table 4-3: Selection of relevant indicators for Safety function indicators for deposition tunnel backfill.....	68
Table 4-4: Performances, indicators and criteria expected from the seals within the galleries in relation to the long-term safety functions.....	68
Table 4-5: Temperature dependency of several processes .....	71
Table A-1: Safety functions, safety function indicators and criteria related to the deposition tunnel backfill and buffer .....	91
Table A-2: Safety function indicators linked to safety functions of the deposition tunnel backfill and buffer. ....	98
Table A-3: Selection of relevant indicators for Safety function indicators for deposition tunnel backfill.....	99
Table A-4: Primary FEPs (left) and less likely FEPs (right) that may affect the shaft seal in rock salt .....	102
Table A-5: Safety functions, relevant processes and parameters linked to the shaft seal .....	107
Table A-6: Design features of the seals within repository galleries and the <i>ILW</i> disposal vault seals related to the long-term safety functions.....	112
Table A-7: Performances, indicators and criteria expected from the seals within the galleries in relation to the long-term safety functions.....	114
Table A-8: Design specifications for backfill and deposition tunnel end plug (Table 2-3 from [Posiva, 2013b],) .....	126
Table A-9: Processes of significance to the long-term safety and related to the evolution of the engineered barrier system.....	127
Table A-10: Processes (and feature) related to migration within the <i>EBS</i> .....	127
Table A-11: Design specifications linked to safety functions of the <i>POPLU</i> deposition tunnel end plug.....	128
Table A-12: Parameters linked to safety functions of the plug. ....	132

## List of figures

Figure 1-1: Example of FEP screening process .....	10
Figure 1-2: Potential evolutions of a parameter in different scenarios covered by a safety case.....	11
Figure 1-3: Potential evolution of a monitored parameter. ‘Scenario A’ here represents an evolution not covered by the normal evolution, but not impairing the long-term safety. ‘Scenario B’ may represent a scenario where an impairment of the long-term safety cannot be excluded. ....	12
Figure 1-4: Classification of indicators .....	13
Figure 1-5: Parameter identification in MoDeRn - step 2.....	19
Figure 2-1: Simplified functional abstraction of seals and plugs during the period of full containment .....	23
Figure 2-2: Generic design of a plug or seal with sealing function.....	23
Figure 2-3: Generic functional abstraction of a plug or seals for performance assessment .....	25
Figure 2-4: Main processes for the assessment of radionuclide migration in PA, key features and parameters, and underlying relevant processes and features.....	26
Figure 2-5: Measured porosity-permeability relation of compacted salt grit (grey diamonds) and sample realizations of the relation based on a calibrated model and its parameter distribution	29
Figure 2-6: Evolution of the permeability of a salt grit plug.....	29
Figure 2-7: Evolution of stress in a salt grit plug .....	30
Figure 2-8: Relation between permeability and stress in a salt grit plug for the calculated time interval.....	30
Figure 2-9: Indicator based on Péclet number. In case the indicator is $<1$ , diffusion is the dominating process for radionuclide diffusion. Because diffusion of radionuclides released from the waste will always occur in saturated porous media, this can be considered as covered by the normal evolution scenario. ....	32
Figure 2-10: Péclet number vs. hydraulic conductivity for different systems. For different systems, different hydraulic conductivities define the transition from an advection to a diffusion dominated system. For the Péclet number, this happens always at $Pe = 1$ . ....	33
Figure 2-11: Distribution of advective and diffusive transport paths.....	34
Figure 2-12: Representation of the travel-time based indicator developed by NRG .....	35
Figure 2-13: Normalized breakthrough curves.....	35
Figure 2-14: Radiotoxicity evolution of the inventory.....	36
Figure 2-15 Integrated amount of brine inflow .....	37
Figure 2-16: Performance indicator related to the safety function “ $R2-RT$ ” of a borehole plug for three parameter sets .....	38
Figure 2-17: Relative contribution of the safety function ‘ $R2-RT$ ’ of a borehole plug to the overall safety for three parameter sets.....	39
Figure 2-18: Standardized rank regression coefficients (SRRC), partial rank correlation coefficients (PRCC) , and the adjusted coefficient of determination $R_{adj}^2$ for the performance indicator ‘permeability of the plug’ .....	39
Figure 2-19: Standardized rank regression coefficients (SRRC), partial rank correlation coefficients (PRCC) , and the adjusted coefficient of determination $R_{adj}^2$ for the safety indicator ‘dose rate in the biosphere’ .....	40
Figure 2-20: General approaches to access the relevance of individual barrier elements and the related processes and parameter on the long-term safety .....	41
Figure 2-21: Proposed indicator analysis workflow.....	43

Figure 3-1: Set-up of NRG’s <i>ELSA</i> demonstrator case (right) based on GRS’s PA <i>LOPOS</i> model (left).....	46
Figure 3-2: Schematic representation of the convergence of an excavation .....	49
Figure 3-3: Deformation mechanisms of (dislocation coupled) recrystallization creep and pressure solution creep .....	51
Figure 3-4: Schematic representation of the <i>NF-PRO</i> pore healing model.....	54
Figure 3-5: Permeability as a function of porosity.....	55
Figure 3-6: Evolution of the Péclet number for the brine outflow from the repository into the vertical shaft for three initial convergence rates $K_{init}$ .....	57
Figure 3-7: Evolution of repository and brine volumes .....	58
Figure 3-8: Evolution of repository and brine volumes – effect of parameter variation.....	59
Figure 3-9: Evolution of indicator and radiotoxicity in repository for three initial convergence rates $K_{init}$ and an inventory of 300 CSD-V containers .....	60
Figure 3-10: Evolution of indicator and radiotoxicity in repository for three initial convergence rates $K_{init}$ and an inventory of 3735 CSD-V containers.....	60
Figure 4-1: Retention curve of MX-80.....	75
Figure 4-2: Measured displacement of the seal (2) and LECA (1 and 3) respectively compared to the concrete back wall .....	78
Figure 4-3: Measured leakage from the weir and the applied water pressure .....	78
Figure 4-4: Total pressure in Section 1 in the bentonite seal. ....	79
Figure 4-5: Relative humidity recordings in the bentonite seal.....	79
Figure 4-6: Material specific relation between density and hydraulic conductivity for three materials with variable salinity.....	80
Figure 4-7: Material specific relation between density and swelling pressure for three materials variable salinity .....	80
Figure 4-8: Recordings of temperature at several locations in the <i>DOMPLU</i> demonstrator .....	81
Figure 5-1: Indicator analysis and demonstrator monitoring .....	84
Figure A-1: The KBS-3 concept for disposal of spent nuclear fuel. ....	87
Figure A-2: Safety functions (bold), safety function indicators and safety function indicator criteria related to containment .....	88
Figure A-3: Safety functions (bold), safety function indicators and safety function indicator criteria related to retardation.....	89
Figure A-4: Principle layout of the reference design of the plug system from SKB.....	93
Figure A-5: Schematic section of the <i>DOMPLU</i> full-scale test. ....	94
Figure A-6: Placement of sensors in the concrete dome in the <i>DOMPLU</i> demonstrator .....	96
Figure A-7: Monitoring of the bentonite seal, filter and backfill in the <i>DOMPLU</i> demonstrator.....	97
Figure A-8: Cross section of the shaft and disposal facility for the generic disposal concept in Gorleben. The purple colour represents the main salt of the Zechstein series, green colours anhydrites. ....	100
Figure A-9: Link between protection goals, safety assessment components, and safety functions. ...	101
Figure A-10: Methodology for the development of scenarios applied in R&D project <i>VSG</i> .....	103
Figure A-11: Methodology Staged approach for the long-term safety assessment.....	105
Figure A-12: Schematic of the shaft seal according to <i>VSG</i> (1 <sup>st</sup> draft). The elements considered in the exemplary safety assessment are framed in red.....	106
Figure A-13: Artist impression of the facilities at <i>Cigéo</i> .....	108
Figure A-14: Safety functions over time.....	110

Figure A-15: Graphical representation of the high-level safety functions *Counter water circulation*, *Limit release of radionuclide elements immobilize them in the repository*, and *Reduce concentration and delay radionuclide migration outside of the disposal cells* and corresponding components..... 110

Figure A-16: Seals emplaced upon closure of an ILW disposal cell..... 111

Figure A-17: Location of the drift seals and ILW disposal vault seals in the French repository concept [DOPAS, 2014]. Drifts are horizontal tunnels, whereas ramps are inclined tunnels..... 115

Figure A-18: 3D view of the *FSS* test box with the breakouts (recesses) in the argillite formation. ... 116

Figure A-19: Reference design of a horizontal drift seal ..... 116

Figure A-20: Alternative design of a horizontal drift seal..... 117

Figure A-21: Longitudinal section view of the *FSS* experiment..... 117

Figure A-22: Artist impressions of the planned Czech deep repository..... 119

Figure A-23: Scheme of *EPSP*..... 122

Figure A-24: Schematic presentation of the KBS-3V design..... 124

Figure A-25: The two alternative disposal methods: KBS-3V (on the left) and KBS-3H..... 124

Figure A-26: Outline of the safety concept for a KBS-3 type repository for spent fuel in crystalline bedrock. Red pillars link characteristics of the disposal system to other characteristics on which they primarily depend. Green boxes and pillars indicate secondary characteristics and dependencies. .... 125

Figure A-27: Scenario classification ..... 128

Figure A-28: Vertical section of Posiva’s wedge plug..... 129

Figure A-29: Designed locations of monitoring system components including displacement sensors at front and back face of the plug..... 130