EUROPEAN COMMISSION
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MoDeRn

Monitoring Developments for Safe Repository Operation and Staged Closure

Case Studies

Final Report

EC Deliverable: D-4.1

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Editor: M. Jobmann (DBE TECHNOLOGY GmbH)

Date of issue of this report: 31/10/2013

Dissemination level		
PU	Public	X
RE	Restricted to a group specified by the partners of the MoDeRn project	
CO	Confidential, only for MoDeRn partners	

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The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° 232598. The research carried out by DBE TECHNOLOGY has also received funding from the Federal Ministry of Economics and Technology (BMWi), Germany.

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1 Introduction

Within the MoDeRn project, a structured approach – the MoDeRn Monitoring Workflow – was elaborated in order to provide a generic methodology for the development and implementation of a monitoring programme that takes into account specific national boundary conditions. The workflow allows the linking of high-level monitoring objectives to the detailed selection of monitoring technologies and sensor placements (MoDeRn, 2013a).

The objective of this report is to propose and evaluate a parameter evaluation and feasibility screening scheme that allows the design of a (practical) monitoring plan that links monitoring objectives with the specific features and needs of a particular disposal concept and the corresponding safety case. For three generic repository concepts in salt, clay, and granite host rock, monitoring plans are therefore developed. The idea behind this was to describe how a monitoring system could look like based on current technology and to identify possibilities and limits of repository monitoring. Additionally, a case study is performed to provide an analytical and practical evaluation of the feasibility to detect possible alternative repository evolutions by means of a monitoring system in facilities for the deep geological disposal of radioactive waste. An assessment of the technical feasibility was performed to

- get an idea of how monitoring systems should be designed in practice,
- evaluate the possibility to detect failures of sensors in case access to the sensors is no longer possible,
- discuss the possibility to detect whether the repository evolution is as predicted, i.e. is in line with the “reference evolution scenario”, or whether a different route is followed, i.e. an “alternative evolution scenario”.

In a first step, a mapping of relevant processes and parameters was performed for the three host rocks considered. A preliminary list of parameters that are considered to be representative for the evolution of the repository was developed. All preliminary parameters are screened to determine their detectability by in-situ monitoring. For parameters and processes that are considered to be representative for the evolution of the safety of a repository, monitoring systems were proposed that allow their measuring under in-situ conditions in the disposal concepts considered.

The ability to identify the cause of a potential deviating monitoring outcome is an important issue. One reason for the deviation may be that the monitored repository component evolves differently than predicted, but an alternative explanation may be a failure of the equipment used. In case the outcome indicates that the long-term safety may be impaired in any way, it will be of utmost importance to be able to exclude a failure of the monitoring equipment to avoid an incorrect conclusion. Thus, detection of potential sensor failures has an essential role in supporting decision making in case of deviating monitoring results and will therefore be discussed in this report.

Finally, example scenario studies are performed in order to evaluate qualitatively and quantitatively the ability of the designed monitoring system to detect alternative evolutions of the repository.

2 Description of the cases

The objective of the case study is to link monitoring objectives and the design of monitoring systems. All studied cases take the main objectives and specific properties of the host rock and the (generic) national disposal concepts as a starting level to identify processes relevant to monitoring and to follow a method for parameter identification and monitoring system design as described in the following chapter. Three representative cases were selected for further evaluations, with the main idea to address all three main types of host rocks – salt, clay, and granite – and with the objective to evaluate three different disposal concepts. This should cover a broad range of monitoring set-ups and technologies.

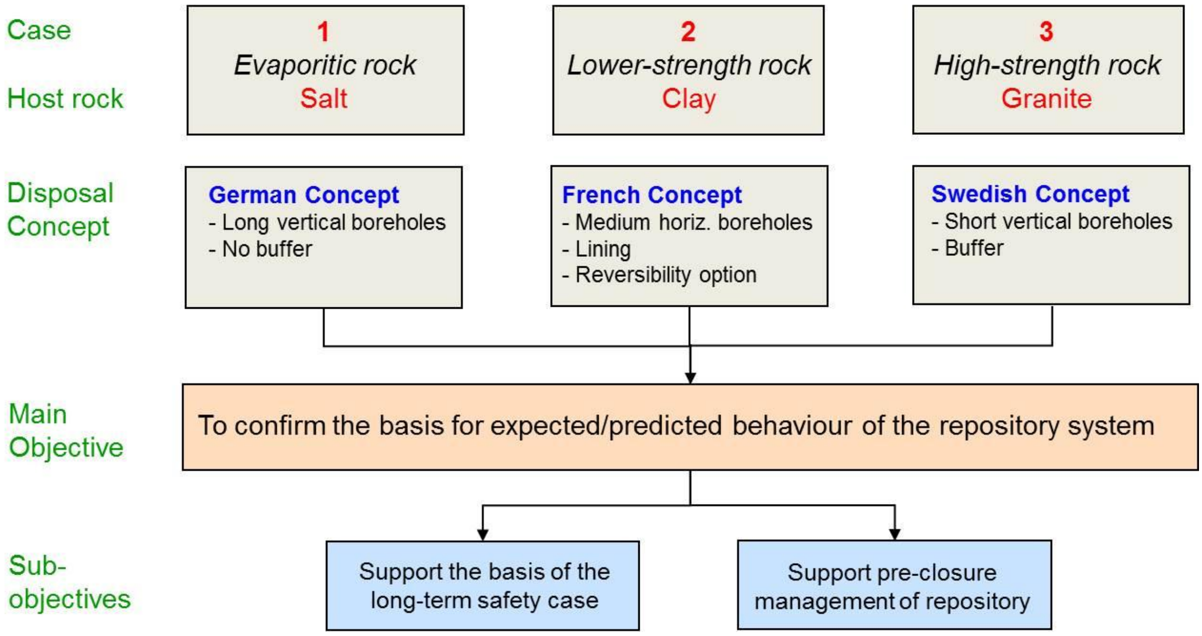


Figure 2-1: Cases defined and monitoring objectives

Figure 2-1 shows the three cases for the three types of host rock and the corresponding disposal concepts. In addition, the main monitoring objectives recently identified (MoDeRn, 2013a) are indicated. The work done in each case study was based on safety functions, as defined in the respective safety cases. The safety functions, which may differ for each type of host rock and national concept, can be related to safety-relevant processes and measurable parameters characterizing each process. The parameter identification process is discussed in more detail in the next chapter.

3 General principle of parameter identification and feasibility screening

It was agreed by all MoDeRn partners that the process of identifying parameters worth monitoring should be transparent and traceable. This is not only useful for the implementer himself in order to keep track of the knowledge and the rationales for the identification but also for the discussions with the authorities and the justification of the decision. Transparency is also important for the lay and expert stakeholders, giving them the opportunity to provide their views and influence decisions. A formal and regular involvement of stakeholders is considered to be essential. Figure 3-1 illustrates the identification process, starting with the first of the monitoring sub-objectives.

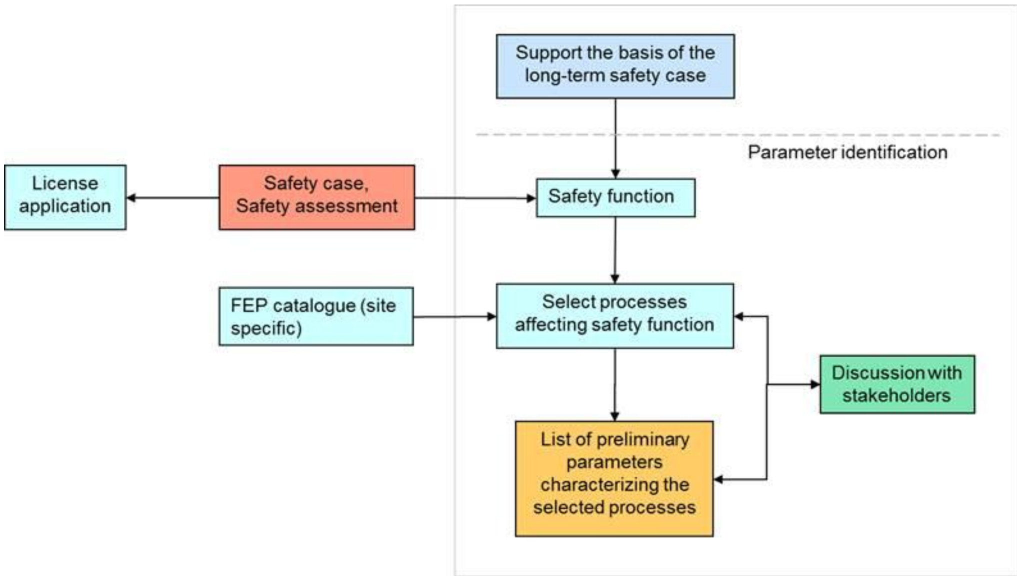


Figure 3-1: Parameter identification process

As part of the safety case, which is the basis of the license application, safety functions are defined which are allocated to the monitoring sub-objective. An important selection approach comes from the FEPs, which characterize all processes related to the possible future repository evolutions. Through a careful assessment of the FEPs and the corresponding evaluation of the repository evolution scenarios, the FEPs that have an adverse effect on a particular safety function can be identified. These processes are then considered worth monitoring in order to confirm that the safety functions are not jeopardized.

The next step is to determine the parameters that characterize the individual processes. Taking into account the available monitoring techniques and equipment, this preliminary list may be changed with regard to feasibility. The final list, including the rationales behind it, is then to be discussed with the stakeholders to come up with a commonly agreed list of parameters worth monitoring.

How the safety case is linked via the safety functions to the selection of processes and parameters is exemplarily shown in the three cases described in the following chapters.

4 Case I - Rock salt

To go through the process levels indicated in Figure 3-1, the safety case or the safety assessment and the FEPs are important input components to identify safety functions and the processes affecting them. For the first case, the German disposal concept for a repository in rock salt has been taken as a reference. In Germany, a new concept for the demonstration of safety, called the "*Safety Assessment Concept*" (Bollingerfehr et al. 2008), has recently been developed. The following chapters give a brief summary of the current concept to demonstrate repository safety by means of the new safety assessment methodology.

The identification and subsequent quantitative analysis and evaluation of scenarios that each represent one of the possible future developments of a final repository system are essential components of the long-term safety assessment for a final repository. The individual scenarios are characterised by features, events, and processes (FEPs) that may influence the future development of the final repository system. As FEPs are essential for defining scenarios, NEA has compiled a FEP data base and defined a generic procedure for classifying FEPs and compiling a corresponding catalogue (Buhmann et al., 2008).

Within the scope of the R&D project ISIBEL (Bollingerfehr et al., 2008), this classification procedure was used to compile a site-specific FEP catalogue (Buhmann et al., 2008). The FEP descriptions in this catalogue are far more detailed than generic, site-independent considerations and apply to a reference site whose specific geoscientific characteristics were defined based on existing data. Based on the safety assessment and the FEPs, the <u>processes</u> that influence the components of a safety assessment are identified. <u>Parameters</u> that characterise the relevant processes are identified as relevant to monitoring.

4.1 German safety assessment concept

For the current safety assessment concept, a systematic review of the safety of final disposal of HLW in rock salt formations – based on the state of the art in science and technology – was carried out in order to determine if and to what extent the technical feasibility and the safety of a final repository can be demonstrated on the basis of the current state of knowledge. A new methodology for the safety assessment of the concept was developed which takes full account of the concept of safe confinement. The key aspect of the long-term safety assessment methodology is the systematic demonstration of the safe long-term confinement of the waste. This is done by demonstrating the integrity of all relevant geotechnical barriers and of the geologic main barrier. In some repository evolution scenarios, an impairment of the integrity of the barrier system that may result in the creation of a continuous pathway for radionuclide migration cannot be ruled out. In these cases, a safety assessment is performed that quantifies the release of radionuclides that may happen. Scenario analysis is performed to evaluate the likelihood of these alternative repository evolutions.

For the geological integrity of the salt barrier at the Gorleben site for example, the block structure of the main anhydrite is of vital importance. For the reference site, this implies that in the case of an undisturbed repository evolution, a release path via the main anhydrite can be excluded. At the same time, the release of radioactive nuclides via the main anhydrite, often regarded as an all-encompassing reference scenario in the past, has become irrelevant. The open volumes (shafts, galleries) created by mining activities are assumed to be the only remaining paths for brine intrusion as well as for the potential release of dissolved radionuclides (Figure 4-1). Once the facility is closed, the waste is totally isolated by the rock salt. The demonstration of *safe confinement* of the waste has therefore become the most relevant aspect of the safety assessment.

The other vital component of the demonstration of the *safe confinement* of the waste is the demonstration of the integrity of the engineered barriers, particularly of the shaft and drift seals. Their diversified positioning prevents any relevant releases of radionuclides in case one of these two technical barriers fails. In addition to shaft and drift seals, the borehole seals, the backfill material, and the disposal containers are considered. In accordance with the safety concept, the individual components have to meet different requirements which can be deduced from the tasks and functions of the respective component within the safety concept.

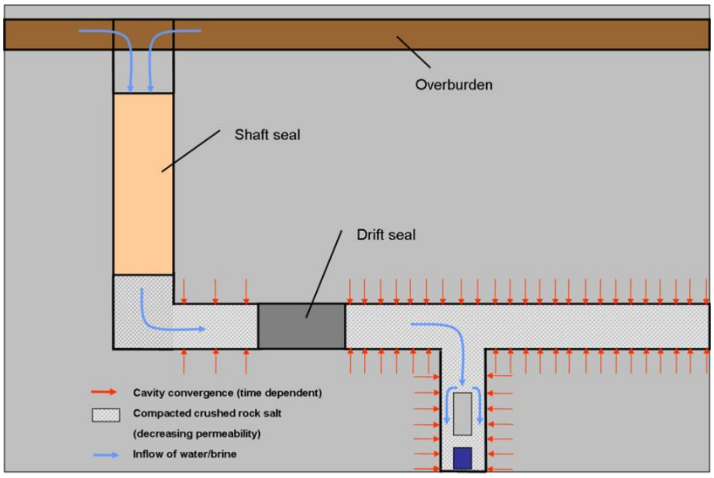
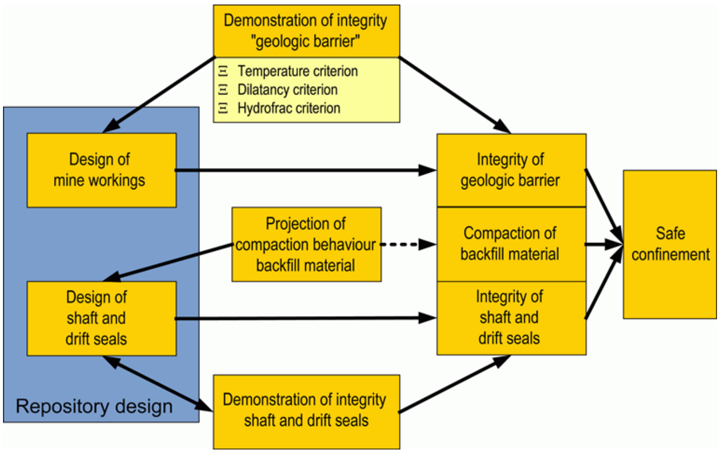


Figure 4-1: Schematic diagram of the potential pathways for water or brine intruding through the barrier system

The design and construction of the final repository takes into account the geology of the site. Plus, the mine layout is designed in such a way that the integrity of the geologic main barrier can be demonstrated. Emplacement cavities will be located at sufficient depth and at a suitable distance to potential fault zones or strata boundaries. To comply with the dilatancy and brine pressure criteria, a maximum temperature of the rock salt of 200°C is considered to be an essential boundary condition.

After placement of the waste canisters, the emplacement boreholes are sealed by means of a pre-compacted mass of crushed salt. If required for the ensurance of safe confinement, a more complex construction with more advanced requirements may be used. When all waste canisters are placed, the entire void volume of all mine workings in the repository will be backfilled with crushed salt which, upon the convergence resulting from overburden pressure, will be compacted further. During compaction, the porosity and permeability of the crushed salt decrease until, in the long term, it exhibits the same barrier properties as rock salt.



The drifts and the access areas to the waste emplacement sites will be sealed by means of shaft and drift seals (Bollingerfehr et al., 2008).

Figure 4-2:
Safety concept of "Safe Confinement"

These geotechnical barriers must be placed and – with regard to their hydraulic resistance and long-term stability – designed in such a way that (i) brine intrusion to the waste via the shaft and the backfilled drifts are excluded to the greatest possible extent, and (ii) a subsequent forcing out of contaminated solutions via the same pathway as a result of increasing convergence need not be feared in the case of the reference repository evolution. The long-term stability and the hydraulic resistance of the geotechnical barriers are chosen in such a way that the disposed waste is completely sealed from the biosphere.

Compliance with all safety requirements described in the previous sections has to be demonstrated by means of engineering-based assessments of the barrier integrity (Figure 4-2)

4.2 Protection goals and safety components

The ultimate aim of the safety assessment concept is to meet the protection goals stipulated in the regulations. These can be divided into conventional (non-radiological) and radiological protection goals. The protection goals are:

- Protection of the surface against repository induced changes (conventional protection goal)
- Protection of groundwater against contaminants (conventional protection goal)
- Protection of the biosphere against radionuclides (radiological protection goal)
- Criticality safety (radiological protection goal)

In the case of an undisturbed repository evolution, the protection of the groundwater is realized by the safe confinement of the radioactive waste. The safe confinement of the waste must be demonstrated for several scenarios. Next to the reference scenario, several alternative scenarios have to be assessed. For example, in case of an abandonment scenario, intrusion of brine has to be considered. In addition to the "safe confinement", the "negligibility of subsidence and uplift" and the "compliance with the container design" have to be assessed, too.

Figure 4-3 shows the protection goals and their relation with the safety assessment components. 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. While most of the components support the isolation of the waste, the component "sufficient compaction of the backfill material" is linked to three different safety functions according to the physical processes behind it. 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. The general methodology to carry out the corresponding safety assessments is described in Müller-Hoeppe et al. (2007) and Kreienmeyer et al. (2008).

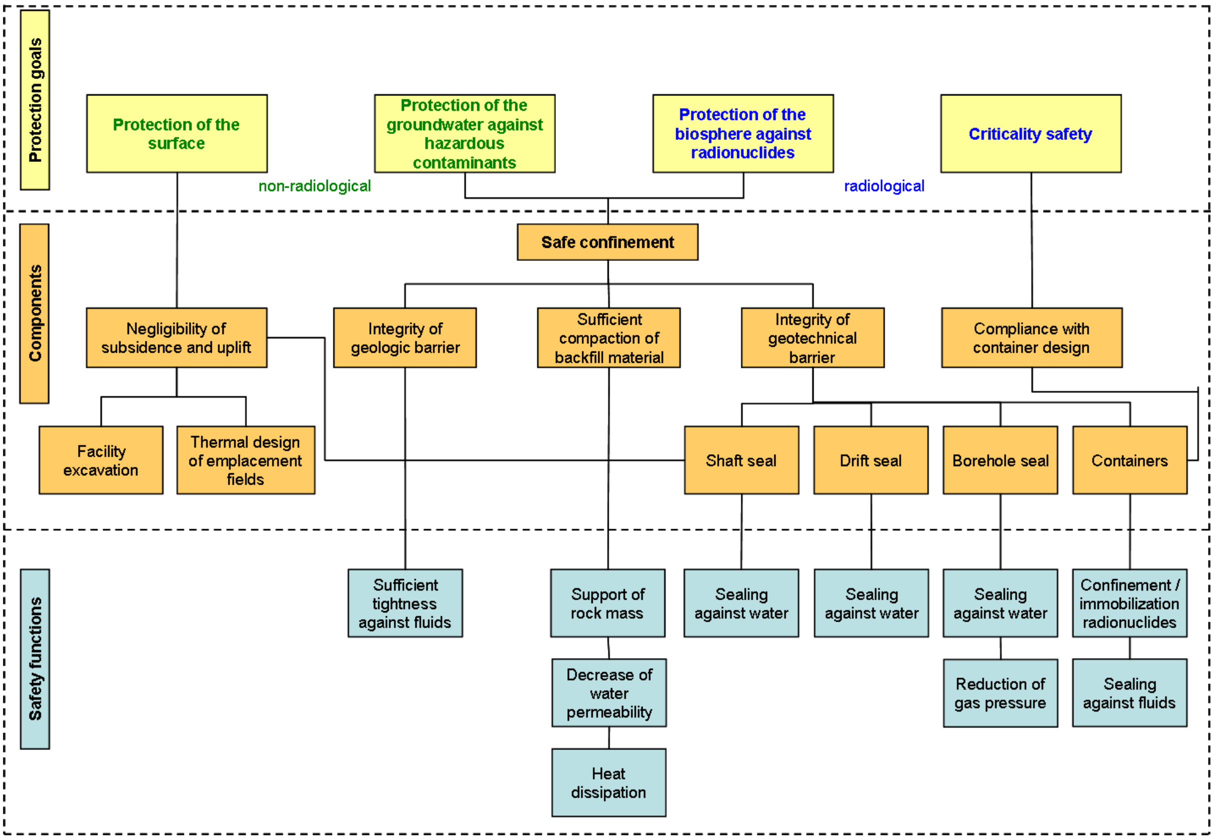


Figure 4-3: Connection between protection goals, safety assessment components, and safety functions

4.3 Processes and corresponding parameters to monitor

The safety functions of the assessment components are connected with processes taking place in a repository that have to be taken into account in the safety assessment.

4.3.1 Safety component “Integrity of geologic barrier”

The safety function attached to the host rock is the "tightness against fluids". Two processes may impair this safety function as natural geologic barrier: the execution of mining works and the local heat input by HLW in the emplacement area. For both processes, the thermo-mechanical impact on the host rock must be assessed since they may result in the generation of open, connected pore volumes. The formation of micro fissures may lead to the formation of pathways that enable the intrusion of brine solutions into the emplacement area. Mechanical and thermo-mechanical model calculations can be used to demonstrate that the host rock is sufficiently impermeable to avoid any fluid movement.

To provide statements for very long periods of time, predictive geomechanical models must be used that accurately describe the physical processes in the rock that are to be expected in the long term. The functionality and integrity of the geologic barrier is considered to be mathematically proven if the formation of pathways can be ruled out from a geomechanical point of view. For rock salt areas capable of creep, two criteria may be applied according to current scientific knowledge (Heusermann et al. 2001, Bollingerfehr et al. 2008):

1. *Dilatancy criterion*

The integrity of the barrier is ensured if the stresses remain below the rock strength so that no expansion cracks occur.

2. *Brine pressure criterion*

The integrity is ensured if the lowest main compressive stress does not drop below the value of the hydrostatic pressure to be assumed at the corresponding depth.

The generally accepted procedure which is currently used to verify the geomechanical integrity of a geologic barrier is based on the calculation and assessment of stress states as an indicator for evaluating the hydraulic properties of the salt barrier (e.g. regarding the permeability of the barrier). According to the site-specific FEP catalogue, the relevant processes influencing the safety function are:

(i) *the stress evolution in the geologic barrier* and
(ii) *the temperature evolution*

First of all, the temperature evolution is a process that gives only indirect information about the stress evolution due to the thermally induced stresses and the thermally accelerated creep behaviour of the rock salt. The latter leads to stress relaxation. As mentioned before, the procedure to verify the geomechanical integrity of a geologic barrier is based on calculations. These calculations rely on the correct representation of the temperature evolution for calculating the long-term stress evolution. The criterion for the thermal dimensioning of a repository in rock salt is 200°C. This means that this temperature limit is not to be exceeded at any point and at any time in the geologic barrier including the near field around the waste canisters. The compliance is ensured by the repository design documented in the safety case as a basis for the license application. Parameters characterising the relevant processes (i) and (ii) are:

- the **rock temperature** in the vicinity of canisters and the underground openings and
- the **anisotropic rock stresses** in the vicinity of the underground openings

For the general placement strategy, it is assumed that it is advantageous to implement monitoring systems in one representative emplacement field and not scattered over the entire repository. In (IAEA, 2001), the use of a pilot facility is considered to be a possibility to monitor relevant parameters in a representative environment and – at the same time – to gain insight into the behaviour of the waste emplaced without compromising the operation of the actual repository. Following this line of reasoning, the monitoring activities in this case study are envisaged only for one part of the generic disposal facility, i.e. field “East 1” (Figure 4-4). East 1 is selected because it will be the first to be filled with waste containers. While emplacement continues in the other emplacement fields, it would be possible to gather data from this representative, sealed “monitoring field”. Thus, the evolution of an entire field could be monitored “post-closure” during the operating phase of the repository. As a result, this information could be used as a basis for forgoing monitoring in the remaining fields, i.e. it provides sufficient confidence in the repeatability of performance making it unnecessary to monitor all fields.

Figure 4-4 (right) shows an enlargement of field East 1. This field is designed for high-level waste (HLW) as well as low-level waste (LLW) and intermediate-level waste (ILW). The black dots indicate emplacement boreholes. The emplacement boreholes indicated with a circle are selected in this study as potential locations for monitoring. These boreholes are either located in the centre of the field so that they are exposed to the highest possible heat development or on the edge of the field so that they are exposed to the highest inhomogeneities of the thermo-mechanical development of the monitoring field.

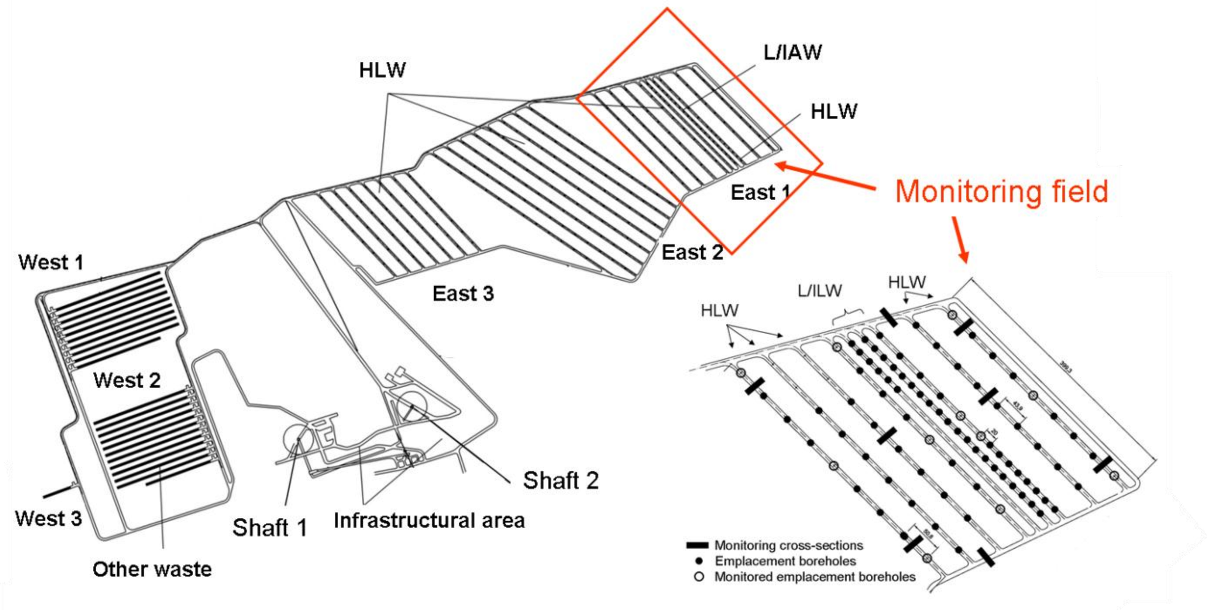


Figure 4-4: Draft of the emplacement fields for the vertical borehole disposal option. Status: January 2011. This draft was prepared within the scope of the Preliminary Safety Analysis Gorleben (VSG) and will be further refined as the VSG continues (Bollingerfehr et al., 2011, modified).

Transmission of the measured data will only be allowed by means of wireless transmission as the routing of cables along the backfill material possibly create pathways, especially as long as the backfill material is not completely compacted. The exact locations of the measurement points should be determined by means of thermo-mechanical design calculations that allow the identification of areas with most significant changes which can be seen as reference locations.

4.3.2 Safety component “Sufficient compaction of backfill material”

The primary function of the crushed salt backfill is to reduce the void volume in the drifts of the repository structure. Furthermore, it is to mechanically stabilise the geologic barrier (support of the rock mass) and to thus contribute to maintaining its integrity. In the emplacement drifts and boreholes, the backfill material also serves to dissipate the heat from the disposal containers into the surrounding rock. All these functions depend on the degree of compaction and on the compaction-dependent porosity of the backfill material; the latter also determines the decrease in fluid permeability.

As the reference periods may be as long as 1 million years, compliance with the safety functions is mainly demonstrated by means of model calculations. Models that are robust and cover the significant effects are a prerequisite for a high degree of accuracy in the predictions. Based on recent laboratory investigations, calculations of the compaction of crushed salt showed that after a period of 1000 years the compacted crushed salt has similar hydraulic properties as the undisturbed rock salt.

The process (FEP) determining compaction in connection with the safety functions mentioned before (Figure 4-3) is

(i) *the drift convergence*.

This process thus determines the development of the porosity, permeability, and thermal conductivity of the backfill material. Porosity and permeability will decrease during compaction, and the thermal conductivity will increase due to smaller void volumes. Additional factors influencing compaction are (i) the humidity development in the backfill changing its capability to be compacted and (ii) the temperature development in the backfill material and surrounding rock salt. Higher temperature of the backfill allows faster compaction. Higher temperature in the rock increases the creep velocity of the rock salt and thus the convergence.

Parameters characterising the compaction process are:

- the **porosity** (absolute and effective) of the backfill
- the **permeability** of the backfill (linked to the effective porosity)
- the **thermal conductivity** of the backfill
- the **temperature** of the backfill and surrounding rock salt
- the **total pressure** in the backfill
- the **displacements** of the rock salt in the vicinity of the cavities
- the **humidity** of the backfill
- the **pore pressure** in the backfill

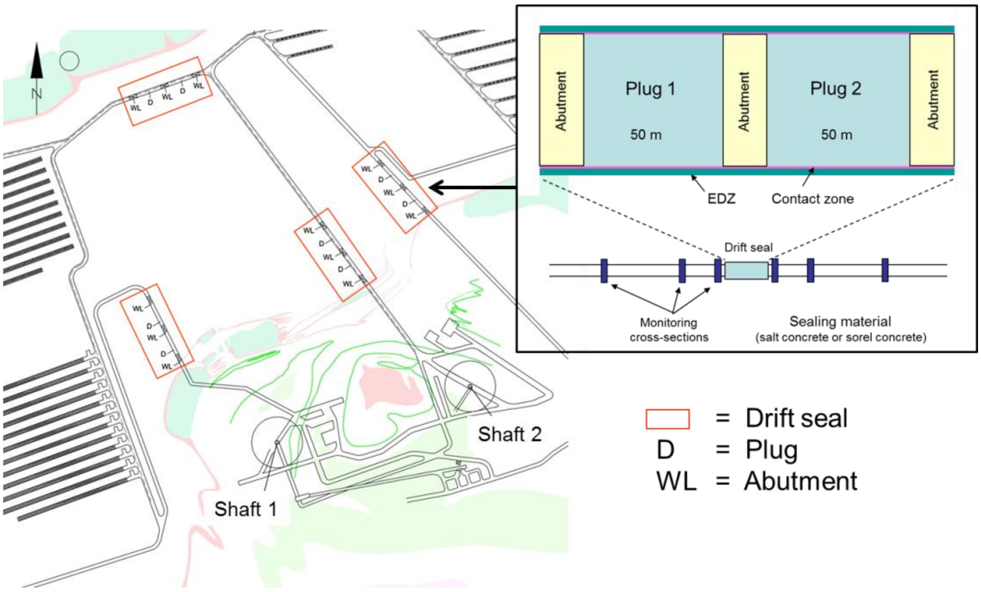


Figure 4-5: Potential position of sealing constructions (indicated in red). Their exact positioning will have to be determined in accordance with the closure concept currently being developed.

The first two parameters are important for evaluating the increasing tightness of the backfill. However, they cannot be measured continuously in-situ. The thermal conductivity is hard to measure/monitor in-situ, especially within a moving granular material. In addition, the measurements must be very precise to evaluate the porosity via an empirical relationship between porosity and thermal conductivity. Thus, only the last five parameters remain suitable and are possible to be monitored. The most effective measurements characterizing the compaction process are the pressure measurements.

In order to be able to detect brine flow through the backfill material, the last two parameters should be measured at different locations on both sides of the construction. This would allow the evaluation of the backfill compaction as well as of the barrier tightness at the same time. A change in moisture and/or in pore pressure would indicate fluid migration. The measurement points for the mechanical parameters stress and deformation could each be restricted to only one side of the sealing construction. A suitable distribution of the sealing constructions across the emplacement field (Figure 4-5) could yield representative information on the compaction behaviour of the crushed salt across the whole field. Furthermore, transmission of the measuring data will only be allowed by means of wireless transmission as the routing of cable along the backfill material or even through the sealing construction possibly create an undesired pathway for fluids. With regard to timing, the sensors should be installed at the same time as the sealing construction is built, and monitoring should last until it is decided they are not necessary any more. The decision should be a joined decision of implementer, regulator, and stakeholders involved.

4.3.3 Safety component "Integrity of geotechnical barrier"

The geotechnical barrier comprises the individual barriers containers, borehole seal, drift seal, and shaft seal.

Containers

The main function of the disposal containers is to fix and secure the radioactive waste they contain and to ensure the safe confinement of the radioactive substances during the transport on the surface and underground. According to the safety assessment concept, the barrier properties of the containers are of a temporary nature, however, it requires that the containers maintain their barrier properties and confine the radioactive substances until the geotechnical barriers (i.e. the backfill material, borehole, shaft, and drift seals) have become sufficiently effective. In each emplacement borehole, the containers will be stacked within a metal liner for retrievability reasons.

During the post-closure phase, relevant processes are:

(i) *static mechanical impacts on the metal liner due to the rock pressure and the thermally induced stress from the waste packages,*
(ii) *quasi-stationary thermal impacts due to the heat input of the waste packages and due to the temperature of the surrounding host rock, which is heated by the adjacent waste packages, and*
(iii) *corrosive impact on liner and container due to radiolysis, oxygen, and – in the case of disturbed repository development – due to fluids.*

Parameters to characterise these processes are:

- the **temperature** in the vicinity of the canisters
- the **radial stress** along the outer shell of the liner
- the **humidity** in the vicinity of the liner
- the flow of electric **corrosion current** along the outer shell of the liner

As mentioned in chapter 4.1, the criterion for the thermal dimensioning of a repository in rock salt is 200°C. This means that this temperature limit is not to be exceeded at any point and at any time in the geologic barrier including the near field around the waste canisters. Compliance is ensured by the repository design documented in the safety case as a basis for the license application. The existence of a corrosion current along the liner seems irrelevant when compared with the mechanical load (radial stress on liner), especially when taking into account that mechanical impacts occur much earlier and can be monitored and assessed during the early post-closure (monitoring) phase.

For monitoring the parameters mentioned above, the placement of monitoring equipment (including power supply, data acquisition systems, and sensors) in a dummy canister at the top of an emplacement borehole directly below the borehole seal (Figure 4-6) is proposed. Equipped with sensors on the outside to measure temperature, moisture, pore pressure, and total pressure, this canister would monitor the conditions at the top of the liner which is filled with containers.

As the gap between the measuring canister and the borehole wall is only a few centimetres, any fluid flow into and out of the borehole would be detected, especially if several sensors were placed on the circumference of the canister. Thus, the risk that radionuclides escape from the container/liner system can be evaluated. Note that the borehole entrance is assumed to be the only pathway. If fissures are encountered during borehole drilling, the bore-borehole will be dismissed. The monitoring data will be transmitted via wireless transmission system to the borehole cellar at the top of the borehole. The borehole cellar is used to store the power supply, data recording, and transmitting devices. In the current disposal concept, there are no special requirements on the backfilling of the borehole cellar, so this may be a suitable site for placing monitoring equipment. It will be necessary, however, to demonstrate that degradation of the monitoring equipment in the long-term will not affect long-term safety.

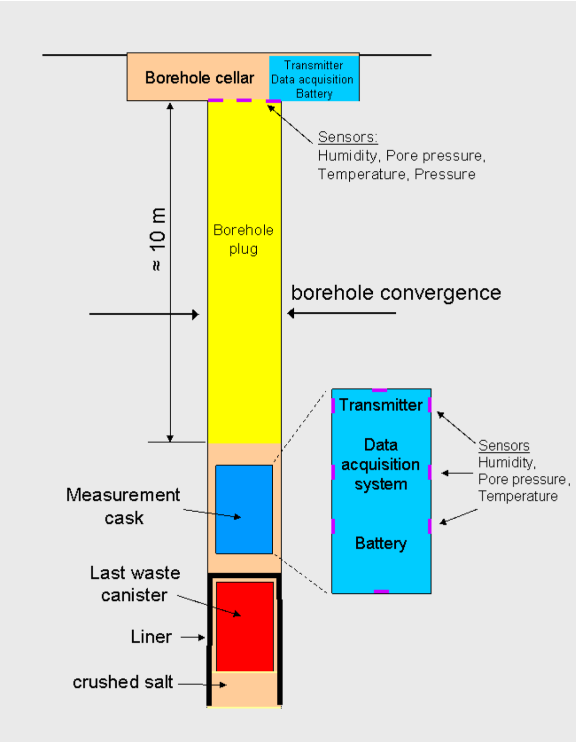


Figure 4-6: Location of a measuring canister in the case of borehole emplacement.

Borehole plug

While the drift and shaft seals are merely to seal the repository against intrusion of brines, the borehole seal has a further function within the safety concept. Initially, i.e. during the operational phase of the repository, the borehole seal must provide protection (i.e. act as a shield) against ionising radiation from the waste packages most recently emplaced. In the long term, the borehole seal, which according to the reference concept consists of a loose backfill of crushed salt, is to assume a sealing function and, together with the other engineered barriers and the rock salt, is to guarantee the safe confinement of the disposal containers. This function was selected because it is considered that the seal is to be permeable to gas during the early post-emplacement phase and impermeable to brines during the later post-closure phase. In order to demonstrate the required performance of the borehole seal in the safety concept, it has to be proven that adequate compaction of the crushed salt will occur. The borehole seal could also be made of salt blocks with an annular surrounding space filled with crushed salt. When using this design, adequate compaction of the crushed salt could be achieved earlier than with a seal completely made of crushed salt.

Processes that could influence the safety function of the borehole seal are
(i) *the convergence of the emplacement borehole,*
(ii) *potential gas pressure from inside the borehole, or*
(iii) *fluid pressure from above.*
(iv) *the temperature development due to the heat release by the canisters.*

Parameters to monitor these processes are:

- the **borehole convergence** at both ends of the plug
- the **humidity** at both ends of the plug
- the **pore pressure** at both ends of the plug
- the **total pressure** at both ends of the plug
- the **temperature** at both ends of the plug

As equipping the interior of a seal with sensors is not feasible due to safety reasons, monitoring in this case could take place on both sides of the seal as well. Convergence measurements in a filled borehole are not possible. For measuring the other parameters, the same system as shown in Figure 4-6 can be used. If equipped with sensors suitable for measuring the parameters mentioned above, the conditions at the bottom of the borehole seal could be monitored. As mentioned above, the gap between canister and borehole wall is only a few centimetres. It is highly unlikely that potential fluid movement (through the seal) is not detected, especially if multiple sensors are used.

Additional sensors can be placed at the interface between borehole cellar and borehole plug. The space in the borehole cellar at the top of the emplacement borehole could be used to store the power supply unit, the data recording unit, and the transmitter. Using the borehole cellar for storing the equipment will not be a problem as there will not be any special requirements on the backfilling of the borehole cellar. Sensors suitable for monitoring the parameters mentioned above could be installed at the interface borehole cellar/borehole seal. The borehole seal, itself, will not be equipped with sensors.

Drift seal

Drift seals form an integral part of the overall closure concept of the repository, and – in case of disturbance – are to prevent or impede fluids that have penetrated the system via the shaft seals from entering into the rest of the mine workings. During disturbed repository development (huge amount of brine inflow), they are also to prevent fluids from leaving the emplacement area. The positioning of the drift seals in the underground construction depends on the layout of the drift system and the geologic situation of the site. The building materials must have long-term stability and resistance to the conditions existing in a repository. Possible concepts for drift seals are described in Kreienmeyer et al. (2008). A detailed concept for a drift seal in a final repository for heat-generating radioactive waste is currently being developed.

Processes that may influence a sealing construction in a drift and that are relevant regarding the safety assessment concept are

(i) the drift convergence,
(ii) the hydraulic load development on both ends of the seal and
(iii) the inflow of potentially corrosive fluids.

Parameters to monitor these processes are:

- the **pore pressure** in the backfill material on both ends of the seal
- the **humidity** in the backfill material on both front sides
- the **normal stress** on both front sides
- the **drift convergence** in the vicinity of the plug (both front sides)
- the **rock displacement** in the vicinity of one front side
- the **total pressure** in the backfill material
- the **pH-value** of the brine
- the **electric conductivity** of the brine

Convergence measurements in a backfilled drift are not possible. Monitoring the electric conductivity and pH-values is not feasible over longer periods of time (e.g. years). Especially pH-measurements are significantly impaired e. g. by device “drifts”. Potential measuring locations for the other parameters are shown in Figure 4-5. Elaborating a detailed measuring concept is only expedient when a complete concept for a drift seal is available. Measuring points within the drift seal are not intended in order to not endanger the sealing function of the seal. As already explained in a previous chapter, it is nevertheless possible to assess whether there is leachate flow in the backfill material and whether the barrier fulfils its sealing function based on measurements at various locations in front and behind the drift seal (Figure 4-5). The sensor systems next to both ends of the seal have to be designed in such a way that especially the contact zone between the sealing construction and the rock mass as well as the excavation damaged zone are monitored. Note that this method is only effective for barrier performance assessments if there is at least some fluid migration on one side of the barrier. But if there is no migration at all and humidity and pore pressure sensors show no reaction, there is no need for a barrier.

Shaft seal

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, 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

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

The parameters characterising these processes 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 **radial pressure** 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

As mentioned in the previous chapter, monitoring the electric conductivity and pH-values is not feasible over longer periods of time. Convergence measurements are not possible in filled/sealed cavities. Monitoring rock radial displacements would require that a couple of boreholes are drilled into the adjacent rock mass, which should be avoided so as not to weaken the geologic barrier next to the shaft seal. Similar but indirect information about the rock movement can be obtained by monitoring the radial pressure. 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. This means that the most important thing to monitor is the hydraulic load evolution characterized by pore pressure and humidity. In the framework of the “Preliminary Safety Analysis Gorleben”, a shaft closure concept has been developed which fulfills these requirements (Müller-Hoeppe, 2012). This concept takes into account the occurrence of three main discontinuities by properly locating the sealing elements as well as the occurrence of different kinds of brine present at different depth levels at the site by using suitable materials to avoid material corrosion. Figure 4-7 shows the composition of the shaft sealing system developed to seal the shaft area at a depth below 350 m, i.e. within the salt dome. The upper sedimentary layers have not yet been considered. The system consists of three different kinds of plugs, one bentonite plug in the upper part to stop the inflow of fresh water from the groundwater system. Below this plug there is a long column of gravel as a support to keep the bentonite plug in place and as a reservoir to take up and thus store any water flowing in through the bentonite plug. The two other plugs are located in the lower part of the shaft to seal the discontinuities. They consist of salt concrete and MgO concrete to take care of the different brine solutions NaCl and $MgCl_2$ in order to avoid material corrosion. The different brine solutions have to be considered because of the different types of salt present at different depths.

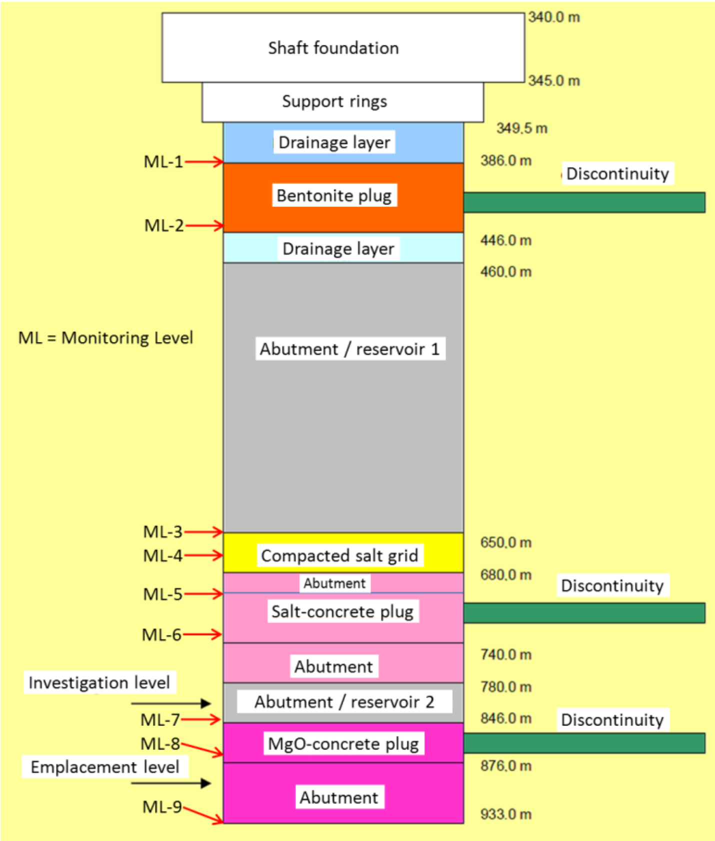


Figure 4-7: Preliminary shaft sealing concept for the German case (Müller-Hoeppe, 2012).

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. The proper functioning should be monitored by measurements on both sides of sealing elements. The preliminary monitoring concept considers this by designing so-called monitoring levels ML-1 to ML-9 between different sealing components (Figure 4-7).

4.3.4 Safety component “Negligibility of subsidence and uplift”

The impact of a final repository for HLW on the surface results from the mine excavation on the one hand and from the emplacement of heat-generating waste on the other hand. In this context it should be pointed out that mine excavation causes land subsidence while emplacement causes uplift due to thermally induced rock expansion.

The usual limit value for the permissible inclination rate of the surface is 1/300 [-] per 100 years for subsidence and 1/600 [-] per 100 years for uplift movement (Tholen et al., 2008).

The calculations carried out within the scope of the studies on the Gorleben final repository concept (Nipp, 1988) revealed that for the reference site the state of knowledge about the thermo-mechanical model parameters is adequate to model the thermo-mechanical problems relevant to the site and to demonstrate compliance with the protection goal. According to current assessments, the uplift of the surface is up to 4 m in the 2500 years following repository closure. The subsequent subsidence (of up to 4 m) due to cooling will take approximately 10000 years. According to current information, the natural uplift of the salt dome is approximately 2 mm in 100 years. This natural uplift is counteracted by "subrosion" which – according to Köthe et al. (2007) – is between 1 and 5 mm per 100 years. Thus, it can be assumed that the thermally induced uplift will be significant and verifiable. An analysis of the inclination rates at the surface has not yet been carried out but is principally possible. A rough estimate based on the existing calculation results leads to the conclusion that the permissible inclination rate of 1/600 per 100 years (limit value for uplifts) is complied with during the reference period to be considered.

As (i) uplift and (ii) subsidence are the relevant processes (FEPs), the corresponding parameters for monitoring are

- level changes in the Earth's surface.

Based on the extent of the underground mine workings and the intended depth of the emplacement level, changes at the surface can be assumed to be regional rather than local. Therefore, measurements regarding level changes should be distributed over a wider region. According to current estimates, the thermally induced uplift of the surface will reach its maximum after approximately 2500 years. A measurement campaign should approximately be designed for at least 100 years in order to be able to detect first repository-induced uplift effects at the Gorleben reference site. If the post-closure monitoring period is shorter than this, monitoring the thermally induced uplift and subsidence is not relevant.

4.3.5 Safety component “Criticality”

Compliance with the container design guarantees compliance with the protection goal "criticality safety". For this protection goal, there are consequently no parameters foreseen to be monitored.

4.3.6 Groundwater protection

In addition to compliance with the radiological protection goals, compliance with the conventional protection goals "surface protection" and "groundwater protection" has to be demonstrated for the German case.
Remark: “Although the focus of the MoDeRn project is on monitoring disposal activities, monitoring for groundwater protection is described here, since – in the German safety assessment – it has to be addressed”.
The heat input causes thermal expansion, predominantly of the rock salt, in the near and more distant vicinity of the disposal fields. As already explained in the chapter above, this causes an uplift of the salt level and of the surface of up to 4 m. Depending on the symmetry of the uplift, this can cause a change in the position of the groundwater table and a change in the hydraulic pressure or its distribution which in turn can cause a change in the flow paths.

Figure 4-8 shows a contour map of the near surface groundwater level of 1998 in the area of the Gorleben salt dome (Klinge et al. 2002). In order to be able to detect changes, the parameters would have to be monitored continuously in representative boreholes distributed over the area being investigated. A prerequisite is that monitoring has started several years prior to emplacement so that it is possible to distinguish natural changes, e.g. caused by annual cycles, from potential repository-induced changes. These preparatory measurements have been carried out in the Gorleben area. A change in hydraulic pressure levels can cause a change in the groundwater flow system and in the flow paths. This can also have local impacts on the depth of the freshwater/saltwater boundary which has a distinctive relief in this region (Figure 4-9) (Klinge et al. 2007).

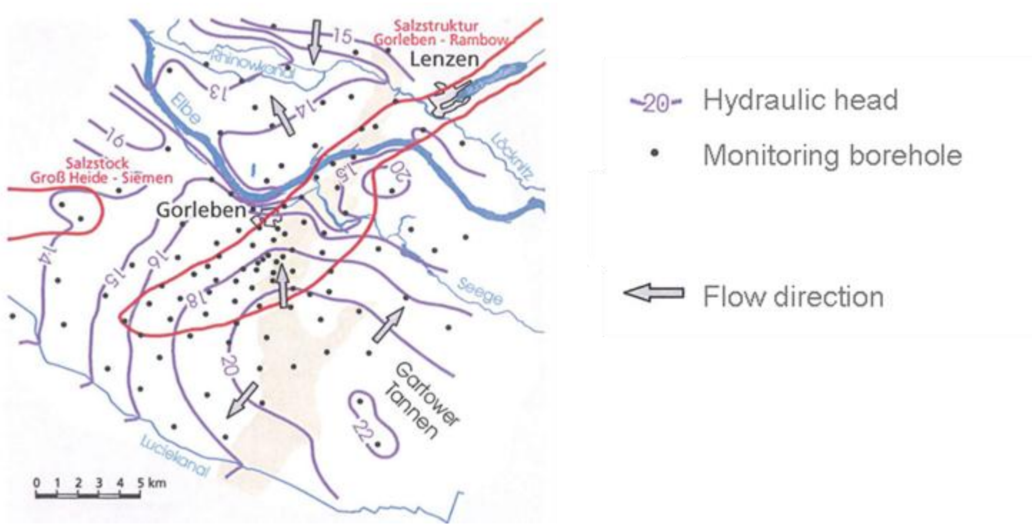


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Figure 4-8: Map of the groundwater contours of 1998 of the groundwater close to the surface in the area of the Gorleben salt dome (Klinge et al. 2002).

According to Klinge et al. (2007) it was established that there is a local, permanent groundwater flow from the Gorleben channel into the north-western rim syncline (Figure 4-10). The increased temperature of this groundwater caused by the increased heat flow through the salt body causes a natural, positive thermal deviation in the north-western rim syncline of 3°C. An increased heat input into the groundwater of the Gorleben channel caused by the heat-generating waste in the salt dome will probably influence this local groundwater flow in particular and increase its temperature, thus increasing this positive deviation. A continuous monitoring of the temperature especially within this flow path would allow an assessment of the thermal impact.

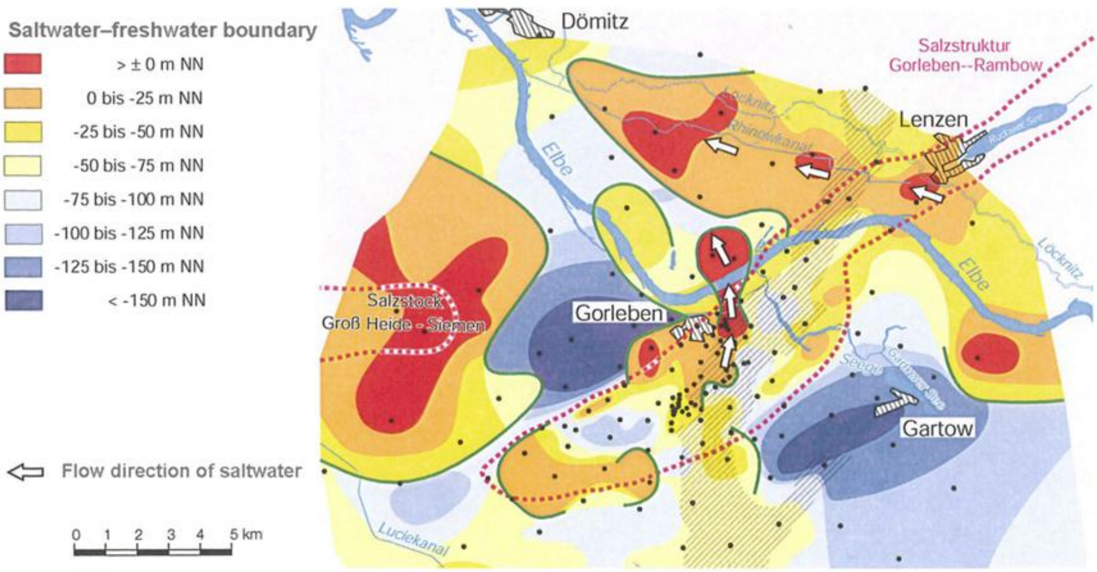


Figure 4-9: Depth of the saltwater-freshwater boundary in the area of the Gorleben salt dome (Klinge et al. 2007)

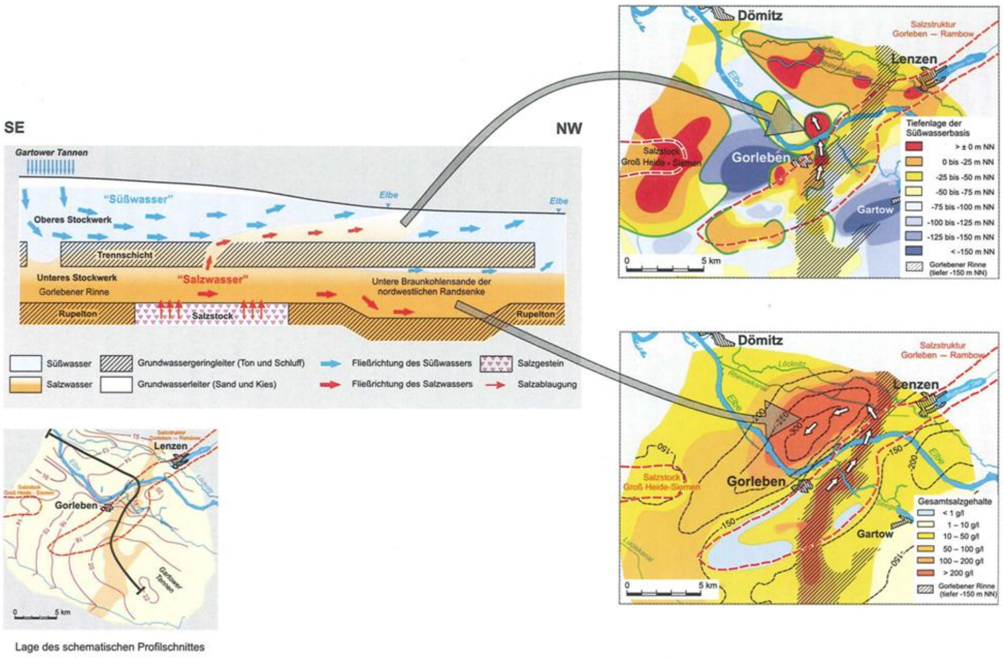


Figure 4-10: Transport of saline water from the Gorleben Channel (Klinge et al. 2007)

It has to be taken into account, however, that the temperature at the top of the salt dome does not start to increase for several 100 years. After several thousand years, the maximum of the heat front reaches the top of the salt dome and locally increases the temperature by a maximum of 15°C. This means that there is no temperature increase at that location in the early post-closure phase (e.g. 100 years after closure). Monitoring groundwater temperature development will thus not provide information about the temperature impact of the released heat on the groundwater.

Regionally extended radiological monitoring may be required. Demonstration of safe confinement means that release of radionuclides into the groundwater does not take place and can thus not be measured, especially during the early post-closure phase to be taken into account. The safety assessment concept, thus, does not require monitoring but maybe public demand does. The processes therefore are

(i) uplift and subsidence,
(ii) heat release and
(iii) confirmation of non-radionuclide release

Parameters characterizing these processes are:

- the **temperature** of the groundwater,
- the **groundwater level** (or pressure level),
- the **depth of the freshwater/saltwater boundary** and
- the **activity concentration** in the groundwater

4.3.7 Processes and parameters identified

In the previous chapters, parameters that may have to be monitored were described from different points of view, taking into account processes and impacts described in the safety assessment concept recently developed. The identified processes have been compiled in Table 4-1 and linked to the corresponding disposal element and its safety function.

Table 4-1: List oft processes and parameters identified for case I (rock salt, German concept)

Disposal component	Safety function of the component	Relevant processes	Preliminary Parameters	Location of measurement
Container	Confinement/immobilisation of radionuclides Sealing against fluids	Pressure evolution at container Temperature evolution near container Corrosion on container surface	Radial stress at container Temperature near container Corrosion current on canister shell	At shell of measurement canister At shell of measurement canister At shell of measurement canister
Buffer / back-fill	Dissipate heat into the rock Prevent advective water flow	Borehole convergence	Backfill temperature Backfill humidity	Next to measurement canister Next to measurement canister
Backfill (in drifts)	Prevent advective water flow (on the long-term) Stabilise geological barrier	Drift convergence	Rock displacement Cavity convergence Total pressure in the backfill Temperature in the backfill Humidity in the backfill Pore pressure in the backfill	On both sides of the drift plugs at three different locations on each side (all parameters)
Borehole seal	Sealing against brine inflow Reduction of gas pressure (on the short term)	Borehole convergence Gas pressure build up from inside Fluid pressure build up from outside Temperature development	Rock displacement Borehole convergence Pore pressure at seal boundaries Total pressure at seal boundaries Temperature at seal boundaries Humidity at seal boundaries	On top and bottom of borehole plug (all parameters)
Drift seal	Sealing against brine inflow	Drift convergence Fluid pressure build up on one or both sides Infiltration of corrosive fluids	Rock displacement Drift convergence Total pressure Pore pressure, Humidity pH-value of brine electric conductivity of brine	On both faces of the drift plug includ-ing EDZ (all parameters)
Shaft seal	Sealing against brine inflow	Rock convergence Fluid pressure build up on one or both sides Infiltration of corrosive fluids Subsidence of the entire sealing system	Shaft convergence Hydraulic pressure at seal top Pore pressure at seal bottom pH-value of water/brine electric conductivity of water/brine Subsidence of plug/components	On top of the whole plug (all parame-ters)
Geological barrier	Sufficient tightness against fluids	Rock stress evolution within host rock Temperature evolution within host rock	Rock stresses Rock temperature	In the vicinity of openings In the vicinity of canisters and under-ground openings
Overburden	No safety function	Uplift and subsidence of the earth's surface Change of groundwater level Change of groundwater temperature	Surface level Groundwater level Groundwater temperature Saltwater/freshwater boundary Activity concentration	Earth's surface at the site All relevant aquifers at the site

4.4 Monitoring system design

For the respective repository components processes have been identified that are representative of the (degradation of the) intended safety functions, and subsequently parameters that characterize these processes have been attributed. These features are described in the following section for the respective repository components. In addition, the types and locations of the monitoring equipment for the determination of the process parameters are specified.

4.4.1 The geologic barrier – the host rock

The safety function attached to the host rock is the "tightness against fluids". The relevant processes influencing the safety function of the host rock are the stress evolution in the geologic barrier and the temperature evolution. It has been identified that this safety function may be impaired by the excavation of mine openings and by the local heat input by HLW in the emplacement area. Both processes may affect the thermo-mechanical evolution of the host rock and may result in the generation of open, connected pore volumes, which could enable the intrusion of brine solutions into the emplacement area. Parameters characterising these processes are:

- the rock temperature in the vicinity of canisters and the underground openings and
- the anisotropic rock stresses in the vicinity of the underground openings

Table 4-2 provides an overview of sensors and parameters of concern in a module of the adopted design, monitoring cross-section A, for the geologic barrier. These monitoring modules are located in the monitoring field “East-1” (Figure 4-4 right). The location of the sensors within the module is indicated in Figure 4-11.

Table 4-2: Overview of sensors and parameters: Monitoring cross-section A (geologic barrier)

Parameter	Typical sensor/ system	Resolution	Accuracy
Temperature	FO distributed sensing, Raman backscattering	In space 1 m In temperature ± 0.1 K	Temperature ± 1.0 K
Rock stresses	Strain gauge system	± 0.01 %	± 0.1 %

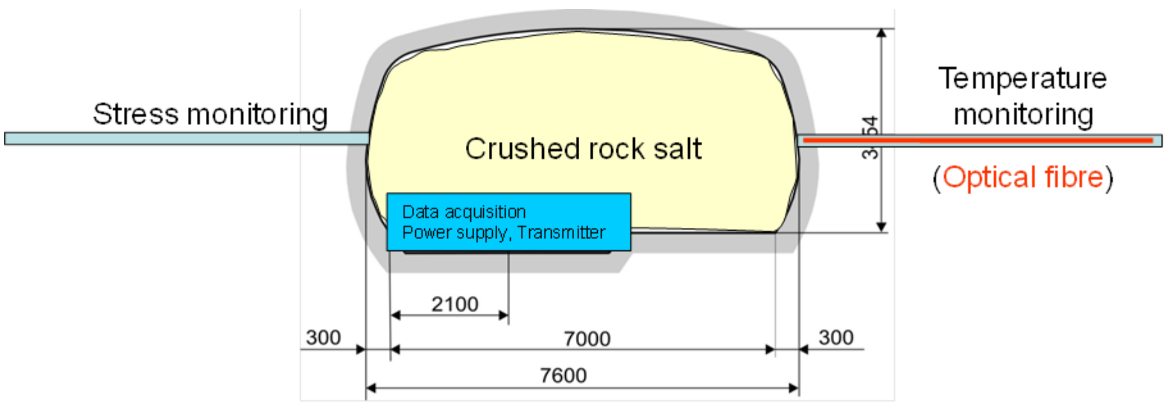


Figure 4-11: Overview of sensors and parameters, monitoring cross-section A (geologic barrier)

4.4.2 The backfill

An overview of the locations of the equipment for determining the status of the backfill material is indicated in Figure 4-5. The sensors are located in the vicinity of the drift seals. The sensors and parameters relevant to the drift seal are indicated in Table 4-3 and shown in Figure 4-12.

Table 4-3: Overview of sensors and parameters at the drift seal, monitoring cross section B

Parameter	Typical sensor	Resolution	Accuracy
Displacements	rod extensometer	± 0.05 mm	± 0.1 mm
Water content	microwave sensors	?	± 0.3 %
Total pressure	strain gauge system	± 0.01 %	± 0.1 %

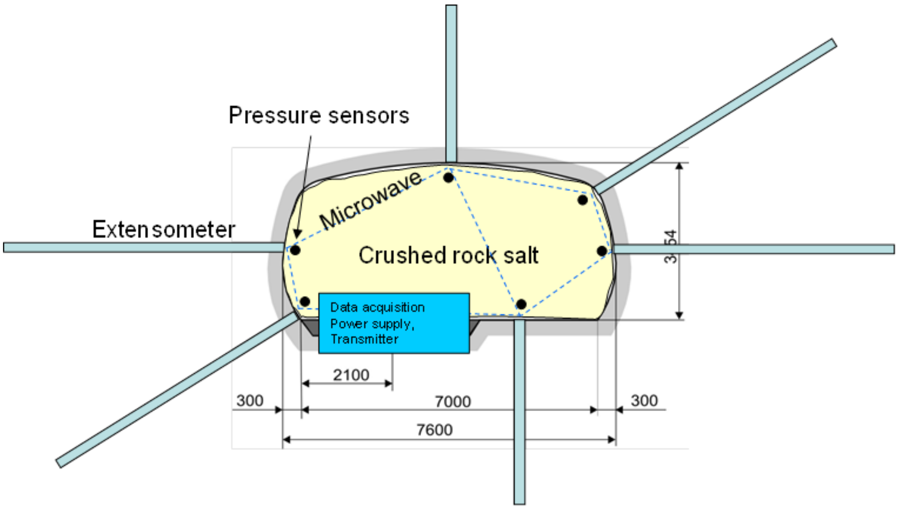


Figure 4-12: Location of the sensors at the drift seal, cross section B

4.4.3 The shaft seal

The most relevant parameters to be monitored are the pore pressure and the total pressure since both of them indicate fluid movement. Thus, each monitoring level is equipped with total pressure and porewater pressure sensors as well as a transmission unit consisting of a wireless transmitter and a long-life battery. Figure 4-13 shows a sketch of these monitoring modules. It has to be noted that the monitoring concept assumes a proper wireless data transmission over the given distances between the monitoring levels and to the earth's surface in the end. And looking at the current developments in the area of wireless data transmission, this seems reasonable.

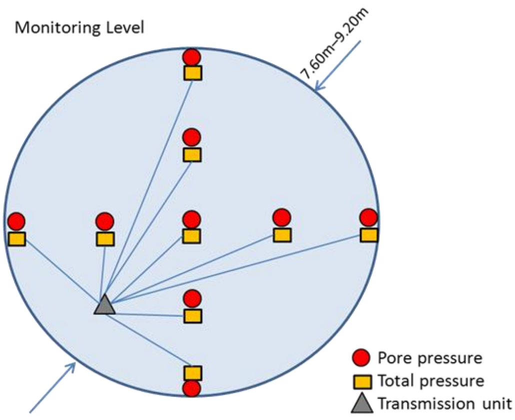


Figure 4-13: Principle design of a monitoring level

4.4.4 Drift seal

The location of the measuring devices has already been indicated in Figure 4-5. As already explained in section 4.3.2, it is possible to assess whether there is leachate flow in the backfill material and whether the barrier fulfils its sealing function based on measurements at various locations on both sides of the drift seal. The sensor systems near the front sides of the drift seals have to be designed in such a way that especially the contact zone between the sealing construction and the rock mass as well as the excavation damaged zone are monitored.

4.4.5 Borehole seal

An overview of the sensors and parameters relevant to the borehole and the seal is given in Table 4-4 and shown in Figure 4-6.

Table 4-4: Overview of sensors and parameters, borehole and plug

Parameter	Typical sensor	Resolution	Accuracy	Number
Temperature	Thermocouple	+/- 0.1	+/- 1.5	14
Water content	TDT Microwave	? ?	+/- 2.0 % +/- 0.3 %	2 2
Radial pressure	Resonant wire sensor	+/- 0.01 %	+/- 0.1 %	6
Pore pressure	VW sensors	+/- 0.1 %	+/- 1.0 %	5

4.4.6 Repository closure

After all boreholes in a disposal drift have been filled and sealed, the disposal drift is backfilled with crushed rock salt. Once all disposal drifts in a repository section, or module, are backfilled, both transport drifts of the disposal field are backfilled with crushed salt as well, after which the disposal field is sealed off from the rest of the repository mine by dams (Figure 4-4 and Figure 4-5).

Table 4-5: Overview of sensors and parameters

Sensors	Per borehole	Per cross-section	Boreholes	Cross-sections	Total
Temperature	28	2	11	7	322
Pressure/stress	12	5 / 6	11	7 / 24	311
Pore pressure	5		11		55
Water content	4	6	11	24	188
Extensometers		6		24	144
					1020

Table 4-5 summarizes the different types of sensors which are to monitor the different relevant parameters in the repository components.

The data measured and the signals from the monitoring devices are conducted to the so-called “relay stations”, indicated in green in Figure 4-14, and collected in the data collection centre, indicated in red. From time to time the data are transmitted to a receiver in a borehole and guided to the surface. It must be noted that the system design for data transmission is postponed until the first results from MoDeRn field experiments are available. Further information about wireless data transmission and long-term power supply to be applied in a salt host rock environment can be found in Jobmann et al. (2012), Jobmann et al., (2011), MoDeRn (2013b), MoDeRn (2013c).

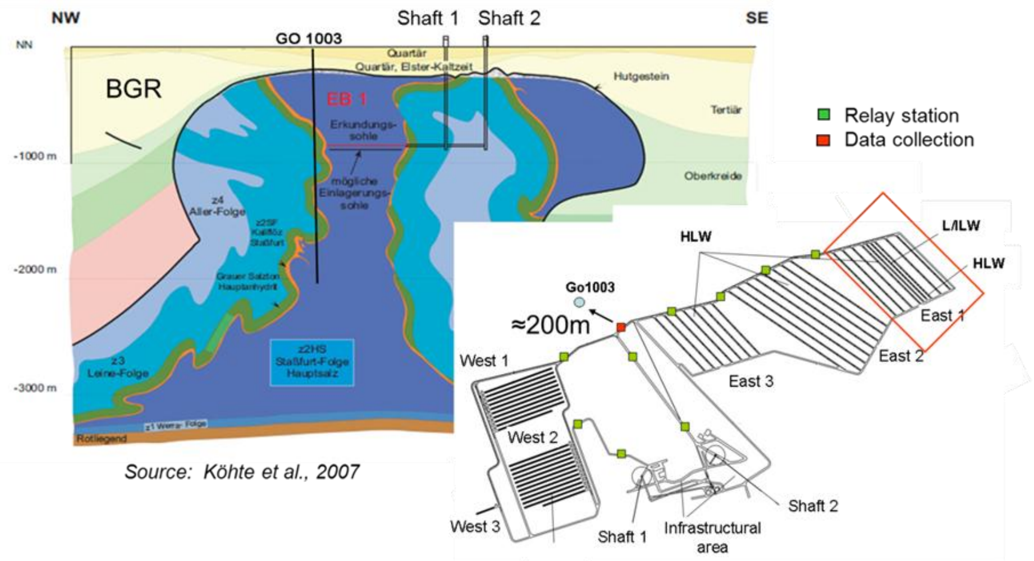


Figure 4-14: Outline of the locations of relay stations and the data collection centre for wireless data transmission

4.5 Concluding remarks

The introduction of safety functions is of vital importance for the development of a monitoring programme. On the one hand, the safety functions are key elements of the safety case and on the other hand, they are the basis for selecting those physical processes from a FEP catalogue that may impair the proper performances of the safety functions and are thus worth monitoring (see chapter 8). Thus, the safety functions are the link between the safety case and the monitoring programme.

Another key element of the German concept is the use of a “monitoring field” which is considered to be a possibility to monitor relevant parameters in a representative environment and to gain insight into the behaviour of the waste emplaced, without compromising the operation of the actual repository. While emplacement continues in the other emplacement fields, it would be possible to gather data from this representative, sealed “monitoring field”. Thus, the evolution of an entire field could be monitored “post-closure” during the operating phase of the repository.

It has to be stated that the current sensor technology is able to monitor most of the relevant parameters identified. But the most challenging tasks are the long-term self-sufficient power supply for about 100 years and the ability to transmit the data to the surface without using wires so that the barriers are not impaired.

5 Case II – Argillaceous rock

For case number 2, the French disposal concept of HL & ILLL waste disposal is selected as the reference for study. The repository concept is designed in such a way that after closure, it will provide adequate assurance that man and the environment will be protected from harmful effects of the radioactive waste (long-term safety), while the disposal process is managed to conform to a reversible approach as developed in the French context.

Remark: The protection of public health and of the environment DO NOT rely on surveillance or institutional control after repository closure, as these cannot be maintained with certainty for longer than a limited time frame. Post-closure safety is ensured passively, without any need for intervention. However, the French Safety Guide also states that a monitoring programme is to be implemented during construction and until closure of the installations. Some of the monitoring approaches could also be pursued after closure of the installations. The need to implement monitoring must be taken into account already at the design stage. The means used for monitoring shall not reduce the repositories' level of safety.

In the French program, monitoring is to verify expected evolutions and to further add to the knowledge available from prior studies and simulation results, in order to provide information to progressive decision making on the disposal process (ANDRA, 2010a). More specifically, the motivations are:

- Confirmation of phenomenological models and parameters used as a basis for the long-term safety assessment
- Further improvement of these models, for instance by aiming at a greater precision in the understanding of margins due to conservative assumptions
- To assist the stepwise disposal process management by anticipating decision making if certain evolutions approach predicted uncertainty limits and by supporting information allowing to progress with reversible management
- To contribute to operational safety and to regulatory requirements

These are consistent with the MoDeRn monitoring objectives:

- To confirm the basis for the predicted behaviour of the repository system
- To support operational safety
- To support environmental impact assessment
- To support nuclear safeguards

It was further concluded that the latter three are considered to be important but will not be further addressed within the MoDeRn project. The first main objective was analysed within MoDeRn with regard to both sub-objectives (MoDeRn, 2013a):

- Support the basis of the long-term safety case
- Support pre-closure management of the repository (reversible management)

Specific discussions on monitoring objectives, processes, and parameters as presented below are structured according to the requirements related to long-term safety performance and requirements related to pre-closure performance for reversible management, where appropriate.

Note that initial monitoring developments carry several risks:

- Providing a list of detailed monitoring activities that is not comprehensive enough to adequately address the overall monitoring objectives

- Providing an over-extensive list including detailed monitoring activities with limited added value to address the overall monitoring objectives
- Promising extensive verification and confirmation where the combination of repository environment, available technology, and/or the time scales of certain processes effectively limit this

The developments described attempt to address all three risks. First, a systematic link between requirements, site and design features and properties, and – where available – of associated performance indicators, provides a comprehensive basis of candidates for monitoring. Second, a careful analysis of these identifies the main features or processes that should be considered for monitoring (what to monitor). Third, considerations of implementation strategy (how to monitor) include considerations of implementation conditions and of the extent any given implementation can respond to a specific monitoring objective.

5.1 Background to French concept and key requirements

The following sections provide an overview of functions that the repository has to realize within its environment as defined by the host rock properties at the selected repository site, in the presence of waste types, properties and quantities intended for disposal in the repository, and making use of engineered barriers designed to work within the host formation to realize the expected functions.

5.1.1 Long-term safety and safety functions

The overall safety objective is to protect man and the environment from radioactivity and toxicity contained in the disposed waste. This objective is further broken down into various sub-objectives that all combine to ensure this overall protection. The depth of the repository protects it from long-term surface erosion and climate evolutions. The long-term protection of man and the environment implies control and understanding of the physico-chemical degradation of the waste and waste forms, of confining radioactive elements and toxic chemicals as close as possible to their source, and control and understanding of potential long-term transfer paths. While a transient potential of gaseous transfer is recognized and transfer in solid form is possible in the event of human intrusion, emphasis is placed on transfer by water, either in dissolved or in colloidal form.

Therefore, one of the key functions identified and further considered here is to limit transfer of disposed radioactive substances to the biosphere by means of water. This can be further broken down to yield the following fundamental safety functions that have to be realized after repository closure (ANDRA, 2010b):

- Counter water circulation – i.e. very strong limitation of convection through repository structures, which justifies the choice of a host formation with a very low permeability:
  - 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 ILLLW disposal cells

- Limit release of radionuclide elements and immobilize them in the repository – i.e. prevent their dissolution, favour precipitation, and/or favour low mobility chemical forms:
  - Protect waste and waste forms from alteration by water
  - Limit solubility of radionuclides

    - Limit mobility of radionuclides

- Reduce concentration and delay radionuclide migration outside the disposal cells – i.e. delay to reduce impact by radioactive decay, reduce concentration by spreading both in space and time:
    - 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 performances expected from these three safety functions rely in part on the favourable properties of the host formation towards long-term safety. Additional requirements are thus specifically aimed at preserving the formation's favourable properties. While all of these may contribute to several of the system-wide safety functions, they are summarized here to provide an overview:

- Limit the extension of the initial excavation damaged zone through choice of excavation method and construction/ground support method
- Avoid or limit propagation of initial mechanical damage by backfilling and sealing all structures and minimizing residual void volumes
- Limit thermal and thermo-mechanical impacts to limit irreversible deformations
- Protect against other possible physico-chemical perturbations (hydrogen production; de-saturation/re-saturation; oxidation; alkaline perturbation, corrosion products)

Additionally, long-term safety has to provide for the repository to:

- Remain sub-critical
- Be seismically resistant

All of the above are realized by a combination of engineered barriers and by the properties of the host formation.

5.1.2 Pre-closure management and retrievability function

Pre-closure management of the disposal process is conducted according to a reversibility principle. The French 2006 Programme Act (Loi, 2006) mandates that the deep geological disposal shall be reversible for a period no less than one century. It also establishes that only a further Act can authorise a closure of the repository. Andra defines reversibility as the possibility for a progressive and adaptive management of the disposal process, preserving some freedom of decisions on this process to future generations. Inherent to a reversible management process is the provision of decision points during the disposal process, serving the purpose to regularly re-examine the disposal process based on available knowledge, to take into account stakeholder input, and to decide on the best way to further manage that process, i.e. to further improve the process in light of stakeholder expectations (e.g. regulators' periodic assessments).

This implies that prior to closure, the disposal process and design of disposal structures provide for an adequate level of flexibility available to take any action that might be required by the decisions regarding the next step in the disposal process: Pursue, delay, redirect, or reverse.

To structure the analysis of design features required to allow reversible management, the disposal process is organized around a series of decisions, concerned with clearing and specifying construction of the next repository segment, as well as clearing and specifying the next step towards emplacing and enclosing waste. The latter is further organized according to a series of steps, as presented in Figure 5-1 (NEA, 2011).

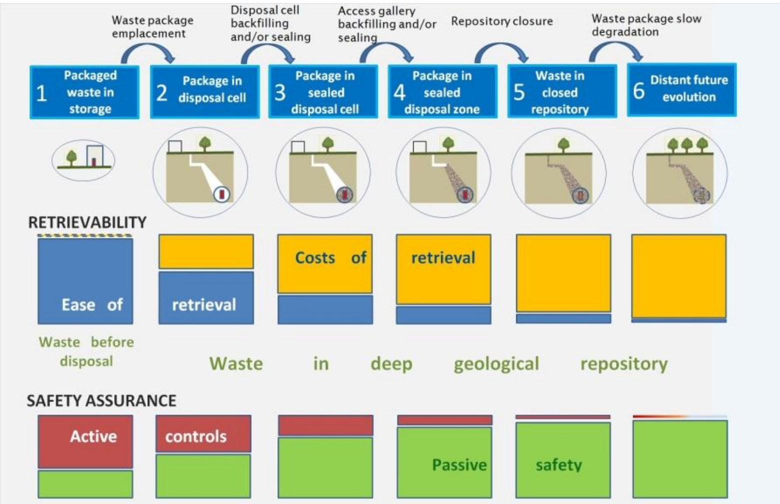


Figure 5-1: Graphic presentation of the repository scale (NEA, 2011)

During the steps in the disposal process, the scale is based on the increasing effort needed for retrieval, which is related to progressive implementation of passive management components and decreasing need of active management. Level 0 is the level of raw waste, not conditioned, which requires intensive monitoring. At level 1, waste is conditioned in a package and stored in an interim surface storage facility.

At level 2, waste is disposed in a deep underground disposal cell which remains accessible and is not sealed. Several hundreds of meters of rock provide a passive protection. At level 3, the disposal cell is sealed but its vicinity remains accessible. At level 4, the access galleries are backfilled and sealed. The disposal zone is closed, and eventually the entire disposal facility is closed. Waste remains contained within the waste disposal packages. At level 5, which takes place a long time after closure, the integrity of the disposal packages may no longer be guaranteed, but waste is still confined within the engineered facility. A significant proportion of short-lived radionuclides have disappeared. This stage is similar to a mine having a high uranium ore concentration.

Prior to making decisions on how to further progress with the disposal process, an evaluation is needed for (i) the conditions under which any decision would be implemented and (ii) the consequences this would have on future evolutions of the repository. By way of example illustrating a pre-closure management approach providing flexibility to the disposal process, the following will focus on the expected function of the waste disposal process (WDP) reversibility from level 2, i.e. prior to the installation of any seals. The general function to reverse the WDP can be analysed by considering the operations and associated conditions that would be needed. It is broken down into several more specific functionalities:

- Preserve conditions providing the option for WDP reversal
- Evaluate conditions in the event of WDP reversal
- Provide for needed dismantling and/or re-equipment prior to WDP reversal
- Retrieve the waste and transfer of the waste to other disposal structures or the surface

These functions lead to a set of design requirements for the waste package, the disposal cells, and the infrastructure. They also refer to the need to evaluate the conditions that will influence this ability and relative ease of waste retrieval, thus highlighting the close link between operational flexibility and continuous reassessment of actual repository conditions. Processes and parameters likely to influence those performances are identified and considered for possible monitoring in order to provide on-going information on retrievability to pre-closure management.

5.1.3 Host rock

The French HL and ILLL radioactive waste programme has investigated a Clay Stone layer over a transposition zone of 200 km^2, located in the East of France. More recently, a more focused zone of 30 km^2 was further investigated as the potential site for the underground structures. The centre of this very homogeneous layer is at about 500 m depth, and its thickness in the focused zone exceeds 140 m.

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

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

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

5.1.4 Waste inventory

The inventory includes all ILLLW, HLW, and the fraction of spent fuel for which reprocessing does not present sufficient interest (for instance all naval spent fuel). This corresponds to approximately 110.000 m^3 of ILLLW primary waste packages, which include:

- Waste from structure and technology origin, conditioned in *Conteneurs standards de déchets compactés* (CSD-C, Standard compacted waste canisters);
- Waste from bituminized treatment of effluents;
- Activated and technological waste conditioned in concrete containers;
- Waste from nuclear reactor dismantling;

There are also an estimated 12000 m^3 of HLW primary waste packages, an order of magnitude less in volume than the ILLLW, which includes:

- Vitrified waste with moderate heat production (less than 10% of the HLW inventory)
- Vitrified waste with high heat production (prior cool-down period necessary)
- Small volume of spent fuel resulting from research and defence activities

The minimum duration of the emplacement operations is estimated at several decades for the ILLLW and the HLW. Taking into account a prior cool-down period for HLW, the operating period will be approximately one century.

5.1.5 Waste disposal package

The waste form is conditioned into primary waste packages (Figure 5-2). The primary waste packages will be repackaged into disposal overpacks. One steel overpack each is foreseen for the vitrified waste. Regrouping of several primary packages into a concrete overpack is foreseen for the ILLLW. Waste disposal packages have a mechanical function which is related to the capacity to emplace and potentially retrieve waste and to maintain the geometrical form of the primary waste package and waste form.

The HLW disposal package contributes to the safety function “limit release” by preventing water from contacting the waste form (borosilicate glass) as long as very low dissolution rates cannot be guaranteed. Thus, the waste overpack has to be watertight until the temperature is below a limit which is set at 50°C. This period is ranging from a century to a thousand years for certain categories of vitrified waste.

Ease of retrieval relies on waste package integrity (retrieval operations of a damaged package might lead to substantial technical complications) as well as on the conditions in the disposal cell (quality of ground support, cell environmental conditions). The disposal cell is capable to resist environmental conditions, which may reach hydrostatic pressures. Surface irradiation rates should be limited.

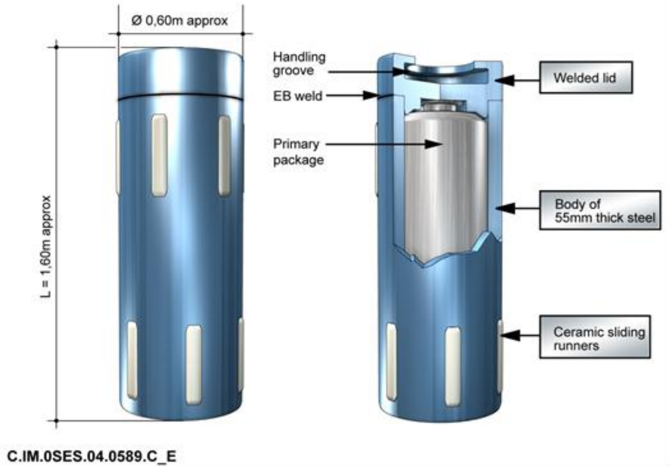


Figure 5-2: Principle of the HLLL waste overpack

5.1.6 Overall layout, key structural components and construction method

The overall repository layout is structured into disposal cells and disposal units. Disposal cells are specifically designed to receive either ILW or HLW disposal packages. Disposal units regroup a sizable fraction of the overall waste inventory. Disposal cells and units are separated from each other so that possible interactions between them are limited as interactions could be detrimental to their expected performance. Among other things, the overall layout should take into consideration:

- The adequate separation of excavated structures to prevent any induced large-scale mechanical disturbance of the host formation
- The adequate overall topology and distances separating disposal units in order to place the repository as a whole in a favourable long-term flow and transport configuration
- The adequate orientation of tunnel sections destined for future sealing, as long as its influence on seal constructability, excavation damage and associated overall seal performance requires such favourable orientation
- The separation between cells and units and ensuing local heat load density to contribute to required thermal management

Prior to backfilling and closure, the basic structural elements used within the repository are either large diameter, concrete lined and ventilated structures or small diameter, horizontal, steel lined, non-ventilated structures. The latter are only used for the vitrified waste cells. The large diameter structure group includes ramps, shafts, connecting and access drifts as well as IL waste disposal cells. These structures have a concrete liner and are all ventilated as long as they remain open. Among these elements, only the disposal cells will contain nuclear waste, the others are the repository's infrastructure.

Construction, i.e. excavation and subsequent ground support methods, should contribute to limit initial perturbations to the host formation near field properties. It should also allow near field properties to be maintained in an acceptable range throughout operation and until closure.

5.1.7 ILW disposal cells

The ILW disposal cells are illustrated in Figure 5-3 below. The structural components respond to the requirements and allow the emplacement and potential retrieval of the waste disposal package. After closure, the concrete surrounding the primary waste packages will modify the chemistry of the groundwater that will eventually reach the radioactive waste, providing waste form dissolution rates, radionuclide solubility and sorption properties of cementitious water.

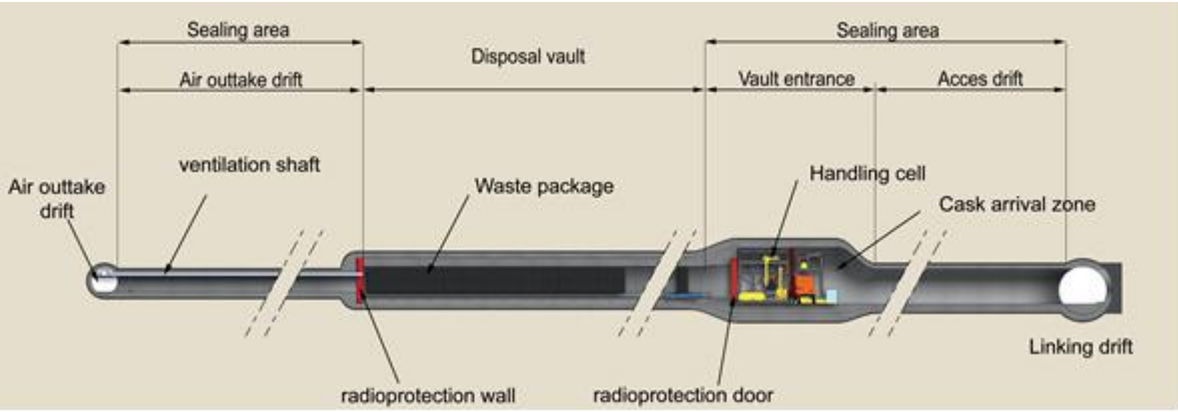


Figure 5-3: Waste cell concept

5.1.8 HLW disposal cells

The small diameter structure group includes all HL waste disposal cells. These horizontal cells will not be ventilated. A cylindrical envelope of non-alloy steel provides mechanical stability. The inner diameters of the disposal cells will be approximately 70 cm. These disposal cells are illustrated in Figure 5-4 and Figure 5-5. This structural component responds to the requirements and allows the emplacement and potential retrieval of the waste disposal package. Its long-term resistance to corrosion – at a minimum during the century scale operational phase – is ensured by its design and by placing the liner in a low-corrosion environment. The latter is achieved by preventing air exchange with the access galleries, thus providing for an anoxic environment.

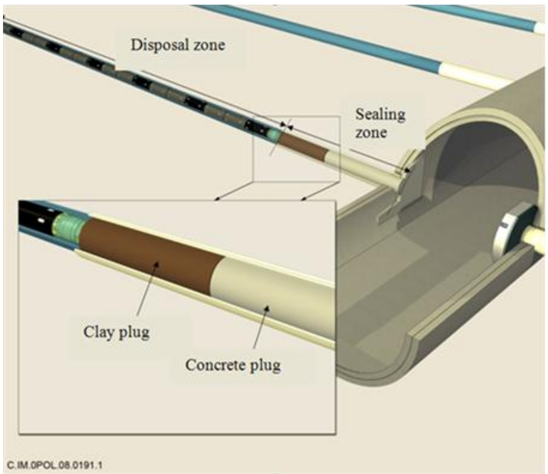


Figure 5-4: HL waste cell concept

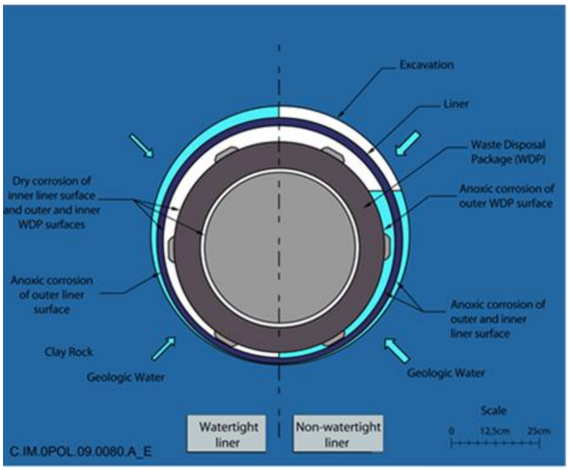


Figure 5-5: HLW cell during exploitation period

5.1.9 Backfill and seals

Various closure elements are used for repository backfilling and sealing. Most of them are made of clay material (swelling clay or clay stones), with the exception of concrete plugs which provide mechanical support for the seals. Specific closure backfills and seals are foreseen at the head of each IL and HL waste cell, and for the entire infrastructure (drifts, shafts and ramps). Figure 5-6 illustrates ILW cell seals, including supporting concrete structures.

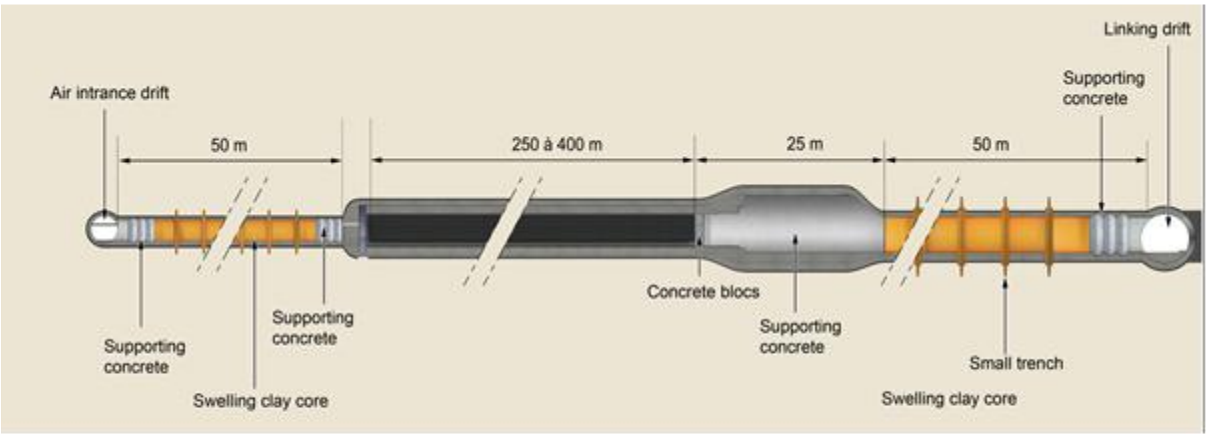


Figure 5-6: Seals emplaced upon closure of an ILW disposal cell

Access tunnel backfill has a mechanical function, i.e. to minimize long-term host rock deformation (and potential associated degradation of transport properties) by minimizing residual void volume. To achieve this, adequate compaction of the backfill is required.

5.2 Barrier system and long-term safety functions

The purpose of this section is to link the basis for safety to host rock and/or engineered system features and processes, identifying - where possible - specific indicators for performance to appreciate such basis for safety. The contributions of the host rock and of the engineered system are related to the repository functions they have to perform.

Host rock and engineered barrier system combine to provide post-closure protection associated to the previously introduced key functions of the repository. While the host rock was selected for the combination of its favourable properties, the engineered barrier system is designed to contribute to the expected overall disposal system functionalities and performances while making use of and preserving the favourable properties of the host rock. The siting of repository structures, the preservation of favourable site properties, the design of manmade components (waste packages, seals, and other engineered components), and the quality of their manufacture are the basis of safety. In addition to the natural environment, three categories of components are highlighted for their specific contribution to safety:

- Seals
- Waste packages - radioactive waste conditioned by the producer into a waste form, a first container, and reconditioned in an overpack prior to disposal
- Other engineered components contributing to the protection of the waste package, ensuring closure of repository cavities and boreholes, and providing backfill of infrastructure and surface-depth infrastructure
- Host rock with its favourable properties for long-term safety

The safety functions are realized by one or a combination of several repository components, as well as by one or a combination of the several repository-scale considerations listed above. In the following sections, an overview for the main safety functions is provided, with a brief discussion on the corresponding basis allowing the evaluating of long-term safety.

5.2.1 Repository components contributing to the first safety function (SF1 – Counter water circulation)

This function aims at limiting the transfer vector “water” that is eventually responsible for the dissolution and transfer of radionuclides. Based on the very low permeability of the Callovo-Oxfordian layer, the overall layout and component design can be developed to limit water circulation through disposal cells and through the repository infrastructure. The link between the safety function and the components and/or overall repository or site features providing the basis for the functions’ contribution to safety is summarized below.

First, during the transient post-closure resaturation conditions, the preferred option is to resaturate the disposal cells and subsurface infrastructure with water from the near-field. Second, during steady-state conditions, it is necessary to ensure that flows through the repository infrastructure are sufficiently slow so that the overall preferred long-term transfer path of radionuclides is by diffusion through the host formation. Third, it is necessary to ensure that flow rates in the disposal cells are sufficiently low so that the degradation rates of the waste disposal packages are limited effectively and local chemical equilibria can be established.

The first contribution to favourable conditions of transient resaturation is referred to as the safety function *Limit water influx from overlying rock formations*. In an ideal situation, resaturation would happen exclusively at flow rates that are controlled by the very low permeability of the Callovo-Oxfordian layer and provide water saturation at a well-known chemistry representative of the host formation. Some infiltration from overlying formations will superpose to this. Therefore, the potential water flux from overlying formations that would also contribute to this resaturation is limited by installing shaft and ramp seals.

The second contribution aims at preventing post-closure conditions that might induce radionuclide transfer through infrastructures to the overlying formations, effectively bypassing the host formation. This is achieved by a combination of several considerations of siting, overall layout, and seals, and refers to two safety functions as described below.
The aim is first to limit the potential source for water flow, i.e. the potential for water influx from the host formation. This is referred to as the safety function *Limit water flux from the host (clay) formation to closed repository*. The limited inflow potential is achieved by siting with adequate thickness of host formation surrounding the repository. This thickness is speci-

fied consistently with the site feature expected to provide the basis for the function *Delay and reduce radionuclide migration*. It is also achieved by providing an overall compact repository design, as overall potential to drain from the host formation is proportional to the overall drained volume.

A second aim is to limit any resulting flow through infrastructures to the access shafts/ramps. This is referred to as the safety function *Limit water flux between repository and overlying formations through shafts/ramps*. First, for initial repository design and construction, all surface to depth infrastructure components are regrouped into a single area. Second, disposal units regrouping a subset of all disposal cells can only be accessed from a unique point or side, thus ensuring that any water flows through those units can only origin from the host formation directly surrounding the disposal unit. Finally, control and reduction of ensuing flow is also provided by shaft and ramp seals. Water circulation is further controlled by emplacing seals in galleries, to provide for some redundancy to the shaft/ramp seals and to more evenly spread out hydraulic gradient through overall subsurface infrastructures.

The third consideration, more specifically concerned with the control of engineered barrier degradation rates in disposal cells as well as eventual waste form dissolution rates, is referred to as the safety function *Limit water flux within the disposal cells*. This is achieved by sealing each disposal cell, i.e. by providing seals at the edges of ILW disposal cells and bentonite plugs at the edge of HLW disposal cells. It should be noted that flow potential through disposal cells is very low, as long as they are controlled by water exchange with the surrounding near field, and providing seals contributes little to further limit water flow. This remains true even in the case of *alternative scenarios*.

Table 5-1 provides an overview relating the safety functions contributing to *counter water circulation* to components and/or design and site features, i.e. other overall design, construction and operation considerations, and properties of the natural environment.

Table 5-1: Key components and/or design and site features relied upon to realize the long-term safety function “Counter water circulation”

Safety function: Counter water circulation	**Key components and/or design and site features**
Limit water influx from overlying rock formations through shafts and/or ramps, during the transient post-closure resaturation phase (~100.000 years)	Seal off surface to depth infrastructure (shafts, ramps)
Limit water flux from the host (clay) formation to closed repository (during permanent, post-closure hydraulic conditions)	Siting with sufficient host formation thickness Siting with very low permeability of host formation A relatively compact overall layout
Limit water flux through the repository structures (to avoid transfer bypass of host formation during permanent, post-closure conditions)	Siting with limited vertical gradients Overall layout: positions of disposal fields relative to shafts adapted to vertical gradient Overall layout: Regroup surface-to-depth infrastructure Overall layout: Regroup subsets of disposal cells into disposal units Disposal unit layout: Provide “dead-end” link of disposal units to infrastructure (access limited to a single point/side) Seal off surface to depth infrastructure (shafts, ramps) Seals within repository galleries
Limit water flux within the disposal cells	HLW disposal cell plug (relative importance with respect to layout is still to be determined) Seals around ILW disposal cells

Assuming that overall design and site features correspond to the basis established for this safety function, any long-term potential of water flow through the closed repository should be limited through adequate sealing. Seal properties used as a basis for long-term safety evaluations are specific to the different types of seals. The associated, expected performances or indicators of these components or features are summarized below.

The greatest importance for ensuring long-term performance of this safety function is given to shaft and ramp seals. Design specifications call for a core of swelling clay allowing achieving low permeabilities in the order of 10^{-11} m/s. The dry density upon emplacement should be commensurate with a saturated swelling pressure between 1 and 7 MPa to ensure good closure with surrounding near field and to prevent excessive pressure being applied on support structures and the near field. Construction of the seal requires dismantling of shaft or ramp liner prior to seal core emplacement. This should minimize residual voids at emplacement, and contact surface between host rock and seal should be as smooth as possible. Surrounding the seal are concrete support structures to provide for long-term mechanical stability of seal emplacement. These will be constructed with low-pH concrete (pH<11) to limit chemical interactions with the swelling clay, which might affect the swelling potential. Initial excavation at future shaft/ramp seals shall not induce permeability increases in the near field greater than 2 orders of magnitude from unperturbed host rock.

Assuming adequate performances of the shaft and ramp seals, the Gallery seals contribute little to limit the overall flow. They do, however, provide redundancy, serve to even hydraulic gradients throughout the repository, and in particular provide an additional resistance to flow relatively close to the source, i.e. the disposal units. Design requirements include similar core material as for shaft/ramp seals, and a length of approximately 40 m.

The limited contribution of disposal cell seals to limit water flow is recognized. At present, it is assumed they have to fulfil the same requirements as gallery seals. Current requirements provide for a 3-m-long swelling clay plug, emplaced inside the metal cell liner. The expected performance for the plug is to provide for a permeability that is lower than 10^{-10} m/s.

Table 5-2 provides an overview relating the key components and/or design and site features to the expected performances and/or indicators providing the basis for the safety function “Counter water circulation”.

In summary, this first safety function is concerned with the transfer vector (water) and relies on:

- Favourable site features such as the very low permeability, a minimum thickness of the host formation, and a limited vertical gradient
- Overall repository layout features
- Properties of seals, their near-field and support structures

Associated monitoring considerations will be further developed in a later section with an emphasis on the seals, their support structures, and the near field. Meeting the overall layout features will be verified upon construction and this does not warrant further monitoring. Any monitoring considerations to confirm site characterization data on favourable site features, and their potential perturbation, will be further developed in a later section.

Table 5-2: Performances and/or indicators expected from the key components and/or design and site features relied upon to realize the long-term safety function “Counter water circulation”

Safety function and associated key components/features	Features and/or expected Performances and Indicators as basis for safety function
Limit water influx from overlying rock formations:	
Duration	Seals should provide this performance until at-depth infrastructures are re-saturated (~ 100.000 years)
Shaft seal	Design specifications cf. below
Ramp seal	Design specifications cf. below
Limit water flux from the host formation to closed repository:	
Thickness of host formation	Expected thickness
Very low permeability of host formation	Site permeability ~ 10^{-13} m/s
Compact layout	Limit surrounding volume of drained rock
Limit water flux through the repository structures:	
Siting – vertical gradient	Target present < 0.2 m/m, with impact long term geodynamic evolution remaining < 0.4 m/m?
Overall layout	Prevent preferential flow to shafts/ramps?
Overall layout	Regroup all surface-to-depth infrastructure into a unique zone
Overall layout	Regroup disposal cells into disposal units
Disposal unit layout	Single point or side access to disposal unit (“Dead end” infrastructure)
Shaft or ramp seal	Permeability ~ 10^{-11} m/s Dry density – cf. swelling pressure Swelling pressure between 1 and 7 MPa
Initial excavation and ground support at shaft/ramp seal	Maintain near-field permeability < 10^{-11} m/s Remove ground support upon seal emplacement and provide smooth interface between seal core and near-field; limit residual voids
Mechanical support for seal	Resist swelling pressure up to 7MPa pH<11 to limit alkaline perturbation of swelling
Gallery seal	Redundancy if performance loss of shaft/ramp seal Even out hydraulic gradients from disposal unit to shaft/ramp Minimum of two gallery seals between disposal unit and shaft/ramp One gallery seal close to source (max 400m from disposal unit) Length ~ 40m Permeability and swelling pressure of core cf. shaft/ramp
Initial excavation and ground support at gallery seal	Limit extent and impact of EDZ (qualitative)
Limit water flux within the disposal cells:	
HLW disposal cell plug	Importance with respect to disposal unit layout to be determined Length ~ 3m inside metal cell liner Permeability of core ~ 10^{-10} m/s
Seals around ILW disposal cells	Cf. gallery seal

5.2.2 Repository components contributing to the second safety function (SF2 – Limit radionuclide release)

Despite adequate performances related to the previous safety function, water will eventually contact the waste form and provide a potential for waste form dissolution and corresponding radionuclide release into water, dissolution of these radionuclides into water and subsequent transport. This safety function aims at limiting the source term of eventual radionuclide migration in the given hydraulic conditions, i.e. waste form dissolution, the released radionuclide solubility and their potential mobility. All are achieved by ensuring the physico-chemical environment in the disposal cell provides for low waste form dissolution, low radionuclide solubility and low radionuclide mobility. In the event an initial, transient period does not provide for the preferred physico-chemical environment, water is prevented from contacting the waste form until such transient has reached acceptable limits.

First, this function relies on *protection of the waste form from alteration by water* and corresponding release of the radionuclides incorporated in the waste form. This function is appreciated according to the varying waste forms, i.e. HL vitrified waste, IL bituminized waste or IL metallic waste. The vitrified (HL) waste matrix performs well, i.e. ensures a very low dissolution rate which can be included as a basis to evaluate long-term safety, given water with a near neutral pH. Corresponding dissolution rates have been established for temperatures reaching 50°C. Their performance is not necessarily significantly degraded at higher temperatures, but the corresponding basis to evaluate safety still needs to be established for higher temperatures. Therefore, dissolution is prevented during a thermal phase when the waste form has temperatures above 50°C. A corresponding, specific safety function is introduced, i.e., *Protect HL waste form from water contact during thermal period*.

The bituminous (IL) waste matrix dissolution rate models were established for a temperature range between 20°C and 30°C. Corresponding thermal management is called for to provide the corresponding basis.

Any waste form will eventually dissolve and thus present the source term for long-term safety evaluations. This function thus further contributes to safety after such dissolution by regrouping considerations contributing to *Limit solubility of* radionuclides and *Limit mobility of* radionuclides. The geochemical composition of water from an undisturbed near field provides for a reducing environment which contributes to both limiting radionuclide solubility and limiting its mobility. Such water would be expected to provide the corresponding context for solubility and mobility in the HLW disposal cell.

The concrete liner and waste overpacks in ILW disposal cells provide for waste being in contact with cementitious water, which contributes to limiting solubility and mobility. In particular, actinides and lantinides precipitate from solution. To prevent remobilization through complexation with certain salts or organic molecules, adequate separation of corresponding IL waste streams will be provided for, and adequate controls of imported materials, such as any related to concrete liner, will be required.

Table 5-3 provides an overview relating the safety functions contributing to *Limit radionuclide release and immobilize them in the repository* to components and/or design and site features, i.e. other overall design, construction and operation considerations, and properties of the natural environment.

Table 5-3: Key components and/or design and site features related to the long-term safety function "Limit radionuclide release and immobilize them in the repository"

Safety function: Limit release and immobilize in repository	Key components and/or design and site features
Protect HL waste form from water contact during thermal period	HLW thermal management Watertight HLW overpack Cell liner material
Protect waste forms from alteration by water	HLW cell: waste form release properties; water properties in contact with waste form comparable to unperturbed host formation water (pH, Eh) ILW thermal management for bitumen ILW cell: Cementitious water in contact with waste form
Limit solubility of radionuclides	Thermal management Materials in cell influencing water properties (pH, Eh), cf. above for HLW and ILW Overall layout and imported construction materials: Prevent risk of complexing agents enhancing solubility
Limit mobility of radionuclides	Materials in cell influencing water properties (pH, Eh), cf. above for HLW and ILW Overall layout and imported construction materials: Prevent risk of complexing agents enhancing mobility

The basis for evaluating performances associated with this safety function is provided as long as waste form dissolution is only expected to happen under conditions that are well understood, thus imposing certain requirements on thermal management and predictive capacity for future thermal evolution. Adequate chemical conditions are provided given preservation of the host formation pH neutral and reducing conditions upon dissolution of radionuclides from HLW, and cementitious environment upon dissolution of radionuclides from ILW.

Water contacting waste forms is prevented at elevated temperatures for several reasons. For all types of waste, temperatures are to be less than 70°C prior to any radionuclide release, to ensure an adequate basis to evaluate solubility and mobility is available. In addition, for vitrified (HL) waste, water contact is prevented as long as temperatures inside the waste form (glass matrix) are above 50°C. Adequate protection of vitrified waste forms requires the design of a watertight overpack that provides mechanical resistance and water tightness for the duration of the thermal period. The expected performances associated with this function are thus influenced by corrosion and mechanical load of the waste overpack.

The bituminous (IL) waste matrix provides for low dissolution rates as long as (i) the geometry is preserved by preventing viscous deformation and increase of the exchange surface with the bitumen (i.e. by containment in the appropriate canister) and (ii) the pH value of dissolving water is between 11 and 12.5.

The expected performances and/or indicators of key components or features contributing to the overall performance of this safety function are summarized in Table 5-4 below.

Table 5-4: Performances and/or indicators expected from the key components and/or design and site features relied upon to realize the long-term safety function “Limit radionuclide release and immobilize them in the repository”

Safety function and associated key components/features	Features and/or expected Performances and Indicators as basis for safety function
Protect HL waste form from water contact during thermal period	
HLW thermal management	Knowledge local heat transfer coefficient Knowledge heat source over time Provide duration until T < 50°C (Predictability transient period until T < 50°C)
HLW overpack	Watertight until T < 50°C Material properties (corrosion and mechanical resistance) Thickness Treatment of welding seams Treatment of any overpack interfaces (runners…) (Predict mechanical load) (Predict corrosion rates)
Cell liner	Material avoiding induced corrosion Mechanical support, cf. retrievability
Protect waste forms from alteration by water	
HLW cell, canister and waste form properties	pH neutral and reducing conditions
ILW bitumen waste cell thermal management	T<30°C for bitumen waste form at all times
ILW activated metal waste	Low corrosion rate environment when water contacts waste form
ILW cell and canister	Cementitious water with 11<pH<12,5
Limit solubility of radionuclides	
Thermal management – all waste forms	T < 70°C when water contacts waste form
Overall layout of disposal cells	Environmental conditions influencing solubility: Prevent risk of certain waste forms enhancing solubility of others through their complexing agents (organics)
Imported construction materials	Environmental conditions influencing solubility: Prevent risk of certain materials enhancing solubility of waste through their complexing agents (organics)
HLW and ILW materials	pH and Eh, cf. “protect waste forms”
Limit mobility of radionuclides	
	Environmental conditions influencing effective diffusion and sorption: Cf. *Limit solubility*

In summary, this second safety function is concerned with the source term and relies on:

- The thermal management of disposal cells (release from waste form)
- The watertight HLW disposal packages (release from waste form)
- 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 waste form (release from waste form)

Associated monitoring considerations will be further developed in a later section with an emphasis on the thermal management and water tightness of HLW disposal packages. The possible monitoring of parameters characterizing the chemical environment needs to be further evaluated, given that chemical equilibria influencing dissolution and release may not be reached for a very long time. Imported complexing agents, e.g. as waste by-products, are identified prior to emplacement, and this does not warrant further monitoring.

5.2.3 Repository components contributing to the third safety function (SF3 – Delay radionuclide migration and reduce radionuclide concentration outside the disposal cells)

Given the expected water flow through the repository infrastructure (first safety function), the expected source term evaluated from release rates, solubility, and mobility of radionuclides inside the individual disposal cells (second safety function), this third safety function considers requirements that may contribute to a delay and reduction of ensuing radionuclide migration (Table 5-5). This function is based on three major contributions. First, repository design requirements should contribute to favourable transfer into the near field and through the host formation, and thus delay and reduce any direct transfer through the infrastructure to the surface as much as possible. Second, repository siting and layout should take advantage of favourable host formation properties. Third, long-term properties of surrounding formations should not be perturbed due to any construction.

Table 5-5: Key components and/or design and site features relied upon to realize the long-term safety function “Delay radionuclide migration and reduce concentration outside of disposal cells”

Safety function: Delay and reduce concentration of radionuclide migration	Key components and/or design and site features
Delay and reduce concentration of radionuclide flux along infrastructure (from cells to shafts/ramps)	Overall layout: Length of disposal cell Length of galleries connecting disposal unit access to disposal cell access Minimum distance between disposal units and access shafts/ramps
Delay and reduce concentration of radionuclide migration through host formation	Siting and thickness of transfer path through host formation Preserve favourable transfer properties (low solubility, high sorption, diffusion coefficient).
Preserve natural dispersion and dilution potential of surrounding formations	Sealing of any surface-depth structure (incl. boreholes) Preserve favourable site properties

Given the performance of the first safety function, evaluated as long term, convective water flow through cells and infrastructures, and given the performance of the second safety function, evaluated as source terms and availability of mobile radionuclides in disposal cells, overall transfer simulations provide indicators to evaluate the performance of this third function. The performance of its first contributing function (flux through infrastructure) can be estimated through an understanding of the transfer potential along disposal cells and infrastructures, relative to the radial transfers into the near field. At different locations in the repository (seal of disposal cell, edge of disposal unit, and base of access shaft/ramp), the indicators evaluate the fraction of radionuclide flux through the infrastructure compared to the flux already transferring through the host formation. The performance of the second contributing function (flux through host formation) is evaluated based on specific siting and ensuing thickness, known transfer properties, and any expected perturbations of these. The performance of the third is evaluated using among other things conservative assumptions on long-term geodynamic evolutions of surrounding formations.

The basis for this function is provided by a number of site and design features (Table 5-6). The basis for its evaluation is provided by a combination of transfer properties in the host formation and through the infrastructure. Specific performance indicators or environmental conditions influencing transfer through galleries can be associated to solubility and sorption in the closed infrastructure, in ground support (backfill, remaining concrete liner) as well as to the diffusion coefficient in seals.

Table 5-6: Performances and/or indicators expected from the key components and/or design and site features related to the long-term safety function “Delay of radionuclide migration and reduce concentration outside of disposal cells”

Safety function and associated key components/features	Features as basis for safety function
Delay and reduce concentration of radionuclide flux along infrastructure (from cells to shafts/ramps)	
Disposal cell	Length (>50m if dead-end; > 100m if both sides access to galleries) (Solubility and mobility in disposal cell: cf. SF2 *Limit release and immobilize”)*
Access galleries in disposal unit	Distance from main infrastructure to disposal cell access Mobility: transfer conditions in closed access galleries
Overall layout	Minimum distance between disposal units and access shafts/ramps Mobility: transfer conditions in closed infrastructure from disposal units to shafts/ramps
Delay and reduce concentration of radionuclide migration through host formation	
Host formation	Thickness surrounding repository (min 50/60 m) Low permeability ~ 10^{-13} m/s
Favourable host formation transfer properties	Diffusion coefficient and geochemical (reducing) conditions providing for low radionuclide mobility in host formation
Preserve natural dispersion and dilution potential of surrounding formations	
Seal all surface-depth structure	Seals of access shafts and ramps, cf. above; Seals of boreholes, if any
Favourable site properties	Cf. preserve favourable site properties

In summary, this third safety function is concerned with radionuclide transport in a given context of water flux (evaluated under SF1) and of source term leaving the disposal cell (evaluated under SF2) and relies on:

- 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

Associated monitoring considerations will be further developed in a later section.

5.2.4 Preserving favourable properties of host formation

As introduced in the sections above on the three main safety functions, to *Preserve favourable host formation properties* supports the three main safety functions. It refers to expected performances actively contributing to this “preservation”.

The favourable properties of the host formation, i.e. its very low permeability, contribute to SF1 (*Counter water circulation)*. They contribute to SF2 (*Limit radionuclide release and immobilize in repository)* by the geochemistry of pore water – close to neutral pH value and reducing conditions -, which contributes to chemical retention in HLW disposal cells. They contribute to SF3 (*Delay and reduce concentration of radionuclide migration)* by its diffusion-dominated transport properties.

Sources of perturbation are excavation methods, construction layout, long-term material evolution and dissipation of residual voids, thermal and coupled thermo-hydro-mechanical perturbations. Additionally, chemical perturbations related to oxidation, alkaline perturbation, hydrogen production, and import of complexing agents have consequences that are limited to the near field and to specific properties in or near the disposal cells and infrastructure. They are addressed directly with the corresponding safety function.

Requirements to limit these perturbations are for the initial mechanical perturbation (EDZ): choice of excavation method and ground support, choice of excavation direction relative to local stress field (Table 5-7). All infrastructures are to be backfilled, where the backfill has to have adequate dry density and resistance to compression to limit long-term deformation around the repository. All these considerations may be regrouped under *mechanical management* of the repository.

Requirements to limit thermal perturbations provide for a *thermal management* limiting maximum temperature at the waste to 100°C, with a design goal of 90°C, including a margin of 10°C. Requirements also include establishing local variability of thermal conductivity prior to disposal cell construction, to compensate any such variability with disposal cell spacing as warranted. Thermal management should also provide the basis for predicting a long-term cooling down to below 70°C around HLW cells after a period not exceeding 1000 years after closure, in order to ensure that the thermal period will not induce mineralogical transformations in the host formation.

Further perturbations, resulting from hydrogen production, from desaturation/resaturation cycles, and from near field chemical perturbations will be taken into account in the long-term safety evaluations.

Table 5-7: Key components and/or design and site features relied upon to “Preserve favourable host formation properties”

Safety function: Preserve favourable host formation properties	**Key components and/or design and site features**
Limit the extension of initial excavation damaged zone through choice of excavation and construction/ground support	Excavation method Ground support
Avoid or limit propagation of initial mechanical damage by backfilling and sealing all structures and minimizing residual void volumes	Residual voids at closure Deconstruction of ground support (if applicable) prior to backfill and/or sealing Compaction at closure
Limit thermal and thermo-mechanical solicitations to limit irreversible deformations	Thermal management
Protect against possible other physico-chemical perturbations (hydrogen production; desaturation-resaturation; oxidation; alkaline perturbation; corrosion products; use of materials importing complexing agents)	Hydrogen production Ventilation Concrete components and degradation products Metal components and degradation products Imported complexing agents

The emphasis is thus placed on all processes that may influence and degrade favourable host formation properties.

Table 5-8: Performances and/or indicators expected from the key components and/or design and site features relied upon to “Preserve favourable host formation properties”

Safety function and associated key components/features	Features as basis for safety function
Limit the extension of initial excavation damaged zone through choice of excavation and construction/ground support	
Excavation method	Resulting near-field transport properties Resulting potential for self-healing Link between this initial and long-term mechanical perturbation
Ground support	Prevent sudden failure
Avoid or limit propagation of initial mechanical damage by backfilling and sealing of all structures and minimizing residual void volumes	
Residual voids at closure	Target 5%; Justified flexibility up to 10% in ILW cells – subject to future re-evaluation Minimize residual apical voids in gallery backfill
Dismantling of ground support (if applicable) prior to backfill and/or sealing	Impact on EDZ and associated near-field transport properties
Compaction at closure	Target of high dry density and good resistance to compression
Limit thermal and thermo-mechanical solicitations to limit irreversible deformations	
Thermal management	T<100°C in host formation (design basis 90°C) Cooldown to T<70°C in less than 1000 years
Protect against possible other physico-chemical perturbations (hydrogen production; desaturation-resaturation; oxidation; alkaline perturbation; corrosion products; use of materials importing complexing agents)	
Hydrogen production	Capacity to evaluate this production
Ventilation	Capacity to evaluate influence on desaturation-resaturation
Concrete components and degradation products	Capacity to evaluate resulting alkaline perturbation
Metal components and degradation products	Capacity to evaluate resulting corrosion products
Imported complexing agents	Capacity to evaluate resulting potential of enhanced transport

In summary, these additional requirements address the risks of lowering barrier and/or host formation performances induced by the construction, operation and closure of the repository. The control, through design and the spreading of heat sources, and the prediction of corresponding thermal evolutions is referred to as thermal management of the repository. The control, through design and the spreading of excavations and their subsequent filling, and the prediction of corresponding mechanical evolutions is referred to as mechanical management. The control of imported materials including air, and the prediction of ensuing chemical interactions is referred to as chemical management.

5.2.5 Summary of expected features and performances considered for monitoring

Each of the three major functions and associated requirements to preserve favourable properties relies on a combination of the favourable site properties, engineered barrier performances, the adequate management of thermal, mechanical, or chemical perturbations, and overall siting and layout features. The latter can be confirmed directly (inspection…) at the outset of construction. There is no need for further monitoring, and these items will not be considered further in the next chapters.

Favourable site properties – note that this refers to the unperturbed site – may be subject to a confirmatory activity, which may be assimilated to a continuation of site characterization to further enhance and/or confirm said properties.

Table 5-9: Main Safety functions and their links to favorable site properties

SF	Contributing Feature/Component	Preserve favourable…	Feature/Component to preserve…
SF-1 Transport vector	Host formation (monitor ?) Layout (verify)	Permeability of repository environment	Thermal management (monitor) Ratio of excavated rock (verify) Backfill (monitor) Residual voids in cells (verify) Self-healing (monitor ?)
	Seals (monitor)	Near-field permeability	Construction (verify) Ground support (monitor) Contact with near-field (monitor) Self-healing (monitor ?)
SF-2 Source term	Thermal management (monitor) HLW disposal package (monitor) Water in disposal cell (monitor) Chemical management (monitor ?) Waste form (?)	Near-field geochemistry: solubility, sorption	Ground support materials (verify)
SF-3 Transport	Host formation (verify ?) Layout (verify) Closed infrastructure (?)	Permeability, diffusion coefficient Near-field geochemistry: solubility, sorption Geochemistry of repository environment	Cf. SF-1 Cf. SF-2 Thermal management (monitor)
	Surrounding formations (verify ?)	Permeability	Borehole seal (?)

Expected engineered barrier performances, specifically those of waste disposal packages, seals and plugs, are subject to performance confirmation.

The risk of perturbations to the expected host formation and engineered barrier performances is addressed through appropriate thermal, mechanical, and chemical management. Note that this includes all aspects addressed under the function “preserve favourable host formation properties”. All of these are subject to monitoring in relation to the barriers’ expected performances. In the particular case of mechanical management, engineered support structures (mechanical support for seal, backfill, and residual voids at closure…) are used and may be subject to monitoring.

In summary, **the first safety function** is concerned with the transfer vector (water) and relies on:

- Favourable site features such as the very low permeability, a minimum thickness of the host formation, and a low vertical gradient
- Overall repository layout features
- Properties of seals, their near-field and support structures

Meeting the overall layout features will be verified upon construction, and this does not warrant further monitoring. Any monitoring considerations to confirm site characterization data on favourable site features, and their potential perturbation, will be further developed in a later section.

In summary, **the second safety function** is concerned with the source term and relies on:

- The thermal management of disposal cells (release from waste form)
- The watertight HLW disposal packages (release from waste form)
- 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 waste form (release from waste form)

Associated monitoring considerations will be further developed later with an emphasis on the thermal management and water tightness of the HLW disposal packages. The possible monitoring of parameters characterizing the chemical environment needs to be further evaluated, given that a chemical equilibrium which influences dissolution and release may not be reached for a very long time. Imported complexing agents, e.g. as waste by-products, are identified prior to emplacement, and this does not warrant further monitoring.

In summary, **the third safety function** is concerned with radionuclide transport in a given context of water flux (evaluated under SF1) and of source term leaving the disposal cell (evaluated under SF2) and relies on:

- Favourable flow and transport properties in the 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

Associated monitoring considerations will be further developed in a later section. The specific transport conditions from disposal cell to access shafts/ramps are currently being addressed in relation to seal performances.

In summary, *the specific requirements to preserve favourable host formation properties* address the risks of lowering barrier and/or host formation performances induced by the construction, operation, and closure of the repository. They address the need to understand and control mechanical, thermal, and chemical perturbations that repository construction, operation, and closure induces on the host formation. The control, through design and spreading of excavations and their subsequent filling, and prediction of corresponding mechanical evolutions is referred to as mechanical management. The expected performances refer to the extent of the initial and long-term, near-field deformation and associated perturbation of its permeability. The control, through design and spreading of heat sources, and prediction of corresponding thermal evolutions is referred to as thermal management. The control of imported materials including air, and the prediction of ensuing chemical interactions is referred to as chemical management. The control of the disposal process should be such that any ensuing chemical interactions resulting from hydrogen production, desaturation, alkaline perturbation, and corrosion or complexing agents remain limited and can be evaluated.

5.3 Monitoring to support the basis of long-term safety

The purpose of this section is to provide an overview of “what to monitor”, i.e. the processes and parameters that can be derived through further analysis of the expected performances developed previously. Note that at this stage, no quantitative evaluation is used as a basis to rank relative importance of processes and parameters to verify component and overall system performance. This section will reconsider safety from the perspective of possible monitoring. Monitoring objectives aim at providing evidence to support the basis to evaluate safety. This basis was previously associated with safety functions and the performances they are expected to provide to the repository.

Monitoring will target a combination of processes and parameters providing either direct indication of such performances or, more likely, a means to verify the basis for evaluating anticipated performance. This may address fundamental processes, such as propagation of heat, mechanical response of the host formation to deformation, or corrosion of metal. It may provide indirect evidence to predict how such fundamental processes will evolve, by looking at the initial and boundary conditions influencing the fundamental process. Both may combine to allow conclusions on the actual performance, say the permeability of a seal, which cannot be measured directly in the repository.

5.3.1 Fist safety function – Candidate processes and parameters for seals

The analysis developed in section 5.2.1 linked the expected performance for this safety function to the natural environment, some overall repository layout considerations, and seal performances. Careful consideration needs to be given to the fact that seal resaturation and swelling will only occur in the distant future, as will the mechanical equilibrium with the host formation and support structures, all of which combine to establish the corresponding seal performance, i.e. permeability.

At the time being, a concept for monitoring seal performances has not been developed and will be a topic for future activities.

5.3.2 Second safety function – processes and parameters for the overpack

The analysis developed in section 5.2.2 linked the expected performance for this safety function to the geochemical properties of the natural environment, thermal management, and expected waste package performances (for both overpack and waste form). The latter is considered in greater detail here and related to a special criterion for thermal management with HLW disposal. Waste disposal packages and the waste form they include contribute to safety by acting on the source term of radionuclide release (second safety function). The discussion below refers to vitrified waste encapsulated in a watertight steel overpack. Careful consideration must be given to the fact that disposal package corrosion is a very slow process and that any mechanical constraints on the package are not likely to be initiated for a very long time.

The dissolution and release properties of the vitrified waste form have been established in long-term experiments under specific conditions. For corresponding environmental conditions, specific waste form dissolution models and long-term radionuclide release rates are used for performance assessment. These models are not verified for temperatures above 50°C. Therefore, the overpack is to remain watertight until the temperatures have dropped below 50°C. In addition, the altered safety scenario considering intrusive boreholes in the repository assumes that there is no release during the first 500 years. Therefore, the overpack is also to remain watertight for a minimum of 500 years.

Note that the relative importance of such release rates and, for example, of early release due to overpack failure for the overall repository performance depends on other factors as well, for instance those influencing the first safety function (water flux) and the third safety function (transport properties). The expected performance, however, is considered here in its own right, irrespective of whether reduced overpack performance does or does not have consequences for the long-term impact on man and the environment.

This performance, i.e. duration of water tightness, is estimated relative to the local thermal management (duration) and is evaluated in the context of initial and boundary conditions. The overpack evolves with its chemical degradation (corrosion) and any mechanical stress it may be subjected to. The former is influenced by the presence of water and the water chemistry, the presence of oxygen, and the intensity of the radiation levels in the disposal cell, the latter by the evolution of the host rock and the cell metal liner, with a view to potential future loading of the overpack itself.

Initial conditions and intrinsic material properties

The initial conditions for the overpack evolution are defined by:

- Overpack material upon emplacement (steel grade and its intrinsic properties)
- Quality of initial overpack construction, including welding and runners
- Hydro-thermo-mechanical conditions inside disposal cell

- Hydro-thermo-mechanical conditions outside disposal cell
- Chemical properties of any water phase in or near cell
- Irradiation rates on overpack surface

Overpack material
The type of steel used determines its intrinsic mechanical and chemical properties. Presently, a P235 type carbon steel is foreseen in the design. The corrosion rates of this material are known under various conditions of temperature and relative humidity, and in direct contact with clay. Associated to this may be an understanding of corresponding corrosion by-product build-up. An initial quality control, i.e. sampling and testing of the steel used, is a candidate activity to verify these intrinsic properties which are part of the basis for long-term safety evaluation. The corresponding quality control conducted in a laboratory would try to confirm the intrinsic mechanical properties and corrosion rates under various conditions, as well as the potential for corrosion product build-up, to confirm the initial conditions of overpack material. Long-term tests can also be performed on material samples to verify whether these intrinsic properties, especially the corrosion rates, remain consistent within an actual repository environment.

Quality of initial overpack construction, including welding and runners
The intrinsic properties of the carbon steel may evolve after the fabrication process. Welding may influence local mechanical and corrosion properties. The inclusion of runners might influence local corrosion. The corresponding quality control and possible laboratory tests should provide a comparison of the relative influence of the manufacturing process on the intrinsic material properties. Any influences due to manufacturing (e.g. at welding seam) can be compared to the process models used to predict the package quality.

Hydro-Thermo-Mechanical conditions inside disposal cell
The initial conditions provide the basis for evaluating and understanding the initial evolutions both inside the cell and of the overpack. The geometry, thermo-mechanical state of the cell liner, presence of oxygen, the relative humidity, and the potential presence of liquid water inside the disposal cell characterize those initial conditions.

Hydro-Thermo-Mechanical conditions outside disposal cell
These initial conditions outside the cell liner provide the basis for evaluating and understanding the initial evolutions of the disposal cell liner and of the in-cell environment. These are the conditions in the cell near field and conditions in the initial gap between liner and near field. In particular, the geometry of the initial excavation, its alignment, and the presence of any break-outs in the gap with the cell liner are important initial conditions that influence future mechanical evolutions as well as the transient material properties of the clay that is in contact with the cell liner.

Chemical properties of any water phase in or near the cell
The chemical properties of water that will eventually be in contact with the overpack may influence corrosion.

Boundary conditions and their evolutions
The boundary conditions influencing the evolution of the overpack are determined by (i) the near-field evolutions, (ii) the evolution of the cell liner, and (iii) the evolution of the in-cell environment. These are subject to monitoring to:

- Verify models of progressive near-field deformation and of mechanical loading on the liner, of rate and chemical composition of water transfer towards the liner
- Verify model predictions of temperature evolutions and of the required duration for the overpack to remain watertight

- Verify the response of the cell liner to its near-field, in particular to verify predictions of mechanical stability, thermo-mechanical stresses and strains, and of any deformations
- Verify the mechanical, hydraulic, thermal, chemical and radiological environment directly influencing the overpack's expected performance of remaining watertight.

Near field evolutions
The key processes to monitor refer to verifying the dissipation of heat from the disposal cell, the deformation and loading of rock on cell liner, water (liquid and/or vapor) influx around and within the disposal cell, air exchange between disposal cell and access tunnel. Direct corrosion monitoring of the cell liner may be considered, although only the mechanical evolution is of direct interest as it influences the overpack evolutions. In particular, monitoring of the temperature field may also contribute to verifying process models that predict:

- decrease of waste form activity
- engineered barrier characteristics and evolution
- near field evolution
- overall host rock properties

The duration of required water tightness for the overpack is inferred from the time needed to cool down below the maximum temperature for first release. In summary, a good understanding of the near field boundary conditions that influence the future overpack performances, directly or indirectly through cell liner performances, call for the monitoring of:

- near-field temperature distribution
- near-field resaturation and interstitial pressure
- near-field deformation and gap closure with cell liner
- loading distribution on the cell liner

Cell liner evolution
The cell liner provides mechanical support during the operational phase but may fail and thus apply localized pressure on the disposal overpack. The cell liner loading is influenced by mechanical loading from the near field deformation, hydraulic loading from resaturation, and thermal loading from the heat-generating waste. If the loading is fairly homogeneous, only very limited deformations of the cell liner are expected. The potential for initial localized loading by the host rock represents some uncertainty. While it is expected that any localized stress peaks will lead to local rock breakup rather than to liner failure, identification of localized loading and its potential for spreading over larger areas may be useful to ensure liner stability.

Monitoring of the progressive loading and deformation of the liner will provide a basis for predictions about its longevity and expected mechanical failure, with special attention to any localized loading. Direct loading of the liner can be monitored directly at selected points, or can be inferred from liner deformation monitoring. A particular aspect is concerned with its thermo-mechanical evolution in order to confirm that no failure occurs due to initial, transient thermo-mechanical stresses and strains.

Cell environment evolution
The first influential parameter is the presence of water. If water passes through the liner of HLW cells, the overpack and liner inside the cell may corrode. This is the currently expected scenario. Therefore, special conditions ensuring low speed corrosion processes must be respected. As soon as a HLW cell is filled in, it is planned to set up an airtight plug right behind the last package, which will limit oxygen exchanges between the drift and the inside of the cell. The way the metallic plug is welded to the sleeve allows the isolation of the atmos-

phere within the disposal cell from the atmosphere within the ventilated access drift. This should ensure a quick establishment of anoxic conditions in the cell, which is mandatory to minimise corrosion of metallic materials within the cell.

Because corrosion speed should be as low as 1µm/year, direct monitoring is not achievable with current technologies. In addition to the conditions contributing to slow corrosion (humidity, absence of oxygen and temperature), the hydrogen concentration (as indicator for anoxic corrosion by-product) and pressure inside the cell may be two pertinent parameters to monitor.

Component (overpack) evolution within its environment

Instead of directly monitoring mechanical stress and strain, it is sufficient to monitor the evolution of the liner in order to predict future types of loading from the liner on the overpack. The overpack will be capable of withstanding homogenous loading. However, heterogeneous loading may lead to mechanical failure of the overpack.

Direct corrosion monitoring of the overpack can be considered. The problem of very low corrosion rates may be circumvented by monitoring in representative corrosion conditions. Establishing representative corrosion rates in comparable conditions may be considered, either by developing a representative structure with comparable environmental conditions but without radioactive substances, or more simply by including representative metal samples in a disposal cell environment, and establishing their average corrosion rate over a given duration. Combining the basis for predicting thermal evolutions and the results of corrosion predictions should then make it possible to confirm that the overpack “water tightness” duration exceeds the “thermal phase” duration.

Overview of candidate processes/parameters for overpack monitoring

Table 5-10 summarizes the candidate parameters for monitoring that are related to overpack performance. It also specifies whether corresponding initial conditions should be established to allow for an adequate interpretation of the monitored evolutions and/or to contribute to the verification of the safety basis. The table distinguishes between the core of the engineered barrier, i.e. the actual overpack, and the surrounding components and the near field, which both influence the overpack’s performance. The latter are monitored under “evolution boundary conditions”, although this distinction is somewhat artificial. This list of candidate processes and parameters needs to be further analysed keeping in mind several criteria:

- Some of the processes and parameters are correlated by available process models; monitoring a subset of them may allow others to be adequately inferred.
- The qualitative analysis neither took into account the acceptable uncertainty range for a given process or parameter, nor its relative importance to support the basis for the expected overall performance (in the example above, the duration of overpack water tightness).
- The proposed candidate listing of processes and parameters did not consider the technical feasibility of the associated monitoring.

Reminder: The list of candidate processes and parameters contributes to the second safety function’s overall performance by ensuring that (i) no early release can happen simultaneously with a potential, early (first 500 years) intrusive borehole and that (ii) the thermal management criteria as boundary conditions for vitrified waste form release are respected. As such, the duration of water tightness determines the initial conditions for waste form release and associated transport (solubility, mobility) properties inside the disposal cell. The long-term performance of the second safety function is provided by the latter, as briefly outlined below.

Table 5-10: Candidate processes and parameters for HLW disposal package monitoring

Component and surrounding influence	Process	Parameter	Initial condition	Evolution Boundary Condition	Evolution component	Comments
Overpack material	Intrinsic material mechanical resistance	Stress (pressure, traction)	x	N/A	x	Verification on lab samples
		Strain	x	N/A	x	
	Intrinsic material corrosion properties	Corrosion under in-situ conditions	x	N/A	x	Possibly verified by retrieving in-situ samples
Overpack	Corrosion	Surface corrosion	x	N/A	x	Possibly verified by retrieving sample canisters
		Weld seam corrosion	x	N/A	x	
		Runner contact corrosion	x	N/A	x	
In-cell environment	Heat dissipation Water exchange from near field	Temperature	x	x	N/A	Verify duration for cool-down
		Relative humidity	x	x	N/A	Verify conditions for corrosion
		Liquid water content	x	x	N/A	
	Gas exchange with access gallery	Oxygen concentration	x	x	N/A	Important: Verify corrosion under anoxic conditions
	Anoxic corrosion	Hydrogen concentration	x	x	N/A	Potential indicator for anoxic corrosion Correlate with risk of higher corrosion rates
	Radiolysis					
	Radiation	Irradiation rate	x	x	N/A	Correlate with risk of higher corrosion rates
Cell liner	Thermo-mechanical loading	Temperature	x	x	N/A	Verify duration for cool-down and correlate with in-cell values
		Strain	x	x	N/A	Verify basis to predict future failure
	Radial mechanical loading	Total pressure at contact surfaces	x	x	N/A	
		Load source position	x	x		Detection of heterogeneous loading
	Deformation	Radial deformation	x	x	N/A	Correlate with liner loading and failure predictions
	Transient to hydraulic equilibrium	Relative humidity	x	x	N/A	Correlate with loading Correlate with in-cell environment evolutions
		Hydraulic pressure	N/A	x	N/A	
Near field	Heat dissipation	Temperature	x	x	N/A	Verify duration for cool-down and correlate with liner and in-cell values
	Transient to mechanical equilibrium	Radial deformation	x	x	N/A	Correlate with liner load Correlate with closure of liner-near-field gaps Correlate with self-healing of EDZ
	Resaturation	Water content	x	x	N/A	Correlate with near-field mechanical evolution Correlate with in-cell environment
		Interstitial pressure	x	x	N/A	

Waste form properties and evolutions within its environment

The disposal overpacks protect the waste forms against alteration so that any release processes are not expected to occur until long after repository closure. The basis for safety can, however, be monitored, first related to the overpack ability to protect the waste forms, second related to environmental conditions that eventually influence release after failure of the overpack. The waste form properties were established as a basis for the license application. It may be decided if pursuing a long-term science program on waste form dissolution properties under in-situ conditions should accompany the disposal process. The expected performance based on the boundary conditions for the vitrified waste form, in addition to thermal management to ensure that the temperatures remain below 50°C at first dissolution, is to provide a neutral pH and reducing conditions. The same boundary conditions are expected as a basis for long-term solubility and mobility of radionuclides inside the disposal cell after release.

Processes and parameters in HLW disposal cells

This section regroups considerations of those chemical processes influencing release, solubility, and mobility of radionuclides in the HLW disposal cell. Given that liner and disposal package materials are carbon steel, the chemical environment influencing the long-term release rates and ensuing solubility and sorption of released radionuclides in the disposal cell is that of the natural environment, influenced by the metal and its corrosion products as well as by materials released from the waste form (borosilicate glass) at the same time as radionuclides are released. Given that actual release will happen in the distant future, it is subject to evaluation whether a representative, long-term test should attempt to reproduce the chemical conditions to be expected at the time of release and/or to verify the associated waste form release rates and ensuing solubility and sorption of released radionuclides in the disposal cell.

Processes and parameters in ILW disposal cells

This section provides an overview of considerations of those chemical processes that influence release, solubility, and transport in the ILW disposal cell.

The thermal criteria are met by the initial design, and no requirement to delay water contact on waste is imposed. Hydrogen-producing waste requires waste overpacks that provide adequate release paths in order to avoid that certain pressure limits (to be defined) inside the container are exceeded. Given that the liner and disposal package materials are concrete, the chemical environment influencing long-term release rates and ensuing solubility and sorption of release radionuclides in the disposal cell is that of cementitious water. Given that the actual release will happen in the distant future, it is subject to evaluation whether a representative, long-term test should attempt to reproduce the chemical conditions to be expected at the time of release and/or to verify the associated waste form release rates and ensuing solubility and sorption of released radionuclides in the disposal cell.

Note that for ILW disposal cells, the processes may be significantly perturbed during transient ventilation and desaturation. Monitoring over several radial distances would thus also provide an indication on the extent of the near-field perturbation, and would provide confirmation (at sufficient radial distance) of the unperturbed properties.

5.3.3 Third safety function – General monitoring considerations for long-term transfer outside the disposal cells

The analysis developed in section 5.2.3 linked the expected performance for this safety function to the transport properties of the natural environment, and the transport properties through the infrastructure, from disposal cells to access shafts/ramps. Specific layout features will be controlled upon construction and do not require further monitoring.

The specific transport conditions from disposal cell to access shafts/ramps are influenced by the relevant seal and backfill transport properties and possibly by the perturbed near field and gallery liner transport properties. The system requirements are developed so that the basis for the safety case provides for a radionuclide migration that is preferentially through the host formation and not through the infrastructure to the accessible environment.

General monitoring considerations for transfer through infrastructure

While the actual transfer will occur in the distant future and cannot be monitored, the emphasis is placed on those initial and boundary conditions that provide the basis for the long-term evolution of the transfer processes. The closed infrastructure will consist of any ground support structures left in place, seals, backfill, and the associated near field.

While backfill has no hydraulic requirement associated to it, it nevertheless provides an important boundary condition for the long-term evolution of the near field surrounding the backfilled galleries. Therefore, the backfill's long-term mechanical evolution provides the basis for predicting long-term deformation of the near field and any associated evolutions of hydraulic properties.

The geochemical properties will depend on the choice of backfill material – presently, it is intended to reuse excavated host rock – and the type and amount of ground support left in place at closure. As ground support includes concrete liner of substantial thickness, the local geochemical environment in the resaturated backfill will be subjected to the mixed influence of cementitious water percolating radially through the liner and initial water content and its properties at the time of backfilling.

General monitoring considerations for transfer into the natural environment

The site features and some site properties govern the possible transfer of radionuclides and, thus, have an important influence on safety: Permeability, diffusion coefficient, solubility, and sorption. These are established during site characterisation and known upon submitting a license application. It is subject to debate whether these properties should be verified. Monitoring focused on these parameters during construction and operation may be motivated by one or both of the following:

- To provide further confirmation of established values
- To verify their homogeneity over the rock volume relevant to the repository

The first possible motivation refers to the possible implementer's preference or obligation (if specified in the regulations) to verify already established parameter values during repository implementation and/or after its closure in order to confirm the basis for safety. This would allow verifying there were no errors and in some cases may contribute to reducing prior uncertainties. The activity could be implemented by pursuing prior site characterization activities.

The second motivation may be related to the need to provide more specific distributions of those parameter values over the actual repository volume. While initial knowledge on parameter variability would also have been acquired during site characterization, the construction of the repository provides for easier access to measure such properties. This may be considered as follow-up site characterization during construction and operation, with the aim to provide distributions with less uncertainty. The activity would, thus, further contribute to the repository baseline by focusing site characterization on the actual construction site, and possibly the tunnels prior to excavation or their near field.

A comprehensive risk-benefit analysis should be carried out for any monitoring that might be envisioned for either of the above two motivations. Indeed, site characterization at the exact repository location must not degrade long-term performances. Therefore, monitoring requiring the drilling of boreholes, thus, creating the risk of generating preferential transfer paths should be precluded. What might be considered are boreholes of a limited size, initiated from the repository infrastructures and not substantially reducing the intact vertical thickness of the host rock. Horizontal excavations would respect those constraints, but these would not provide the basis to verify the properties of the varying host formation layers.

In addition, a further important motivation for monitoring site properties is to evaluate any perturbations caused by the repository construction, operation, and closure. This third motivation was explicitly identified as a key element supporting the three main safety functions.

5.3.4 Preservation of favourable host rock properties – General monitoring considerations

The analysis developed in section 5.2.4 linked the corresponding requirements to those specific favourable properties that contribute to the other three safety functions. They address the need to understand and control mechanical, thermal, and chemical perturbations of the host formation that are caused by repository construction, operation, and closure. It also addresses expected performances contributing to maintaining these perturbations within acceptable limits consistent with the safety case. These are achieved through specific design and construction features that contribute to thermal management, mechanical management, and chemical management.

The favourable properties explicitly identified as contributing to the safety functions are:

- The very low permeability – the expected host formation permeability should remain within 5.10^{-13} m/s and 5.10^{-14} m/s. -, a minimum thickness of the host formation, and a limited vertical gradient
- In-cell environmental conditions favourable to low release rates; partly ensured for HLW by providing a watertight overpack
- Geochemistry of groundwater favourable to low release rates, solubility and sorption
- The diffusion coefficient of 2.5×10^{-10} m^2/s for cationic species and 5×10^{-12} m^2/s for anionic species, as well as reducing conditions favouring sorption and favouring precipitation, with species-specific solubility and sorption properties evaluated based on a thermodynamic data base for the context of unperturbed interstitial water and rock mineralogy

Another site-scale property is the vertical hydraulic gradient. The current value at the site can be verified. This gradient, however, is subject to evolution over the next 1,000,000 years. The basis for predicting this evolution is knowledge about surface erosion, glacial events, and ensuing modifications of the overall hydro-geological boundary conditions.

Regarding the three main safety functions, the aim is to have a basis to:

- Quantify the actual perturbation of considered “favourable property” upon construction, throughout operation and, where useful, upon closure; or alternatively
- Quantify the process likely to induce such perturbation (heat source for thermal evolutions; construction and residual voids and backfill or disposal package compressibility for mechanical evolutions; construction materials for chemical evolutions)
- Quantify the extent of said perturbation
- Predict, as possible, future evolutions of said perturbation, especially after closure; in particular
- Quantify the potential for “self-healing” of initial perturbations after closure.

Near field perturbations

These are addressed directly within the context of the main safety functions and expected component performances. Near field excavation damage and associated perturbation to hydraulic conductivity as well as the potential for long-term self-healing will be considered together with seal performance (SF1) and is already considered with transport properties through the closed infrastructure (SF3). Near field perturbations of chemical properties are considered as part of the chemical environment influencing waste release and mobility in the disposal cell (SF2) and as part of the (near field) radionuclide transfer through the host formation (SF3).

Monitoring of chemical perturbations can be envisioned through sampling at selected, representative locations and at different points in time of the operating period.

Monitoring of mechanical perturbations at construction and of their evolution until closure and after partial closure of some disposal units (including the potential for long-term deformation through compaction of backfill and filling of residual voids) can be envisioned at select, representative locations to confirm the basis for long-term evolutions of near field fissuring and fracturing, the potential for self-healing and associated expected permeabilities.

Monitoring of the thermal perturbation is carried out within and near the heat sources (selected disposal cells) and corresponding access infrastructure to verify initial heat distribution and evolution, and to verify the basis for long-term predictions of the thermal field.

At the disposal unit scale, thermo-hydro-mechanical perturbations could cause some fissuring or fracturing of the host formation. This would happen when thermally induced overpressures exceed rupture of the host formation. Prior calculations show that a temperature increase during the first decades after a HLW cell has been filled can induce a pore pressure increase inside the near field host rock that exceeds approximately 5 MPa several decades after the packages have been placed in the cells. More precisely, calculations show that the value and the peak position of the pore pressure increase depend not only on the heat sources (type of packages) but also on the remaining space between the cell sleeve and the host rock.

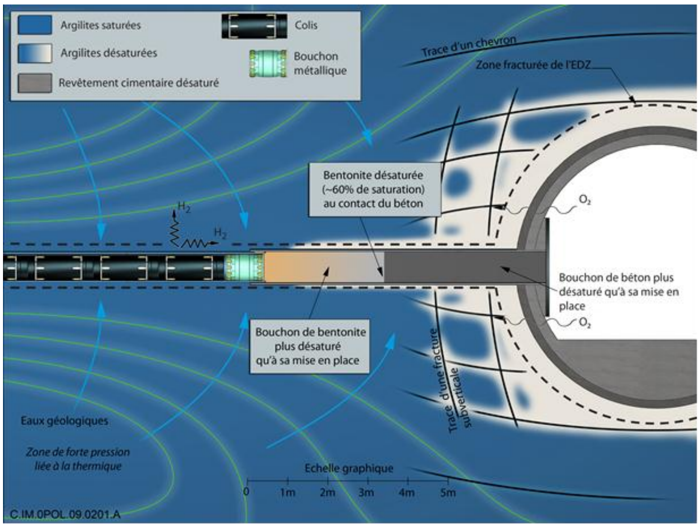


Figure 5-7: Global expected evolution of HLW cell several years after packages have been emplaced

Far field perturbations

The transfer properties through the unperturbed host formation are fundamental to the safety case:

- They act on the potential source term and transfer through the infrastructure by effectively limiting the potential for water inflow (SF1)
- Due to this low water inflow (SF1), they provide robustness even in the event of a complete failure of the seals
- The long-term radionuclide transfer processes reduce and delay transfer of the three most mobile, non-sorbed radionuclides (^{129}I, ^{36}Cl, ^{79}Se) over several 100,000s of years (SF3)
- They limit the transfer of all other radionuclides after 1,000,000 years (i) to the vicinity of a few meters from the repository if highly sorbed and (ii) to a few tens of meters within the host formation, if moderately sorbed

Presently, in the absence of any intrusions into the host formation (e.g. boreholes) other than access shafts/ramps and the repository infrastructure and disposal cells, only two mechanisms are considered as providing a potential for large scale, far field perturbations of the host formation. At the repository scale, overall thermo-mechanical coupling can lead to deformations at the formation scale. This can be observed at the surface by ground subsidence and at the top of the host formation layer. The expected overall deformations remain small, however, and no degradation of the transfer properties is expected.

At the repository scale, long-term degradation and re-compaction of the backfilled infrastructure and the disposal cells will lead to some deformation of the host formation. At first, this will lead to some transient perturbation of near field properties, in particular permeability. Depending on the extent of deformation at each of the structures, this might add to deformations at the repository scale, and the perturbation would then also encompass the entire host formation. To ensure that no reduction of the host formation permeability will occur, the near field degradations should not exceed a certain limit.

Surrounding formations

The long-term transfer properties into surrounding formations may be perturbed through the drilling of boreholes. It should be verified that any such perturbation is being compensated by sealing prior to abandoning the site.

Components contributing to preserve favourable properties

Other engineered features and operating decisions also contribute to the basis for overall safety, although they do not provide an engineered barrier per se. Instead, they ensure that the favourable host formation properties or barrier performances are preserved. These properties then contribute to long-term safety performance. Design specifications, thus, include requirements to limit mechanical, thermal, chemical perturbations and associated perturbations of favourable hydraulic and transport properties. These are regrouped here under thermal, mechanical, and chemical management of the repository.

Thermal management aims at respecting certain criteria that were identified as a basis for safety to preserve favourable host rock properties, to preserve favourable environmental conditions for engineered barrier evolutions, for waste form dissolution and for transport properties. The control, through design and spreading of heat sources, and the prediction of the corresponding thermal evolutions is referred to as thermal management of the repository. Temperature evolutions at select locations (near packages, near disposal cells…) can be monitored.

Mechanical management, like thermal management, refers to certain criteria that were identified as a basis for safety. The control, through design and spreading of excavations, installation of ground support controlling mechanical/permeability perturbation prior to closure and their subsequent backfilling to limit overall long-term deformations of the host formation, and prediction of corresponding mechanical evolutions is referred to as mechanical management. All engineered structures other than those having a direct performance contribution to safety (Packages, buffers and seals) contribute to this mechanical management of the repository. There is a strong link to hydraulic performances, as a mechanically damaged host formation has an increased permeability.

Processes influencing ground support and near field evolutions, e.g. initial deformation, residual voids or backfill density, as well as those influencing barrier stability, e.g. deformations and applied pressures, may be monitored. First of all, their construction, the materials chosen, and the evolution prior to closure should not induce conditions in the near field or in safety-relevant barriers that could reduce their ability to contribute to safety. Second, their evolution upon and after closure, including possible ground support retrieval, compression of backfill and of voids therein, should not degrade the engineered barriers' and host formation's abilities to provide for safety. Third, seal support anchors ensure that the seals remain in place to provide the expected hydraulic performance. At this stage, it appears as difficult, however, to provide direct verification of the long-term mechanical evolution. The potential for monitoring the initial and the boundary conditions was presented in the context of a seal, and comparable considerations apply here. The main difference is related to the specific properties and the emplacement procedure of backfill material.

Another line of evidence supporting the preservation of favourable properties is based on the rheological properties of the host formation. It is known that a limited relative deformation will not lead to fissuring. Therefore, the maximum potential deformation (although it may lead to local and partially or wholly transient damage) will not induce damage at larger scales.

Chemical management refers to certain criteria that were identified as a basis for safety. The chemical interactions between the imported materials, the air, ventilation and desaturation characteristics of the operational phase, on the one side, and the near field and engineered barriers, on the other side, must be understood. This refers to processes likely to induce increased corrosion (oxygen, acidic pH), lower swelling pressures (alkaline pH). It also refers to imported materials and complexing agents likely to increase solubility and transport of certain radionuclides.

5.4 Monitoring System Design

This case is based on the French disposal concept and illustrates monitoring design considerations in a clay environment, with the intent to provide current information of ongoing developments and recommendations to take under advisement when developing technical solutions to implement a monitoring program.

The example developed here describes monitoring developments that allow the verification of the basis for the expected performances of the high-level waste disposal package (HLW-DP). First, the detailed monitoring objectives previously introduced and justified are presented as a table of candidate processes and parameters for monitoring. The term *candidate* is maintained at this stage to highlight that the relative importance of each of the processes and parameters to inform on the expected performance has not yet been finally evaluated. Irrespective of this distinction and of the future decision whether all or only some of the listed processes and parameters will be monitored, it is necessary to develop viable monitoring solutions.

Several important considerations should be addressed to develop viable monitoring solutions. First, monitoring systems for geologic repositories are subjected to harsh environmental conditions and to certain constraints specific to the disposal of radioactive waste, foremost the requirement not to reduce the expected performances of the component. Second, monitoring systems are relied upon to provide reliable information over long durations. All of these are summarized as technical requirements and were presented previously in the “technical requirements report”. An approach to develop monitoring systems that meet these technical requirements is presented. The different elements for the monitoring system design are then illustrated for the HLW disposal cell, in order to provide information on the list of candidate processes and parameters in an actual repository component. It may be required to overcome remaining technical limitations of available monitoring technology and/or to avoid perturbing the expected component performance through monitoring. In that case, it is recommended to plan on instrumenting “active demonstrators”, also called “sacrificial disposal cells”, or representative prototypes.

In the event natural or design-induced variability influence the monitored processes and parameters, it may be necessary to verify this variability for an adequate verification of the expected performances. Temperature variability induced by the concept of construction and operations, i.e. of progressive construction, emplacement and ventilation inducing heat-gradients throughout a HLW disposal unit are illustrated. To adequately reflect such variability, and to correctly evaluate monitoring results compared with process models and parameters, a strategy for distributing the monitored components is presented. Finally, the initial list of candidate processes and parameters is reviewed and the completeness of possible design solutions is verified.

5.4.1 Monitoring technical objectives

Candidate processes and parameters that determine the technical monitoring objectives were identified and described in a previous section. The following table summarizes these for the specific example of monitoring related to HLW overpack performance. This table includes processes or parameters that influence the performance as initial or baseline conditions, such as intrinsic material properties or geomechanical properties of the host formation. It includes processes (e.g. heat dissipation) induced by specific features (e.g. spreading of heat sources) or events (e.g. closure of disposal cell) that may influence the expected performance (duration of overpack's water tightness). It also includes processes that provide direct (e.g. corrosion rate, deformation) or indirect (e.g. environmental conditions, mechanical loading) verification that this performance will be attained. The table distinguishes between the core of the engineered barrier, i.e. the actual overpack, and the surrounding components and the near-field, which influence the overpack performance.

Table 5-11: Candidate processes and parameters influencing HLW disposal package evolution

Component and surrounding influence	Process	Parameter
Overpack material	Intrinsic material mechanical resistance	Stress (pressure, traction)
		Strain
	Intrinsic material corrosion properties	Corrosion under in-situ conditions
Overpack	Corrosion	Surface corrosion
		Weld seam corrosion
		Runner contact corrosion
In-cell environment	Heat dissipation Water exchange from near field	Temperature
		Relative humidity
		Liquid water content
	Gas exchange with access gallery	Oxygen concentration
	Anoxic corrosion	Oxygen concentration
	Radiolysis	
	Radiation	Irradiation rate
Cell liner	Thermo-mechanical loading	Temperature
		Strain
	Radial mechanical loading	Total pressure at contact surfaces
		Load source position
	Deformation	Radial deformation
	Transient to hydraulic equilibrium	Relative humidity
		Hydraulic pressure
Near field	Heat dissipation	Temperature
	Transient to mechanical equilibrium	Radial deformation
	Resaturation	Water content
		Interstitial pressure

5.4.2 Reliable monitoring technology

Sensor qualification procedure

Given the possibly harsh conditions in an underground repository (e.g. radiation levels, temperature, water pressure, and pH in the HLW disposal cell), and given some less common specifications for the monitoring technology, in particular durability and non-disturbance of barrier performance, we know that many off-the-shelf monitoring technologies will rapidly fail to provide reliable measurements. It is therefore recommended that available state-of-the-art monitoring technology is adapted and qualified to meet these requirements.

To illustrate this recommended approach, a succinct description of the qualification process that Andra has put in place (Buschaert, 2012) is provided. It entails testing and qualifying the complete measurement chain in progressive steps in order to know and to be able to anticipate the failure rates and to be able to master possible long-term drifts. The overall process is inspired by the qualification guide for non-destructive methods (Qualification guide, 2005). A global test sequence includes four stages:

- Stage one consists of acquiring in-depth knowledge about the sensing technology, engineering solutions, and practical implementation constraints in order to be able to select the technologies suited to the requirements of monitoring nuclear waste repositories.
- Stage two consists of carrying out laboratory tests under fully supervised and/or controlled environmental conditions, in order to qualify the sensitive component and to assess the complete measurement chain performance.
- Stage three consists of outdoor tests, to evaluated field implementation influence.
- The fourth stage involves an adaptation to the actual environmental conditions.

Presently, T-H-M sensors are finishing qualification process while C-R- sensors are still at the laboratory stage.

Strategy to provide robust monitoring information

Despite the use of qualified technology to design the monitoring system, measurements are always at risk of providing misleading information. While signal diagnostic tools can be used to discriminate as much as possible between “good” and “bad” signals (see section 7), it is also proposed to address this risk with the monitoring system design. Simply put, sensing chains should never be used alone. Rather, redundancy should be provided in number and in approach. It is recommended that various technologies be associated and selected to provide redundancy or/and complementary approaches. Amongst monitoring units, the sensors would be placed in surplus on the one hand and associated according to their complementarities on the other hand: Proven technologies next to innovative sensors, localized measurements associated with devices providing distributed measurements.

Finally, metrological references will be placed nearby to evaluate whether sensing chains are subject to long-term drifts. With this combination of approaches and of tools, it is possible to strengthen the confidence in the global monitoring system and to provide durable and reliable information. This general approach is shown in Figure 5-8 using the example of concrete liner instrumentation. It will be implemented in the HLW cell access gallery liners. The monitoring system design for the vitrified waste disposal cell follows the same general approach. Thermal monitoring is ensured with platinum probes (Pt100 or similar) placed near distributed optical fiber sensors (OFS) based on Raman scattering. A reference element is inserted into the sensing line. Sensors are numerous because gradients are expected. Mechanical monitoring will be performed with vibrating wire extensometer located on 3 axes.

A reference sensor is isolated into a cylinder for metrological insurance. Collocated optical fibres connected to Brillouin or Rayleigh measuring devices will provide distributed strain measurements. In addition to strain measurements, stress applied on the concrete liner by the host rock is also measured indirectly with a long-based-field-extensometer. Finally, a Time Domain Reflectometry (TDR) sensing system measures water content. It is complementary to the measurement of interstitial pressure cells (IPC).

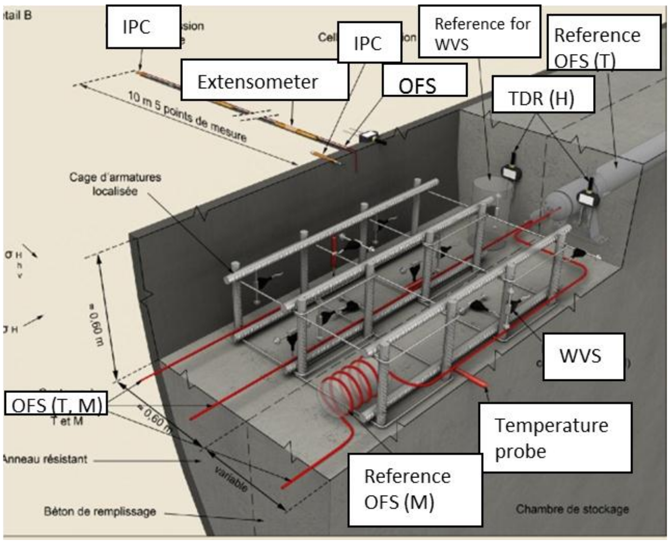


Figure 5-8: Example for concrete instrumentation to provide T-H-M characterizations which will be implemented in the access gallery liners

5.4.3 Design for a HLW cell instrumentation

The comparatively small diameter of the vitrified waste disposal cell and its method of construction cause a series of challenges for its instrumentation. To design a corresponding monitoring system, several instrumentation possibilities are examined: (i) equipping the cell liner with monitoring devices, (ii) monitoring the behaviour of the rock with boreholes nearby (either parallel or perpendicular, if the cross-entries are close by), (iii) moving the monitoring equipment to the sealing plate.

Instrumented boreholes surrounding disposal cells

Instrumented boreholes would allow the nearby rock to be monitored in a sustainable way. Done from the access galleries or cross-entries, these boreholes, parallel or lateral to the cell, would contain instrumentation that allows a characterisation of the thermal fields and would provide several humidity measurement points, the interstitial pressure and the distortions in the rock. A large part of the technical objectives listed in section 5.4.1 can thus be addressed.

The locations and lengths of the boreholes must be optimized based on expected T-H-M evolutions. The example of thermal gradients in claystone is illustrated below. At the scale of a single storage cell, the maximum temperature will be reached 8 years after waste emplacement (Figure 5-9). The thermal field will be anisotropic. Thus, boreholes must be placed on two cross sections, for instance on the side and on top of the cell (Figure 5-10). Their lengths may be reduced to 25 m, 15 m of which would be in the vicinity of the waste and the rest parallel to the cell plug. One long borehole is preserved to provide data on interstitial pressure as detailed later.

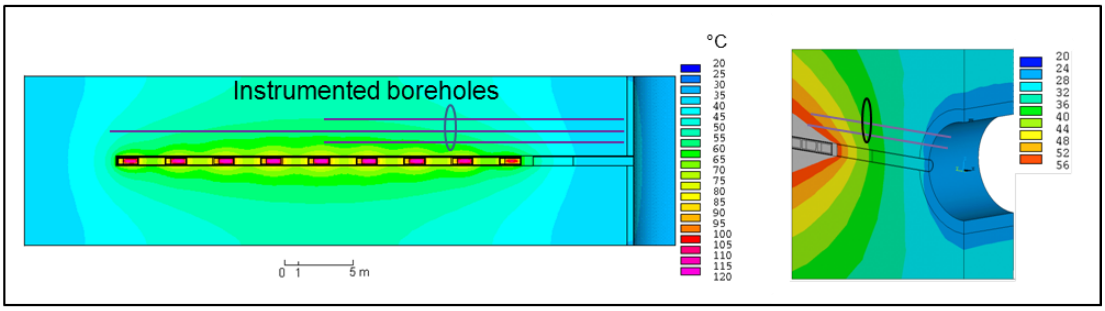


Figure 5-9: Thermal simulation around a HLW cell when the temperature is at its maximum (horizontal and vertical cross-section)

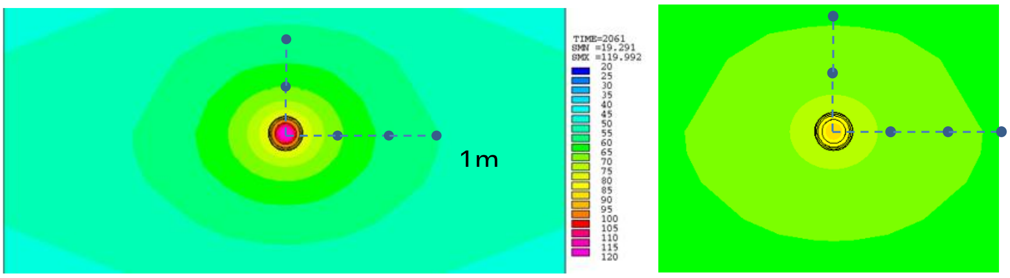


Figure 5-10: Instrumented borehole locations visualized on thermal simulation around a HLW cell: transverse cross-section when the temperature is at its maximum (left) and after 70 years when the temperature is at its maximum in the access gallery (right)

For instance, five boreholes are envisioned to fully characterize the thermal process, two on top and three between two cells. They are all inserted inside the EDZ to reduce the potential impact on long-term safety. These boreholes will be instrumented with Pt100 and optical fibre sensors based on Raman scattering which provide distributed measurements with a spatial resolution of 1m and a temperature resolution of 0.1°C. They will also include inclinometers to confirm that the clay layer is moving within the expected range, and will probably include extensometers.

In anticipation of potential stakeholder expectations, one borehole will also include gamma sensing sensors to verify that the calculations have fully predicted the radiologic evolution. Temperature increase induces interstitial pressure increase in the clay. This is one of the coupled effects to be characterized. The boreholes will be instrumented with interstitial pressure cells that are based on vibrating wire sensors, which benefit from dam instrumentation know-how. This sensor type has been tested in the Andra URL in the vicinity of a HLW cell demonstrator ("Bure demonstrator report").

Instrumented sealing plates

To detect the presence of water in the cell, the possibility of incorporating sampling lines in the HAW cell plug in some cells is being studied, as shown in Figure 5-11. The speed of corrosion will be assessed using indirect measurements. The progressive establishment of anoxic atmosphere, a condition necessary for low corrosion speed, would be monitored using sampling lines from the plug and oxygen measurements.

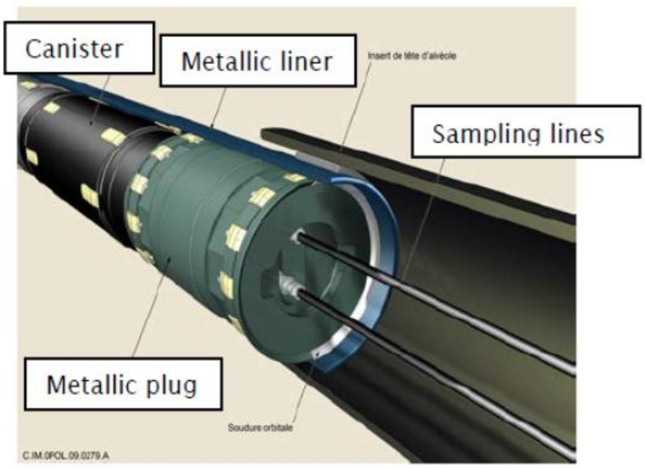


Figure 5-11: Instrumentation of HLW cell plug

A main limitation is the maintenance costs of such sampling lines during the monitoring period (an order of a century is envisioned). Moreover, they provide measurements up to the stage when the cell is sealed, not afterwards. In the medium term, direct monitoring of the gas content in the cell could be considered using a miniature spectrometer which would be introduced into the cell top. Such a structure would also allow direct measurements of the corroded thicknesses of the waste overpack, as well as the monitoring of any seizing of the package sliding runners.

Liner instrumentation

Temperature monitoring is planned to contribute to verifying the assessment basis for long-term safety. This allows verifying whether prior predictions for the duration of the thermal period and the expected thermal peaks are consistent with the monitoring results. In addition, the conditions to be expected in the event of waste retrieval can be verified as well. The instrumentation is a major challenge. On the one hand, the ability of the instrumentation to withstand the dose rates, which remain significant even on the external surface of the liner, is an identified risk of degradation of the monitoring devices. On the other hand, the sensors and their cables must withstand very large stresses during liner pushing operations.

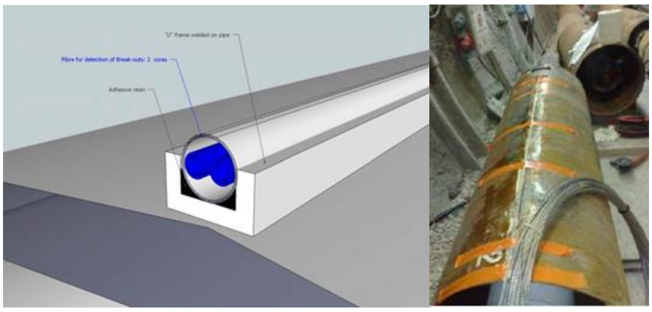


Figure 5-12:
Sketch of the HLW cell liner instrumen-tation on the external surface (left) and picture of the demonstrator before exca-vation (right)

The HLW cell demonstrator in the Andra URL showed that the optical fibre sensor survived liner excavation, as illustrated in Figure 5-13 and Figure 5-14. This sensor is expected to detect the location of claystone break-outs and progressive pressure loading on the liner.

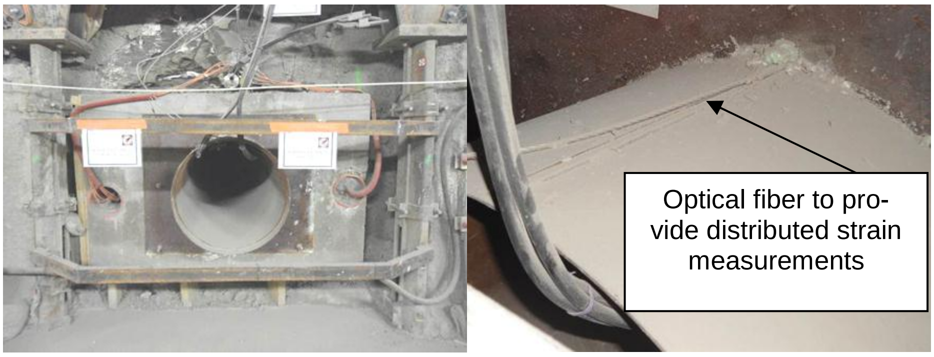


Figure 5-13: Pictures of the finalized demonstrator in the Andra URL with a zoom on the top surface (right)

Instrumented cross-sections provide precise but local measurements that would be combined with indications of overall distributions provided by distributed temperature and strain fibre optic sensors. Their purpose would be to verify the distribution of the mechanical loading and changes to it. The monitoring devices would be covered with a protective cap welded on to the liner. The monitoring devices could also be incorporated into grooves. However, this would affect the basis for the safety assessment, which partially relies on the thickness of

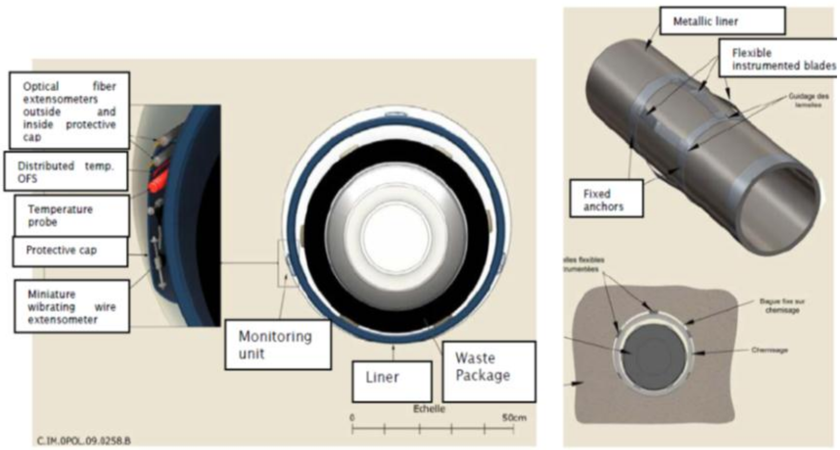


Figure 5-14: Sketch of cell liner instrumentation

the liner. For this reason, installation in grooves would only be allowed into “sacrificial structures”, a concept dedicated to monitoring further developed in section 5.4.4. Finally, cables could be replaced by radio transmitters, if the battery lifetimes were improved, especially at the expected high temperatures.

Highly instrumented structure: “witness” structure

Instrumented HLW cells would take advantage of all these technical possibilities. The design of the overall monitoring system would look like the illustration shown in Figure 5-15. Such a highly instrumented structure is called a “witness structure”. Only a very few disposal cells would contain so many monitoring devices. The instrumented cell is complemented by the access gallery monitoring which consists of the liner instrumentation sketched in Figure 5-15 as well as by ventilation monitoring.

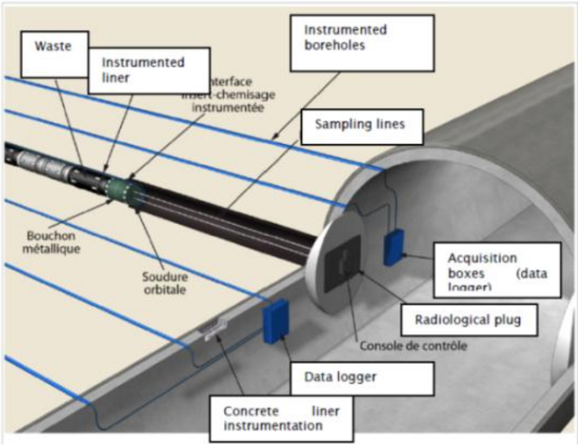


Figure 5-15: Monitoring system in a highly instrumented HLW cell (witness structure)

5.4.4 Complementary structure: active demonstrator or “sacrificial cell”

Currently, high levels of uncertainty exist concerning the ability to supply continuous and sustainable chemical measurements between now and 2025, even more so for as harsh an environment as the contact with the overpack for high level waste. This is why sampling lines were included into witness cells. More precisely, to measure the speed of corrosion, electrochemical probes have been developed further but some specific features pose major difficulties, particularly, the transmission of information out of the cell. At this stage, the only qualified technique is weighing material coupons. Long-lasting pH sensors do not exist. Faced with these technological challenges, R&D is on-going, and mitigatory solutions need to be considered. One of these consists of providing one or more “sacrificial cells” similar to a demonstrator structure (Figure 5-16). Because temperature and dose rates influence the speed of corrosion, these structures must contain real containers.

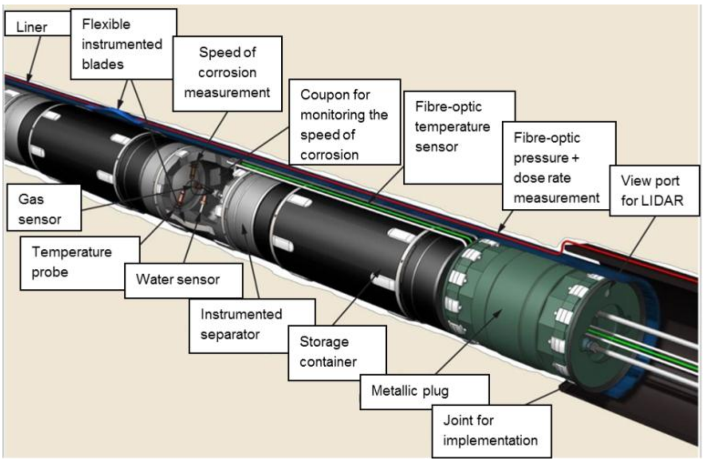


Figure 5-16: Scheme for monitoring a sacrificial cell

It is expected that the transition towards low corrosion speeds will occur on a scale of several years to decades. The demonstrator structure would therefore be open for fifteen, thirty, or possibly fifty years after backfilling and closure of structures to allow the recovery and subsequent weighing of coupons that were placed, for example, in or on the surface of a separator. These openings would have adverse effects on the anoxic atmosphere and the hydric conditions.

Thus, a demonstrator cell would ideally be necessary for each opening. Therefore, at least two and preferably three would be needed. These demonstrator cells may have a reduced length, for example 25 m (10 m of insert and 15 m usable). This concept is quite similar to the “Pilot Facility” proposed in other countries, with the exception that sacrificial cells are planned to be in representative locations inside the main part of the repository, as detailed in the next section.

5.4.5 Overall design

To verify and confirm the assessment basis for canister performance, monitoring must also take into account possible variabilities due to the variabilities in the host rock properties, and in the design and construction, as well as due to variabilities caused by the concept of operations. The properties of the waste packages will be verified. A waste package acceptance process is developed to ensure the effective compliance with the acceptance criteria and technical specifications. Non-destructive methods and analyses of waste packages will be performed with special equipment in a fixed or mobile unit as second level controls or for later controls linked to a possible withdrawal of wastes from reversible disposal.

However, the proposed instrumentation may seem abundant or even exaggerated. The consequences of extensive instrumentation – costs, invasiveness, construction slow-down – call for reaching a good equilibrium between instrumenting every structure and only instrumenting a single prototype. These aspects are further discussed below, in an attempt to provide some insight into the design of a representative, repository scale monitoring strategy.

Instrumentation density decrease

To find equilibrium between the monitoring needs, the constraints of implementation, and the associated costs of monitoring equipment, a reasonable density of embedded sensors should be achieved. For this purpose, the global design will take advantage of the complementarities of different technical approaches available by putting progressively more emphasis on visual inspections and on non-destructive tests while decreasing the number of embedded sensors. For this purpose, it entails optimizing the arrangement of sensing means in order to spread the instrumentation in a largely inhomogeneous way by taking advantage of the similarity between structures, in particular the kilometres of access tunnels and the thousands of disposal cells for long-lived high-level waste (5000 cells currently foreseen). By taking advantage of the similarities of some expected phenomenological evolutions (linked to the large homogeneity of the host rock and assuming a selection of disposal cells for similar canisters), the monitoring strategy suggests to follow a sequence of structures, referred to as “witnesses”, current and non-instrumented, whose density of embedded instrumentation is progressively decreased. If necessary, this could be complemented by a “sacrificial structure”. Each structure thus labelled has a precise function towards monitoring.

- The “witness” structure is chosen amongst the first structures built. It must be exhaustively equipped to fulfil the monitoring goals. Beside the first constructions, the witness structures will be chosen for specific locations that ensure a representative monitoring area.
- The “current” structure is less instrumented, monitored by comparison with a “witness” structure.
- The standard cell is generally not instrumented. It would only contain essential equipment for the operational safety and would be the target of occasional inspection and control.
- If monitoring technologies do not comply with all monitoring objectives, real withdrawal tests of HLW canisters in some “sacrificial cells” are also planned to provide the possibility to carry out visual inspection, destructive analyses, and sampling on construction materials. These cells are planned to be dismantled because of the potential disturbance of their component performances by the testing process.

One issue is how to locate witness structures to ensure the representativeness of the monitoring results and to correctly take into account any variability as further developed below, and to, thus, provide adequate information to verify and confirm the prior assessment basis for the expected safety and reversibility performances.

Implementation of witness cells inside a module to characterise thermal process

The operating period is characterized by a succession of relatively short periods of activity (construction, loading, closure) that are interspersed with waiting phases of variable durations, structured by decision milestones of the pre-closure management of the disposal process, whose governance is in accordance with reversibility in the French concept. The chaining together of these various phases initiates various processes such as physical evolutions, simultaneous or sequential, independent or coupled, expressed with contrasting characteristic times. The particular needs can thus be evaluated based on prior knowledge of the expected evolutions for a given design and concept of construction and operations, for instance, the duration of progressive construction and waste emplacement and the duration and characteristics of ventilation. This is illustrated below using the example of a design for the HLW disposal unit considered for the French disposal concept in 2009. While the latter is subject to evolution, the lessons learnt for the monitoring strategy remain valid. On the scale of a HLW disposal unit, the monitoring strategy must meet the following needs:

- Checking the interaction between the disposal cells and the access galleries, linked in particular to the gradual loading of the module (see Figure 5-8, left) and its consequences on interactions with the access galleries mainly due to ventilation.
- Checking the effects of waiting time between the construction of a cell and its loading (1 to 10 years) on changes in processes H, M and HM from one cell to another.
- Checking the peripheral THM-influence from adjacent disposal cells which are filled at different times.

Based on these three objectives, the monitoring strategy anticipates the integration of an initial module constructed from witness cells respectively distributed (i) in the core of the module and at its edge (ii) along the length of the access gallery (air intake and air return) and (iii) along the module (first cells loaded against the last cells loaded). With some witness cells able to meet both objectives, a pooling of resources made it possible to restrict the number to 9 witness cells (out of approximately 200 in the case of the Andra (2009) architecture) within the initial waste disposal module (Figure 5-17). This is not a definitive figure and will be amended over time as containers arrive and will be adapted to the disposal design choices.

The cell instrumentation would be supplemented by observation and monitoring in the galleries. For example, an optical fibre providing distributed temperature measurements would help to monitor the gallery temperature evolution due to ventilation and to monitor the expected temperature increase of 4°C along the access gallery (depending on ventilation direction). Concrete liner monitoring is also planned.

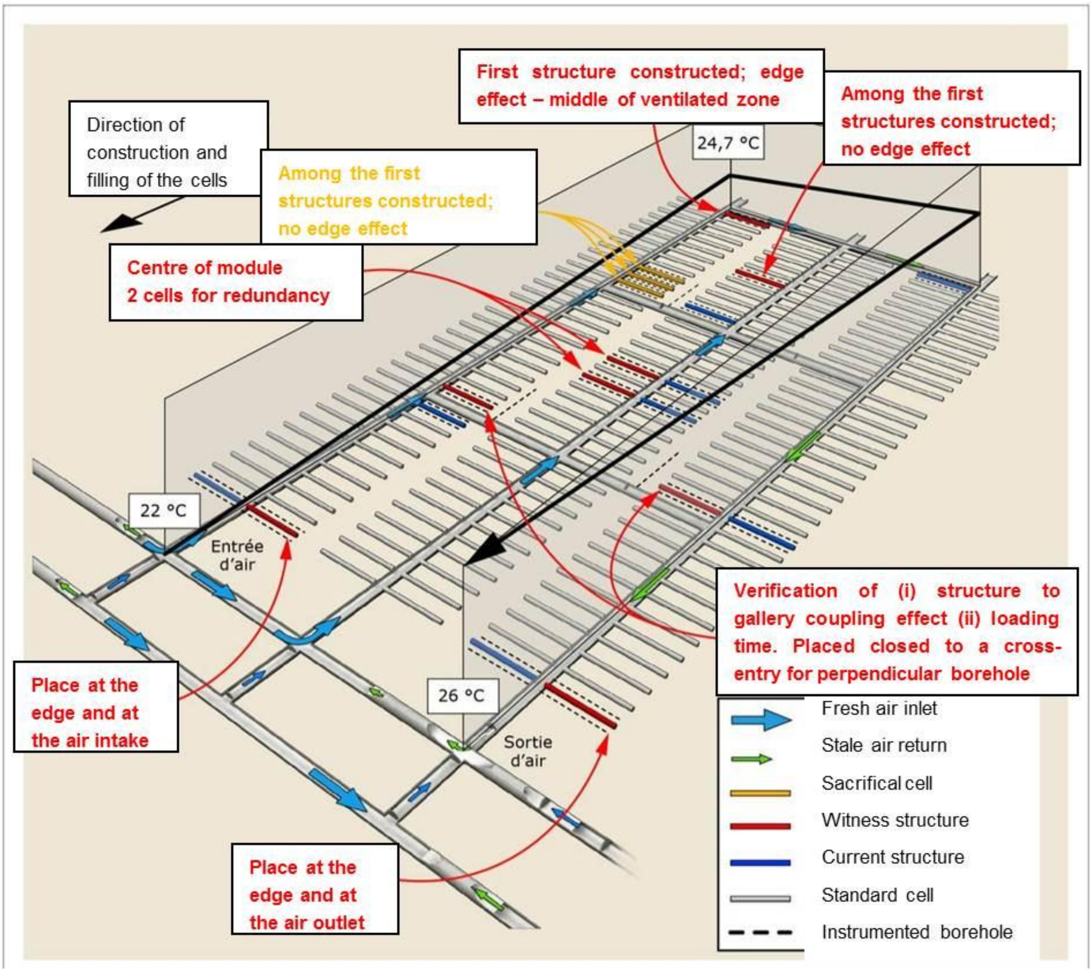


Figure 5-17: Example of the distribution of the instrumentation in an HLW module

Complementary techniques

While in-situ monitoring techniques will be reduced, monitoring in standard cells will be performed during occasional inspection and control, based on remote sensing. An example is corrosion monitoring techniques which are currently under development. To monitor the corrosion rate, complementary approaches are under development (Figure 5-18, Figure 5-19).

Figure 5-18: Corrosion specimen support with samples developed in CMHM URL in the MCO experiment

Figure 5-19: Wavemaker Pipe Testing Equipment is used in a wide variety of industrial environments and applications

The first technique makes use of corrosion monitoring specimens which have to be (i) produced from the same materials as the target element and (ii) installed on the sacrificial structure in such a way that realistic behaviour of the investigated structural element surface is simulated. Currently, a series of corrosion specimens is planned into sacrificial cells which are to be periodically withdrawn for physical (mass evaluation) inspection. For all the other structures, the use of non-destructive and non-intrusive techniques is promising. The Guided Waves Ultrasonic Technique provides an attractive solution to this problem because the waves can be excited at the cell entrance and will propagate many meters along the liner allowing screening corrosion detection. The technique is now applied for pipeline monitoring.

5.4.6 Is the design complete?

The final step is to evaluate whether the proposed design covers all the identified monitoring parameters. Even though not all of these may ultimately be required for the actual performance confirmation, it is considered relevant to propose viable approaches for each of the candidate parameters. Table 5-12 shows that with the developed strategy it is possible to provide a monitoring solution for identified relevant parameters.

Table 5-12: Monitoring parameters and related monitoring techniques

Component and surrounding influence	Process	Parameter	Proposed monitoring technique
Overpack material	Intrinsic material mechanical resistance	Stress (pressure, traction)	Verification on lab samples
		Strain	
	Intrinsic material corrosion properties	Corrosion under in-situ conditions	Indirect measurement (water and oxygen contents) with sampling lines Possibly verified by retrieving in-situ samples Many on-going developments for direct measurement
Overpack	Corrosion	Surface corrosion	Indirect measurement (water and oxygen contents) with sampling lines Possibly verified by retrieving sample canisters (sacrificial cells)
		Weld seam corrosion	
		Runner contact corrosion	
In-cell environment	Heat dissipation Water exchange from near field	Temperature	Pt100 and optical fibre sensors inside sacrificial cell. Remote sensing from clay temperature monitoring.
		Relative humidity	Instrumented plug
		Liquid water content	
	Gas exchange with access gallery	Oxygen concentration	Instrumented plug Many on-going developments for direct measurement (at least in sacrificial cells)
	Anoxic corrosion	Oxygen concentration	
	Radiolysis		
	Radiation	Irradiation rate	Sensing in sacrificial cell with optical fibres on the metallic liner (under development)
Cell liner	Thermo-mechanical loading	Temperature	Pt100 and optical fibre sensors on the liner
		Strain	VWS and OFS on the liner
	Radial mechanical loading	Total pressure at contact surfaces	
		Load source position (Detection of heterogeneous loading)	
	Deformation	Radial deformation	
	Transient to hydraulic equilibrium	Relative humidity	Instrumented plug Developments for sensors in the sacrificial cell (flexible instrumented blades)
		Hydraulic pressure	
Near field	Heat dissipation	Temperature	Pt100 and optical fibre sensors in boreholes
	Transient to mechanical equilibrium	Radial deformation	Extensometers in boreholes
	Resaturation	Water content	TDR and interstitial pressure cells in boreholes
		Interstitial pressure	

5.4.7 Key messages

Examples were given for the design of a monitoring system in an underground repository in claystone. They will be adapted to structure design evolutions and increasing knowledge (acquired in URL, for instance). They are intended to illustrate the recommendations and the monitoring strategy developed within the MoDeRn project.

Monitoring system design is based on prior knowledge of the underground repository evolution, both short- and long-term. This is mandatory for the monitoring system to be efficient, i.e., on the one hand, for sensors to be localised where variations will occur and, on the other hand, for the instrumentation to resist aggressive environmental conditions for decades. For the latter, qualification procedures are developed based on known environmental conditions.

It is illustrated why it is mandatory that the design of the monitoring system takes into account a variety of scales, temporal scale (long term versus operational scale) as well as spatial scales (focus on disposal cells then on disposal units). In addition, the limits of monitoring technology are illustrated and some solutions to bypass them are proposed, with the concept of “sacrificial cell” which is very similar with the “pilot facility” of other underground repository concepts.

Recommendations developed within this case study provide arguments in favour of distributing instrumented structures over the entire repository in order to ensure that representative information is provided for performance confirmation. The overall strategy proposes to decrease the instrumentation density with increasing knowledge and assurance gained from available performance confirmation.

6 Case III – Hard rock

6.1 Disposal Concept

6.1.1 Repository site

As Olkiluoto is an island in the Gulf of Bothnia (Figure 6-1), the area that has to be considered in the repository project consists of both land and sea, and because of post-glacial uplift, the expected long-term evolution is governed by the shoreline receding towards the west and the site gaining more inland characteristics over the next several thousand years. At present, Olkiluoto is mostly covered by forest, except at the western end of the island where the nuclear power plant lies. The topography is flat and the surrounding sea is shallow. Bedrock depressions are filled with a relatively thick layer of overburden (mainly till), but bedrock outcrops, glacially smoothed, are also common. Freshwater ecosystems are few in the area as there are no natural lakes in Olkiluoto.

The crystalline bedrock of Olkiluoto belongs to the Svecofennian Domain (developed between 1,930 and 1,800 million years ago) of the Precambrian Fennoscandian Shield and consists mainly of different gneisses and pegmatitic granites. The fault zones at Olkiluoto are mainly SE-dipping thrust faults originating from the latest stages of the Svecofennian orogeny. NE-SW-striking strike-slip faults are also common. Groundwater flow in the bedrock occurs mostly in hydraulically active deformation zones (hydrogeological zones) and in fractures. During the last 100,000 years, Olkiluoto has been alternately dry land, covered by a thick continental ice sheet, and under waters with salinities varying from fresh meltwater to notably saltier than the present brackish Baltic Sea. Due to this diverse history, the chemistry of the fracture groundwater and the stagnant matrix porewater is quite complex, characterised by a relatively layered system with a significant range in salinity.

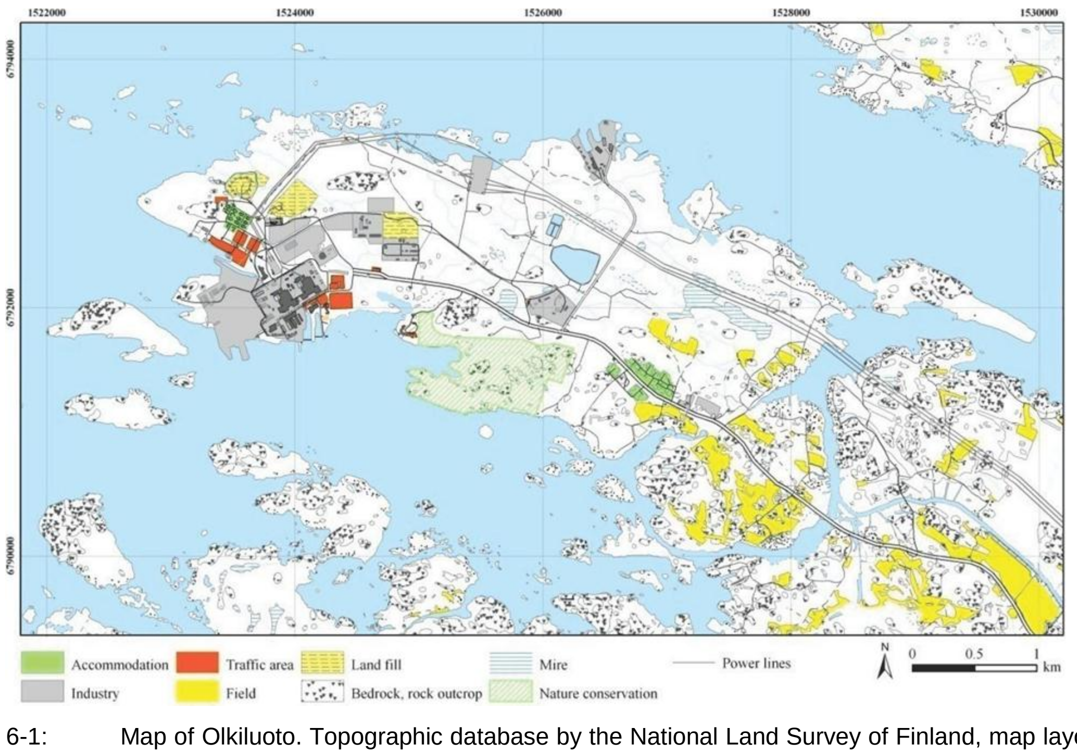


Figure 6-1: Map of Olkiluoto. Topographic database by the National Land Survey of Finland, map layout by Jani Helin/Posiva Oy. (Hjerpe, Ikonen, and Broed, 2010)

Figure 6-2 shows a conceptual drawing of the completed disposal facility in its projected extent. The layout of the tunnels containing the disposal boreholes is based on the maximum capacity of 9,000 tU of spent fuel, which is the amount allowed by the decisions-in-principle of the Government. They take into account the spent fuel from the four currently operational nuclear power plants in Finland, the one under construction, as well as the planned fourth reactor unit in Olkiluoto. This amount, corresponding to 4,500 canisters, is also the figure considered in the present Safety Case.

In Figure 6-2, the spiralling ramp and the vertical shafts constitute the main parts of the ONKALO together with some of the halls and tunnels near the lower end of the shafts. The panels of the tunnels that grant access to the disposal boreholes can only be excavated after the construction licence for the actual repository has been granted, and their final layout is still to be decided on the basis of rock properties, required capacity, disposal method, and other factors.

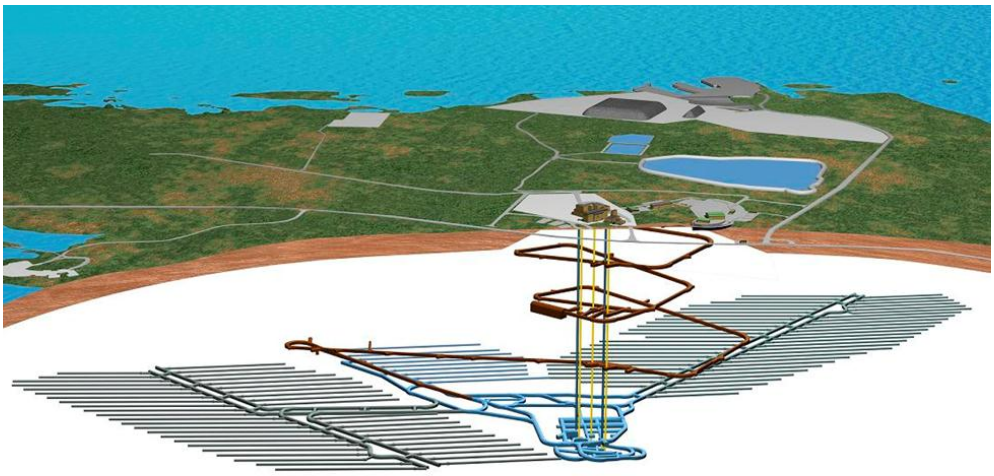


Figure 6-2: Conceptual drawing of the repository beneath the central part of Olkiluoto, approximately at the size needed. The encapsulation plant is located on the surface at the upper end of the vertical shafts.

6.1.2 Components of the disposal system and their safety functions

The current reference disposal method of Posiva is KBS-3V. Spent nuclear fuel held inside whole fuel assemblies is encapsulated in canisters made of cast iron and copper. The canister is emplaced in a vertical borehole (KBS-3V) in crystalline bedrock hundreds of meters below surface and surrounded by a buffer of compacted bentonite (Figure 6-3).

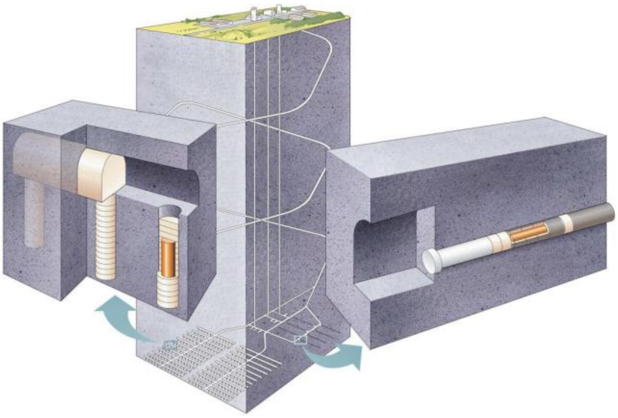


Figure 6-3: The two alternative disposal methods: KBS-3V (on the left) and KBS-3H (on the right).

According to the safety concept, safe disposal is achieved primarily by long-term isolation and containment of the nuclear waste using multiple barriers until the waste no longer poses a risk, and secondarily, by ensuring that in the unlikely event of an early canister failure, safety is maintained by limiting and retarding the release and transport of radionuclides. Each component of the barrier system has one or several safety functions which describe its role in achieving the general goal of safe disposal.

The barriers and their safety functions are (Posiva, 2012b):

Canister:
- To ensure a prolonged period of complete containment of the spent fuel

Buffer:
- to contribute to mechanical, geochemical, and hydrogeological conditions that are predictable and favourable to the canister
- to protect canisters from external processes that could compromise the safety function of complete containment of the spent fuel and associated radionuclides
- to limit and retard radionuclide releases in the event of canister failure

Backfill and plugs for tunnels granting access to the disposal boreholes:
- to contribute to favourable and predictable mechanical, geochemical, and hydrogeological conditions for the buffer and canisters
- to limit and retard radionuclide releases in the event of canister failure
- to contribute to the mechanical stability of the rock adjacent to the tunnels

Closure:
- to prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats of humans, plants, and animals
- to contribute to favourable and predictable mechanical, geochemical, and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water-conductive flow paths through the openings
- to limit and retard inflow into and release of harmful substances from the repository

Host rock:
- to isolate the spent nuclear fuel repository from changing conditions on the surface and from the surface environment and normal habitats for humans, plants, and animals
- to limit the possibility of human intrusion
- to provide favourable and predictable mechanical, geochemical, and hydrogeological conditions for the previous barriers,
- to limit transport and retard the migration of harmful substances that could be released from the repository

The first four barriers constitute the engineered barrier system (EBS). The closure comprises the structures and materials that will eventually be used to close and seal all the underground openings of the repository (other than disposal holes and tunnels), including backfill and plugs in central tunnels, access tunnels, shafts, and other excavated spaces, and seals in investigation boreholes. It is worth noting that the surface environment (biosphere) does not have safety functions and is in that respect different from the other systems discussed in this report.

On the basis of the rather general safety functions listed above, a more detailed set of requirements has been defined for each barrier, in terms of quantitative parameters when possible. These are called the performance targets of the engineered barriers, or target properties in the case of the host rock. Some of the numerical values of quantities are still under consideration.

The performance targets of the **canister** are to:
- be initially intact and remain so for hundreds of thousands of years
- withstand corrosion in the expected repository conditions

- withstand the expected mechanical loads in the repository
- remain subcritical (with respect to self-sustained chain reaction of nuclear fissions in the spent fuel) in all postulated operational and repository conditions including intrusion of water through a damaged canister wall
- not impair the safety functions of other barriers

It is also required that canisters are stored, transferred, and emplaced in a way that the copper shell is not damaged, and that their design facilitates the retrievability of spent fuel assemblies from the repository.

The performance targets of the bentonite **buffer** are to:
- mitigate the impact of rock shear on the canister
- limit microbial activity
- be impermeable enough to limit the transport of radionuclides from the canister into the bedrock
- be impermeable enough to limit the transport of corroding substances from the rock onto the canister surface
- limit the transport of radio-colloids to the rock
- provide support to the walls of the disposal borehole to mitigate potential effects of rock damage
- keep the canister in the correct position and prevent sinking and tilting
- transfer the heat from the canister efficiently enough to keep the buffer temperature below +100°C
- allow gases to pass through it without causing damage to the repository system
- have a limited content of substances that could adversely affect the canister, backfill, or rock
- preserve required properties in repository conditions over hundreds of thousands of years

In order to meet these requirements, the bulk hydraulic conductivity of the buffer may not exceed 10-12 m/s, and the swelling pressure must reach 2 MPa. Essentially, all performance targets are met if the saturated density of bentonite lies between 1900 and 2050 kg/m^3.

The performance targets of the **backfill** in the tunnels granting access to the disposal boreholes are to:
- limit advective flow along the tunnels
- keep the buffer in place
- contribute to the mechanical stability of the tunnels
- contribute to preventing the uplifting of the canister in the disposal borehole

During the operational phase of the repository, the **plugs** are required to:
- hydraulically isolate the tunnels granting access to the disposal boreholes
- keep the backfill in place

The performance targets of the **closure** are to:
- prevent unintentional human intrusion through the closed volumes. Retrieval of the spent fuel canisters shall, however, remain technically feasible.
- restore the favourable, natural conditions of the bedrock as well as possible
- prevent the formation of preferential flow paths and transport routes between the surface and the tunnels and boreholes

In addition, all components of the repository 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. A general requirement of the **host rock** states that the repository shall be located at a minimum depth of 400 metres. The target properties of the host rock, mainly concerning the near field of the repository, are:

groundwater flow and solute transport:
- under saturated conditions, flow per fracture width in a fracture
- intersecting a disposal borehole shall be at most in the order of 1 L/(m·year) for most of the boreholes
- inflow of groundwater to the tunnels shall be limited
- migration paths in the vicinity of the disposal borehole shall have a transport resistance *WL/Q* higher than 104 years/m for most of the disposal boreholes and at least a few thousand years/m
- properties of the host rock shall be favourable for matrix diffusion and sorption

chemical composition of groundwater at the repository level:
- reducing conditions: no dissolved oxygen shall be present after the initially entrapped oxygen in the near field has been consumed
- pH between 6 and 10 (up to 11 due to degrading cement allowed in the initial phase)
- initial ionic strength of more than 4 mM in terms of charge equivalent of cations
- salinity in terms of total dissolved solids below 35 g/litre in the future expected conditions; salinities up to 70 g/litre can be accepted during the initial transient caused by construction
- low content of solutes that are detrimental to the EBS: concentrations of HS−, K+, Fe-total, NO2 −, NO3 −, NH4 +, and acetate CH3CO2 − limited, and [Cl−]<2 mol/L
- low amount of dissolved CH4 H2, and S_{total}
- low colloid and organic matter content

mechanical stability:
- likelihood of a shear displacement exceeding 5 cm in fractures intersecting a disposal borehole at the height range of the canister shall be low

6.2 General process screening

Processes occurring inside the copper canister cannot be monitored because the overpack must be kept intact. Moreover, it is reasonable to assume that even if some canisters corroded much faster than expected, none of them would breach during the monitoring period of 100 years at most. Thus, the processes start only after the loss of canister integrity can be ignored in the monitoring programme. Based on these arguments, heat generation from radioactive decay and the highly penetrating gamma and neutron radiation are the only canister processes that are relevant to the monitoring programme. Also, the position of the canister with respect to the emplacement borehole could be considered as an indicator of the behaviour of the surrounding bentonite buffer.

As to the processes within the bentonite buffer and tunnel backfill, mineralogical alteration can safely be assumed to occur too slowly to be detected within any conceivable monitoring period. Meanwhile, water uptake and resulting swelling are essential processes that bring the barrier system from its initial state towards the intended target state during the years or decades during which monitoring is possible. The related processes of desirable self-sealing and, on the other hand, detrimental mechanical erosion are also relevant. As with the buffer and backfill, mineralogical changes in the host rock or alteration of fracture fillings can be deemed too slow to be monitored, but all other geosphere processes are relevant for the programme: Isostatic uplift as well as horizontal tectonic movement, development of rock stress, induced displacements, and phenomena related to the formation of an excavation damaged zone, such as spalling.

A significant part of the processes and target properties of the host rock concern the composition and chemistry of groundwater. Therefore, it is evident that hydro-geochemical monitoring must have an important and well-defined role in the programme. Relevant chemical characteristics to be monitored include: overall salinity, pH, redox state, microbes, colloids, and concentrations of

- various ions (Mg^{2+}, Ca^{2+}, K^{+}, HS^{-}, NH_4^{+}, Cl^{-}, $Fe^{+2/+3}$ etc.)
- nitrates and other organic compounds
- dissolved gases (oxygen, radon, methane)

These provide information on processes like chemical rock-water interaction, excavation-induced movement of deep saline groundwater and release of matrix porewater, and influence of foreign materials.

Among the migration processes, there are only a few that actually can be monitored, but the hydro-geochemical monitoring is likely to provide indirect information on both actual and potential migration processes. Groundwater flow, which affects advection of substances as well as saturation of bentonite, depends on the hydrological state of the repository. This state can be monitored by observing, for example, the hydraulic head, flow rates, and inflow.

6.3 Environmental impact

Remark: "Although the focus of the MoDeRn project is on monitoring disposal activities, monitoring for environmental impact is described here, since it is addressed in the Finnish case".

In addition to monitoring the processes related to the long-term safety of the repository or its capability of isolating the radioactive waste, monitoring has to gather information on the more conventional environmental impact of the construction and operation of the facility. The aforesaid treatments present some processes that affect the surface environment but have no significant effect on repository performance. These include perturbation of surface hydrology such as drawdown of water table, or ground subsidence resulting from hydraulic processes at depth, and redistribution of rock mass by bringing the blasted rock to the surface and subsequent leaching of rock spoil by surface waters, potentially releasing naturally occurring radionuclides or other pollutants into the biosphere. All these processes can induce different kinds of modifications of the surface ecosystem.

A more extensive analysis of conceivable environmental effects of the entire repository project has been made in the framework of the Environmental Impact Assessments (EIA), a process required by law. Posiva has issued two EIA Reports (Posiva 1999 and 2008), which discuss the following aspects:

- Emissions and concentrations of radioactive materials, radiation dose rates, and impacts on human health. Weather data and numerical simulations based on them are needed to estimate the radiological impact because it is expected to be much smaller than the natural radioactivity.
- Radiation effects in the environment. Baseline concentrations in air, water, soil, agricultural products, gathered products and game, and other organisms need to be determined before the operation of the repository starts.
- Noise, dust, and other non-radioactive emissions from traffic and the storage and crushing of blasted rock.
- Groundwater table level around the rock facilities and the distribution of vegetation in the potential groundwater impact area.
- Impact of the buildings and other structures constituting the repository on land use, cultural heritage, and landscape.
- Production and management of conventional and nuclear waste.
- Utilisation of natural resources.
- Image of the municipality of Eurajoki.

- Occurrence of radiation fears in the public.
- Socio-economic impacts.

Furthermore, Posiva has an environmental programme to which monitoring should provide data concerning two aspects:
- Amounts and properties of water leaking into underground rooms. The water is brought to the surface by first pumping it into clarification basins and then allowing it to flow into the sea through a ditch.
- Releases from the storage of blasted rock which may be in the form of dust in the air or substances either dissolved or suspended in surface waters.

6.4 Identified processes and parameters

Excavated space filled with air at atmospheric pressure is a significant perturbation to the natural state of the geosphere, especially to hydrology at depth. Ingression of water will continue until the backfilled repository is completely saturated and leads to a decrease of hydraulic head and groundwater flow towards the repository from a substantial volume of rock, both above and beneath. This flow may result in an evolution of groundwater salinity distribution such that highly saline water from greater depths rises to the repository level, or to the release of rock matrix fluids that would otherwise remain stagnant. The exposure to atmospheric O_2 and CO_2 in the tunnels and possible drawdown of shallow meteoric groundwater causes carbonation and oxidation of groundwater, and the decrease of pressure to degassing or exsolution of other gases, like methane, dissolved in the groundwater. Degassing of the rock mass itself is also possible (radon being the main concern because of the radiological hazard to personnel) as well as aeration of rock mass which means that water in pores and fractures is replaced with air. These and a number of other processes expected to occur in response to the construction of the ONKALO were listed and assessed by Miller *et al*. (2002) to identify the monitoring targets for the previous monitoring programme. Their list of processes is presented in Table 6-1 and Table 6-2, with each process rated as having either high, medium, or low significance to repository performance and site understanding. The tables also indicate how the monitoring of processes has been dedicated to the disciplines of the monitoring programme: rock mechanics (RM), hydrology (Hy), chemistry (Ch), surface environment (SE), and foreign materials (FM). Some processes are not included in the monitoring programme for the following reasons:

- Some processes are considered unfeasible to monitor (marked “unfeas.”) either because they are extremely slow or, in the case of EDZ development (process P1), occur instantaneously and then essentially stabilize.
- Monitoring of air temperature in the tunnels and of gases in the groundwater will start in “coming” years when the progress in construction work allows the installation of a measuring system for air temperature, and suitable equipment becomes available for sampling gases in groundwater.
- Sinking of satellite boreholes is a “human” activity instead of a physical phenomenon.
- Processes that are of low significance (“low sig.”) to both site understanding and repository performance are not specifically monitored. The redistribution of rock mass, while having a medium significance to site understanding, has also been decided to be included in this category. (Leaching from rock spoil, however, is monitored because of its possible environmental effects.)
- Some of the identified processes in solid materials are monitored “indirectly” by studying the groundwater they interact with.

The magnitudes of various effects have later been assessed by Vieno *et al*. (2003), in some cases by numerical simulations. Comments and refinements on the process list of Miller *et* *al*. have been presented by Alexander and Neall (2007). These sources concentrate on induced changes in the geosphere and in the surface environment, whereas the Process Report by Miller and Marcos (2007) and the Review of Research and Development TKS-2009 (Posiva 2010) also discuss processes in the disposed of spent fuel itself and in the engineered barrier system (EBS). Both aspects, alteration of the surroundings and evolution of the waste and EBS, are significant for the long-term safety of the repository and, therefore, need to be taken into account in the monitoring programme. In the 2012 update of the Process Report, the treatment is expanded to cover features, events, and processes (FEPs), also in the surface environment. The FEPs have been selected through a screening process from an extensive FEP database on the basis of whether they are "considered potentially significant for the long-term safety of the disposal facility" (Posiva, 2012b).

Table 6-1: Physical and hydrogeological processes resulting from the construction of ONKALO compiled by Miller et al. (2002) and their significance to site understanding and repository performance (Low / Medium / High).

Process number	Process name	Site	Perform	Discipline	Why out
Physical processes:					
P1	Development of an excavation damaged zone (EDZ)	H	H		unfeas.
P2.1	Evolution of the fracture network: Reactivation of existing fractures	H	H	RM	
P2.2	Evolution of the fracture network: Generation of new fractures	H	H	RM	
P3	Aeration of the rock mass	H	M		unfeas.
P4	Planned introduction of foreign fluids	H	L	FM	
P5	Planned introduction of foreign solid materials	H	H	FM	
P6	Microseismicity	M	L	RM	
P7	Sinking of satellite boreholes	H	M		human
P8.1	Temperature changes: in the rock mass	L	L	RM	
P8.2	Temperature changes: in the groundwater	M	L	Hy	
P8.3	Temperature changes: in the air	M	L		coming
P9	Degassing of groundwater	M	M	Ch	coming
P10	Ground subsidence	L	L		low sig.
P11	Isostatic uplift	M	H	RM	
P12	Inadvertent introduction of foreign substances	M	L	FM	
P13	Degassing of rock mass	L	L		low sig.
Hydrogeological processes:					
H1	Evolution of hydraulic network	H	H	Hy	
H2	Evolution of hydraulic heads	H	H	Hy	
H3	Evolution of fracture properties	H	H	Hy	
H4	Ingression of water	M	L	Hy	
H5	Egression of water	M	L	Hy	
H6	Density-driven flow	H	H	Hy	
H7	Release of rock matrix brines	M	L	Ch	
H8	Seismic pumping	M	L	Hy	
H9	Perturbation of the hydrology	M	L	Hy	
H10	Evolution of the saline water interface	H	H	Hy+Ch	

Table 6-2: Geochemical and biological processes resulting from the construction of ONKALO compiled by Miller et al. (2002) and their significance to site understanding and repository performance (Low / Medium / High).

Process number	Process name	Site	Perform	Discipline	Why out
Geochemical processes:					
Solids:					
GS1	Redistribution of rock mass	M	L		low sig.
GS2	Evolution of fracture-coating materials	H	H		unfeas.
GS3	Evolution of rock matrix	H	H		unfeas.
GS4	Maturation of cement	L	L		low sig.
GS5	Degradation of cement	M	M		indirect
GS6	Cement-rock interaction	M	L		indirect
GS7	Ageing of minerals and mineraloids	M	M		unfeas.
GS8	Degradation of metallic components	L	L		low sig.
GS9	Degradation of resins and plastics	L	L		low sig.
GS10	Leaching of rock spoil	H	L	SE	
GS11	Degradation of inadvertently introduced foreign solids	L	L		low sig.
Liquids:					
GL1	Influences of groundwater mixing	H	M	Ch	
GL2	Influences of water-rock interactions	H	M	Ch	
GL3.1	Influences of introduced air: Oxidation of groundwater	H	M	Ch	
GL3.2	Influences of introduced air: Carbonation of groundwater	H	M	Ch	
GL4	Influences of degrading cement	M	M	Ch	
GL5	Influences of microbial activity	H	M	Ch	
GL6	The influences of temperature changes	M	L	Ch	
GL7	Influences of planned introduced fluids	H	L	Ch	
GL8	Influences of degrading metallic components	L	L	Ch	
GL9	Influences of degrading resins and plastic components	M	L	Ch	
GL10	Influences of inadvertently introduced foreign materials	L	L	Ch	
Gases:					
GG1	Exsolution of gases	M	M	Ch	coming
GG2	Introduction of gases from machinery	L	L		low sig.
Biological processes:					
B1	Perturbation of microbiological populations	H	M	Ch	
B2	Perturbation of microbiological activities	H	M	Ch	
B3	Biodegradation	H	M	Ch	
B4	Biocatalysis	M	L	Ch	
B5	Biofilm growth	M	L	Ch	
B6	Biocolloid formation	M	L	Ch	
B7.1	Floral colonisation of the tunnel	L	L		low sig.
B7.2	Faunal colonisation of the tunnel	L	L		low sig.
B8	Modification of the surface ecosystem	L	L	SE	

Table 6-3 presents the processes in (Posiva 2012b) related to the evolution of the engineered barrier system, and Table 6-4 the processes (and one feature) related to the migration of substances within it. The list of processes starts from the spent fuel itself, where actinides, unstable fission products, and activation products go through a series of radioactive decays, the rate of which only depends on the isotope. Energy is released mostly as kinetic energy of the emitted alpha and beta particles and is absorbed by the canister materials and transformed into heat. A small fraction of the energy is radiated out of the canister in the form of gamma and neutron radiation despite effective attenuation of the radiation by canister metal. Alpha decays also give rise to the production of helium gas.

Table 6-3: Processes of significance to the long-term safety and related to the evolution of the engineered barrier system by (Posiva 2012b)

FEP No.	FEP name	
Spent fuel evolution		
3.2.1	Radioactive decay	
3.2.2	Heat generation	
3.2.3	Heat transfer	
3.2.4	Structural alteration of the fuel pellets	
3.2.5	Radiolysis of residual water (in an intact canister)	
3.2.6	Radiolysis of porewater	
3.2.7	Corrosion of the cladding tubes and metallic parts of the fuel assembly	
3.2.8	Alteration and dissolution of the fuel matrix	
3.2.9	Release of the labile fraction of the inventory	
3.2.10	Production of helium gas	
Canister evolution		
4.2.1	Radiation attenuation	
4.2.2	Heat transfer	
4.2.3	Deformation	
4.2.4	Thermal expansion of the canister	
4.2.5	Corrosion of the copper overpack	
4.2.6	Corrosion of the cast iron insert	
4.2.7	Stress corrosion cracking	
Buffer and backfill evolution		
5.2.1	6.2.1	Heat transfer
5.2.2	6.2.2	Water uptake and swelling
5.2.3	6.2.3	Piping and erosion
5.2.4	6.2.4	Chemical erosion
5.2.5	-	Radiolysis of porewater
5.2.6	6.2.5	Montmorillonite transformation
5.2.7	6.2.6	Alteration of accessory minerals
5.2.8	6.2.7	Microbial activity
-	6.2.8	Freezing and thawing
Auxiliary components evolution		
7.2.1	Chemical degradation	
7.2.2	Physical degradation	
7.2.3	Freezing and thawing	

In leaking fuel rods, where atmospheric gases and cooling water can get trapped despite the drying and evacuation procedures during encapsulation, intense radiation gives rise to radiolysis of water and atmospheric gases and production of nitric acid. Structural alteration of the fuel pellets and fuel cladding due to ionising radiation, temperature gradients, accumulation of helium gas, mechanical stresses, and other reasons, starts already in the reactor and continues throughout transport, interim storage, and encapsulation. Radiolysis of water and other direct consequences of ionising radiation have a smaller spatial extent than the heat because of rapid attenuation of radiation in solids and water.

The copper overpack will start to corrode immediately after manufacture through reaction with air, and further after emplacement as it comes into contact with groundwater. The process is, however, expected to proceed very slowly. No significant corrosion of the iron insert and the fuel assembly is conceivable before the overpack is breached and water intrudes the canister. When that occurs, internal corrosion products which have a lower density and, therefore, occupy more space than the original metallic components, may cause deformation of the canister or clogging of pathways. Eventually, when groundwater gets inside the fuel rods, dissolution of the fuel matrix and release of the labile fraction of the inventory starts with dissolution rates ranging from instantaneous to extremely slow depending on species.

Groundwater and bentonite buffer surrounding the emplaced canister exert a substantial pressure on it – the hydrostatic pressure alone is about 4 MPa. This causes plastic deformation of the copper overpack, which eventually closes the small annular gap between the overpack and the iron insert. Another reason for deformation of the canister is thermal expansion and later contraction. On the outer surface of the canister, deposition of salts is possible as temperature variation changes their solubilities.

Other engineered barriers include the bentonite buffer and the tunnel backfill. In addition to them, the repository will contain auxiliary components such as plugs and seals in tunnels and boreholes, and grout, which are not considered part of the barrier system but may have an effect on its evolution.

Perhaps the most critical process affecting the performance of the engineered barriers, at least among those processes that are expected to occur during the operational period, is the water uptake into the buffer and backfill. It starts when unsaturated bentonite (and other clay) comes into contact with groundwater, and continues until the water-absorbing clays have saturated and hydraulic gradients have relaxed. Wetting of bentonite gives rise to swelling and development of swelling pressure when there is no more free space to swell into. The desired consequence of swelling is a process of homogenisation and self-sealing of the buffer and backfill materials. On the other hand, intrusion of bentonite into fractures in the surrounding rock or advection with flowing groundwater in the wetting phase may cause unwanted mass redistribution.

Two possible mechanisms of erosion of bentonite or backfill material have been identified: piping and chemical erosion due to very dilute waters. The former process occurs before saturation, if groundwater flows strongly enough to form conductive channels through the clay. The latter is considered possible at the proposed repository depth at Olkiluoto only in case meltwater intrudes in the final stages of a glacial period.

Chemical processes within other engineered barriers include montmorillonite transformation and alteration of accessory minerals and impurities. Among the transformation processes that montmorillonite could undergo, illitisation has been identified as the most important, possibly together with reactions with dissolved iron originating from corroded iron insert in the case of breached canister. However, if the temperature remains below 100°C and groundwater composition within the defined limits, transformation of montmorillonite will not affect repository performance significantly. The effect of alteration of accessory minerals and impurities is also expected to be negligible.

Chemistry of groundwater around the repository and within the EBS will inevitably be influenced by foreign materials that, although they do not belong to the engineered barriers, are introduced in the repository either on purpose (“engineering materials”) or inadvertently (“stray materials”). Most of the engineering material will consist of cement used e.g. for grouting of fractures, as shotcrete, in tunnel plugs and borehole seals, and other necessary structures. Degradation of cementitious materials due to radiation, thermal effects, and reactions with groundwater generates very alkaline leachates that may endanger buffer performance by enhancing erosion and mineral transformation. Other types of engineering materials include drilling fluids and metallic components like rock bolts and support meshes, whereas conceivable stray materials range from exhaust fumes, soot, and oils from machinery to organic waste and litter left by humans. The estimated amounts of different kinds of materials permanently left in the repository vary over a wide range, as well as their anticipated effects.

Table 6-4: Processes (and feature) related to migration within the EBS by (Posiva 2012)

FEP number					FEP name
Fuel	Canister	Buffer	Backfill	Auxiliary	
3.3.1	4.3.1	5.3.1	6.3.1	7.3.1	Aqueous solubility and speciation
3.3.2	4.3.2	5.3.2	6.3.2		Precipitation and co-precipitation
3.3.3	4.3.3	5.3.3	6.3.3		Sorption
3.3.4	4.3.4	5.3.4	6.3.4		Diffusion
	4.3.5	5.3.5	6.3.5		Advection
	4.3.6	5.3.6	6.3.6		Colloid transport
	4.3.7	5.3.7	6.3.7		Gas transport

Migration of radionuclides is, of course, a crucial issue for the safety of the repository, but of equal importance is the presence and mobility of other substances that facilitate the corrosion of the canister, impair the properties of the bentonite buffer, or are otherwise unfavourable to the safety functions of the barrier system. Most migration processes can occur in all components of the EBS (see Table 6-4) but advection, colloid transport, or gas transport, are not considered possible in the fuel where there are no open spaces.

Before the radioactive material in the canister can start to migrate after the failure of the copper overpack, it has to dissolve into the groundwater, which depends on aqueous solubility and speciation. Where there are wide cavities, gaps, or openings, the dissolved material, whether radionuclides from the spent fuel or other substances of interest, can be transported in groundwater by advection, but particularly in the bentonite buffer and backfill developed according to their performance targets, diffusion is the only effective transport mechanism. Diffusion occurs in all other components of the repository as well, from the fuel pellets to the host rock matrix. Most released radionuclides are effectively retained by sorption on solid surfaces and, in principle, by precipitation and co-precipitation, although their concentrations are assumed to be too low for new solid phases to appear. It is conceivable that gas phases of e.g. hydrogen, helium, or methane form at some stage of the evolution of the repository, giving rise to gas transport, which can either facilitate or inhibit migration of radionuclides or other significant substances. Colloid formation and transport are unwanted processes that may occur, for example, as a consequence of excessive flow of groundwater in contact with bentonite.

Processes occurring inside the copper canister are difficult to monitor because the overpack must be kept intact. Moreover, it is reasonable to assume that even if some canisters would corrode much faster than expected, none of them will be breached during the monitoring period of at most 100 years. Thus, the processes start only after the loss of canister integrity can be ignored in the monitoring programme. Based on these arguments, heat generation from radioactive decay and the highly penetrating gamma and neutron radiation are the only canister processes that are relevant to the monitoring programme. Also, the position of the canister with respect to the disposal borehole could be considered as an indicator of the behaviour of the surrounding bentonite buffer.

As to the processes within the bentonite buffer and tunnel backfill, mineralogical alteration can safely be assumed to occur too slowly to be detected within any conceivable monitoring period. Meanwhile, water uptake and resulting swelling are essential processes that bring the barrier system from its initial state towards the intended target state during the years or decades during which monitoring is possible. The related processes of desirable self-sealing and, on the other hand, detrimental mechanical erosion are also relevant.

A list of FEPs related to the geosphere and considered to be significant for the long-term safety is given in Table 6-5 (Posiva, 2012). For many of the listed issues, there is a corresponding process in the list of Miller et al. (2002). Five of these FEPs have been decided to be included in the rock mechanics (RM) programme, three in the hydro-geochemical programme (Ch) and one, groundwater flow, in the hydrogeological programme (Hy). The remaining FEPs are not included in the monitoring programme for the following reasons:

- Glacial processes can only occur after several millennia.
- Erosion is considered to be too slow to monitor.
- It is more reasonable to study most of the migration-related issues in the laboratory (lab) instead of monitoring.

Table 6-5: Geosphere FEPs, responsible monitoring disciplines, reasons for not monitoring the FEP, and corresponding processes in Miller et al. (2002)

FEP no.	FEP name	Discipline	Why out	Miller 2002
	Evolution processes			
8.2.1	Heat transfer	RM		P8
8.2.2	Permafrost formation		glacial	
8.2.3	Stress redistribution	RM		related to P2
8.2.4	Reactivation-displacements along existing fractures	RM		P2.1
8.2.5	Spalling	RM		
8.2.6	Creep	RM		
8.2.7	Erosion and sedimentation in fractures		slow	GS2
8.2.8	Rock-water interaction	Ch		GL2
8.2.9	Methane hydrate formation		glacial	
8.2.10	Salt exclusion		glacial	:
8.2.11	Microbial activity	Ch		B1, B2, GL5
	Migration feature			
8.3.1	Aqueous solubility and speciation		lab	
	Migration processes			
8.3.2	Precipitation and co-precipitation		lab	
8.3.3	Sorption		lab	
8.3.4	Diffusion and matrix diffusion		lab	
8.3.5	Groundwater flow	Hy		H1
8.3.6	Colloid transport	Ch		
8.3.7	Gas transport		lab	

Transfer of heat generated by nuclear reactions in the spent fuel obviously concerns the entire repository, with an effect diminishing with increasing distance from the fuel. Thermal expansion of rock increases mechanical stress and may cause spalling or other deformation, particularly on the walls of the disposal boreholes (or drifts) where the heating is most intense and the thermal gradient is steepest. Moreover, temperature is a crucial factor in many other processes, especially chemical ones, significant to the repository performance. The development of the temperature field depends on the thermal power produced in each canister, on the repository layout, and on the capability of various components to conduct heat into the surrounding rock mass.

The creation of open spaces in the rock causes stress redistribution which may lead to reactivation-displacements of existing fractures or even creation of new fractures. Stress concentrating on exposed rock surfaces and blasting is known to generate an excavation damaged zone (EDZ) in the rock and cause spalling, which, in turn, affects the hydraulic conductivity in the near field. The much slower process of rock creep also deforms the geosphere. Processes of a more chemical nature in the geosphere may also be initiated by the increase of groundwater flow and perturbations of groundwater chemistry near the repository. Erosion and sedimentation in fractures can change the hydraulic properties of the host rock, and rock-water interaction potentially affects the retention capability of the rock and its buffering capacity against changes in acidity and redox state. All these processes potentially contribute to the evolution of the hydraulic network.

Microbial activity is a process common to almost all components of the repository. The natural microbial populations are likely to be perturbed by the construction and operation of the repository, and to have an influence on its performance through their role in chemical processes. In particular, microbes contribute significantly to the restoration of reducing hydrochemical conditions after closure by consuming oxygen.

Several millennia after the closure of the repository, the average atmospheric temperature at the site is assumed to decrease to a level at which first permafrost and later a continental ice sheet start to form. If the temperature at the depth of the repository decreases sufficiently, freezing of groundwater occurs in the buffer and backfill. Even if permafrost will not reach the repository level, exclusion of salt from groundwater turning into ice closer to the surface may lead to increasing concentrations of dissolved solids. If the groundwater is supersaturated with methane, decrease of temperature together with the high pressure may lead to the formation of solid methane hydrate.

6.5 Identified parameters

The following tables give an overview of the identified parameters characterizing the processes described in the previous chapter. The parameters have been structured into mechanical, hydrological, and hydro-geochemical parameters related to the host rock as well as parameters related to the engineered barriers (EBS).

Table 6-6: Parameters for monitoring mechanical parameters

Objectives						**Process**	**Targets**	**Overlap, comments**
1: Long-term safety	2: Site characterisation and modelling	3: Environmental impact	4: Feedback constructors and design	5: EBS performance	6: Compulsory radiological monitoring			
X	X		X			Stress redistribution	Displacements, and stress (orientation, magnitude)	
							Visual observations	
							Microseismic activity	
X	X					Reactivation of existing fractures / zones, formation of new fractures	Microseismic activity	
							Displacement in fractures/fracture zones	Changes in fracture aperture and observed fracture slips possibly affect hydraulic properties
							Visual observations	
X	X		X			Rock creep	Rock displacements	
							Visual observations	
							Loads in rock bolts	
X	X		X	X		Spalling	Visual observations	
							MS-monitoring	
X	X	X		X		Rock temperature evolution	In situ temperature measurements	Flow log measurements and geophysics
							Temperature monitoring	
X	X	X				Isostatic uplift/bedrock stability	Rate of regional land uplift	
							Relative uplift	
X	X					Tectonic bedrock movements	Horizontal displacements	
X	X					Seismicity	Magnitudes, locations, slips and source radii of seismic events	

Table 6-7: Parameters for monitoring hydrological parameters

Objectives: 1: Long-term safety	2: Site characterisation and modelling	3: Environmental impact	4: Feedback constructors and design	5: EBS performance	6. Compulsory radiological monitoring	Process	Targets	Overlap, comments
X	X	X	X			Evolution of groundwater table	Groundwater level in boreholes and groundwater observation tubes	
X	X		X			Evolution of groundwater flow	Flow in/out/across boreholes	
X	X		X			Evolution of hydraulic properties in the bedrock and the overburden	Flow and transmissivity of fractures in boreholes	
							Hydraulic conductivity in observation tubes	
							Pressure responses due to field activities and inflow into tunnels	
X	X		X			Evolution of hydraulic head	Hydraulic head in open and packed-off boreholes (fresh water head)	
X	X		X			Inflow into tunnels	Total inflow into the ONKALO	
							Inflow at measuring weirs	
							Individual leakage points	
							Leakages in shafts	
							Visual mapping of leakages	
							Air flow and humidity	
							Amount of technical water used	
X	X		X			Evolution of groundwater salinity distribution	EC of drill hole water	Hydro-geochemistry
							EC of fracture water	
							Salinity of water samples	
X	X					Influence of Korvensuo reservoir	Korvensuo water level	environment
							Water table and hydraulic conductivity in seepage tubes of the dam	
	X	X				Perturbation of surface hydrology	Groundwater table, runoff, infiltration, sea level, ground frost, precipitation	environment

Table 6-8: Parameters for monitoring hydogeochemical parameters

1: Long-term safety	2: Site characterisation and modelling	3: Environmental impact	4: Feedback constructors and design	5: EBS performance	6. Compulsory radiological monitoring	Process/Issue	Targets	Overlap, comments
X	X	X	X			Evolution of groundwater properties	Chemistry of groundwater	
							Groundwater salinity distribution	
							Microbes and gas in groundwater	
							Colloids in groundwater	
	X					Influence of Korvensuo reservoir	Isotopic composition in shallow and deep groundwater	
X		X	X			Influence of foreign materials	Foreign materials and/or their effects in shallow and deep groundwater	foreign materials
	X	X	X			Inflow into the ONKALO tunnels	Chemistry of water in groundwater stations, measuring weirs and leaking fractures	
		X				ONKALO process water	Chemistry of process waters (pool & ditch)	foreign materials and surface environment
		X				Leaching from rock spoil	Chemistry of surface waters near blasted rock storage	surface environment
							Chemistry of shallow groundwater near rock storage	surface environment

Table 6-9: Parameters for monitoring EBS parameters

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

6.6 Monitoring system design

Investigations for case 3 are based on the layout of a demonstration repository for monitoring according to the KBS-3V Swedish/Finnish concept and are limited to the development of an example of a near-field monitoring system that provides a possible sensor layout using a wireless data transmission system. These investigations are a complement to the work in case 2, since in case 2 the focus has been put on the disposal cell monitoring where here in case 3 the focus is on monitoring explicitly the bentonite barrier performance. The system design is based on the processes and parameters identified.

Based on the tables given in the previous sections, the example for a monitoring system design contains the parameters: Temperature, total pressure, pore-water pressure, and moisture content.

6.6.1 Monitoring system for a demonstration facility

The monitoring system is designed for an application in demonstration boreholes and emplacement tunnels filled with dummy canisters instead of real waste packages in disposal tunnels. Preferably no monitoring system should be installed into barriers designed to retain radionuclides. It has to be noted that plans presented in this chapter are at general level, and made with the assumption that the proposed wireless system could be applied and works properly. And it has also to be noted that the placing of the sensors is to be justified by coupled thermo-hydro-mechanical design modelling.

Figure 6-4 shows the general layout of a monitoring system used for monitoring buffer performance. The distance between the disposal boreholes is approximately 10 m, and the total length of the backfilled tunnel will be in the range of 50 m to 60 m. The disposal boreholes are numbered from 1 to 4 and the cross sections of the tunnel are E, F, G, and H. The red circles show the positions of the transmitters and the blue circles show those of the receivers and the orange circles show the relay transmitters necessary to ensure a successful transmission to the final receivers behind the drift seal. The red arrows show the direction of the electromagnetic flux. This direction can be selected according to the arrangement of the transmitters and receivers.

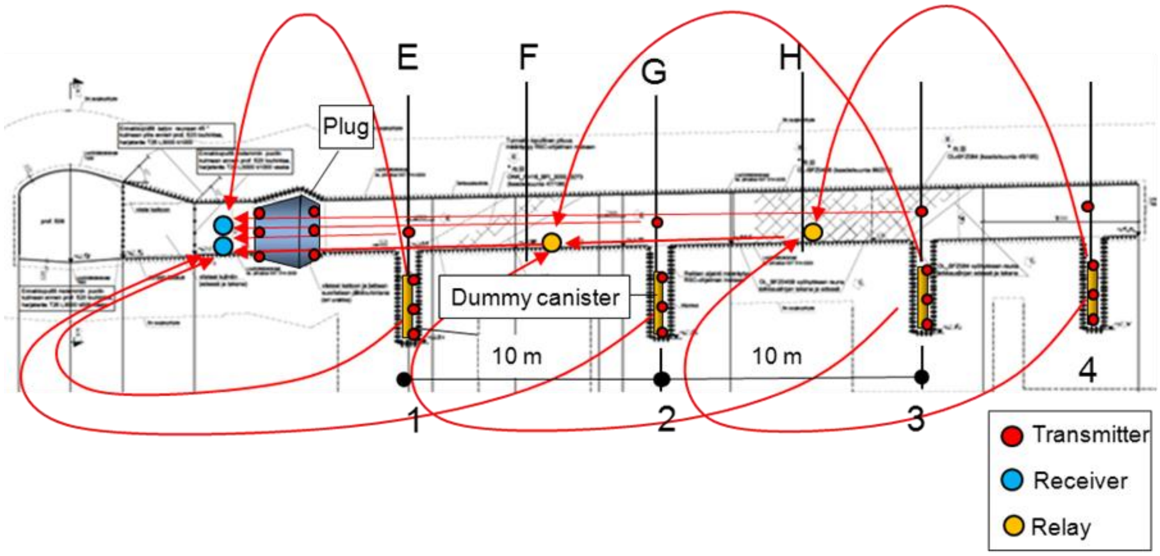


Figure 6-4: Principle scheme of a near-field monitoring system

Figure 6-5 shows the cross-section of the backfilled tunnel and the disposal borehole. The inner solid line presents the theoretical excavation line. The outer solid line presents the tunnel profile for maximum excavation volume which means +400 mm in the floor and +300 mm in the walls and roof. There are two types of bentonite blocks planned. System A with a height of 330 m and a length of 550 mm and system B with a height of 330 m and a length of 470 mm. The gap between the rock wall and the bentonite blocks will be filled with bentonite pellets.

Figure 6-5 (right) shows the cross-section of a disposal borehole. The diameter of the borehole is 1.75 m and the height 7.8 m. The buffer includes 10 pieces of bentonite rings and full blocks. The diameter of the dummy canister is 1.05 m and the width of the gap between buffer and rock is about 50 mm which will be filled with small bentonite pellets. The gap between the bentonite rings and the dummy canister is 10 mm. The height of the complete bentonite buffer is about 960 mm and the thickness of the rings is 300 mm.

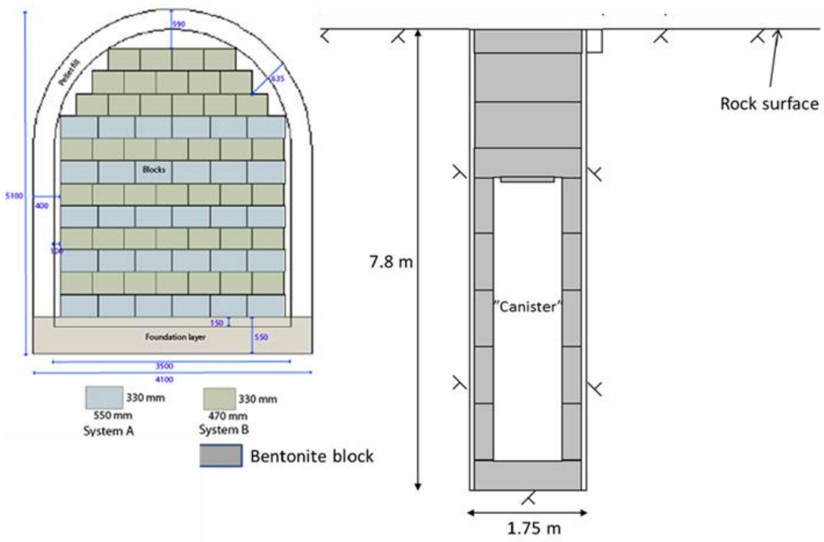


Figure 6-5: Cross-section of a backfilled tunnel (left) and a disposal borehole (right)

In the disposal borehole sensors are arranged at three levels minimum, two of which are just below and above the canister and the other is in the middle of the dummy canister. Two different types of moisture sensors are proposed at certain points. The reason for using different types is that their measurement ranges overlap and hence make them complementary.

At each level, measurements will be made in four vertical sections A, B, C, and D (Figure 6-6), where B and D are oriented in the axial direction of the tunnel and A and C perpendicular. Figure 6-7 shows the layout of sensors with wireless monitoring in tunnel sections G and H.

All recorded data will be transmitted wirelessly. Due to the strong attenuation of the electromagnetic waves, the wireless data transmission system, which can be used in partly or fully saturated bentonite, has to work with very low frequencies. The lower the frequency, the smaller is the attenuation of the wave within the bentonite. The frequencies used in this system are 1 kHz and 10 kHz. Two types of transmitters are proposed for the system. The first is a short-range type which could attach one sensor outside of the transmitter.

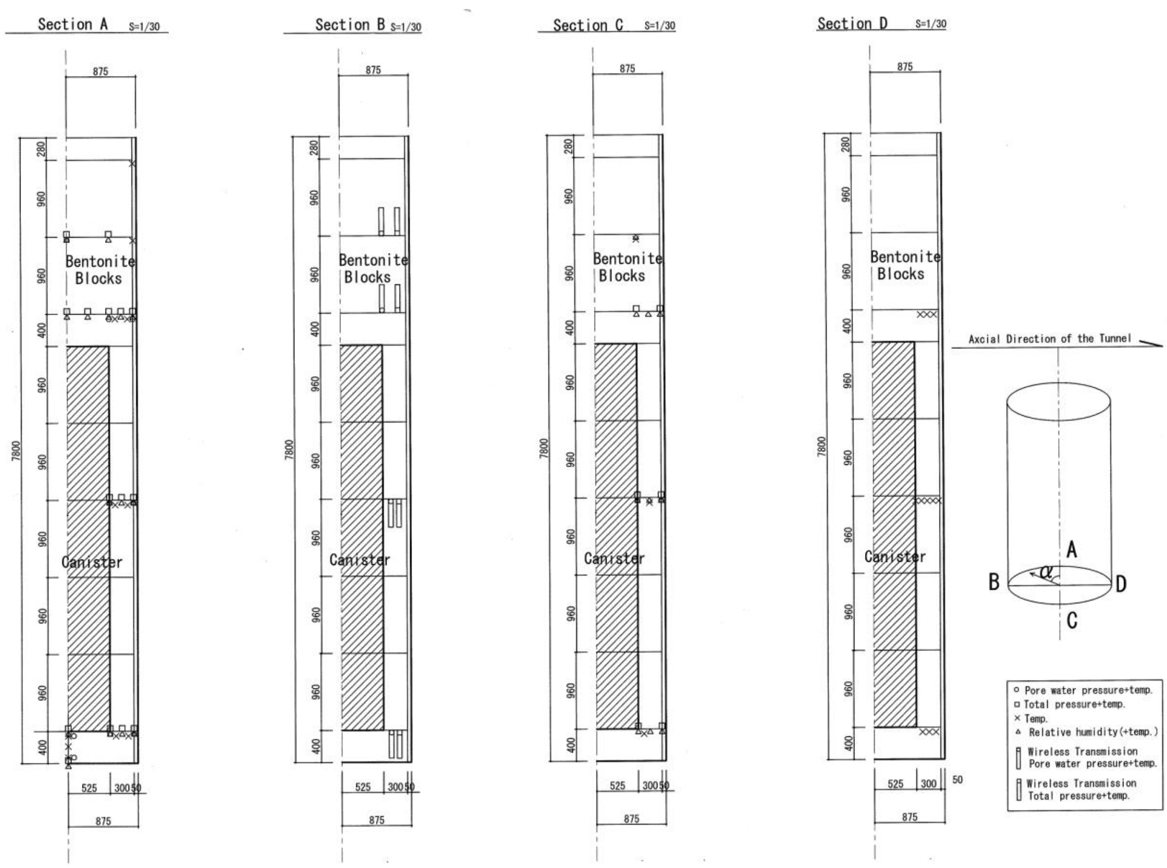


Figure 6-6: Layout of sensor system

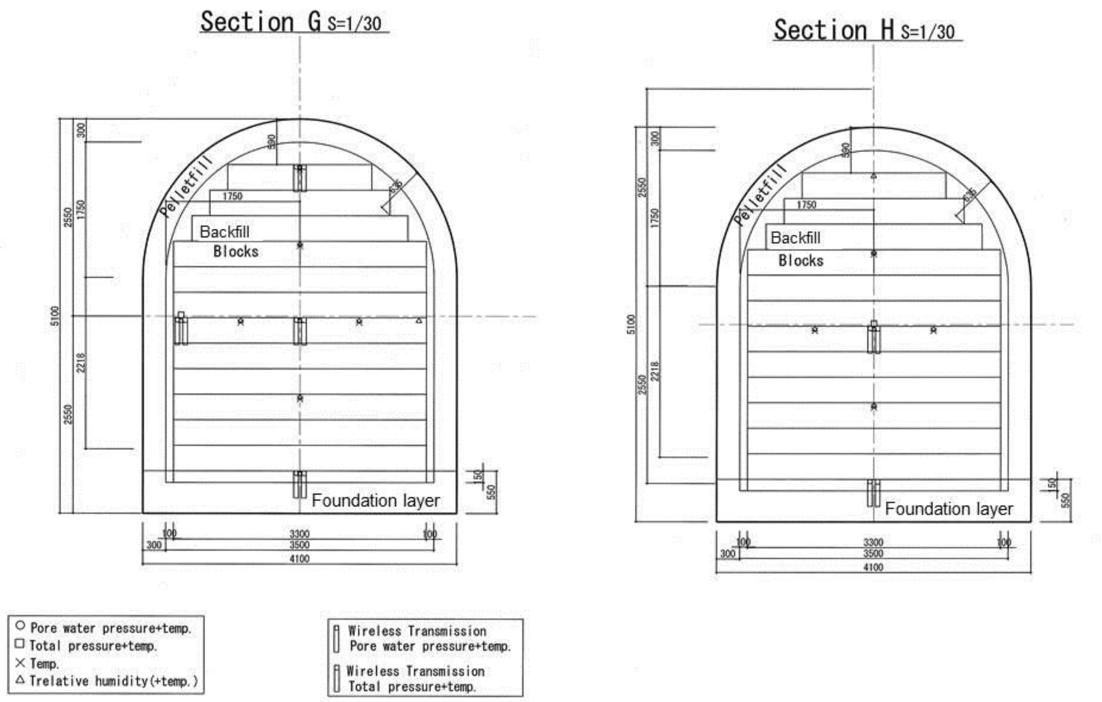


Figure 6-7: Layout of sensor system for tunnel monitoring

This system could be installed in the disposal borehole because of its small size and its water tightness of up to 10 MPa. When data has to be transmitted over 25 m or more, a relay transmission system has to be applied between the transmitter and the receiver since the transmission distance is limited. The middle-range type, which could attach four sensors outside of the transmitter, could be used for an installation in the backfilled tunnel because sufficient space is available. The sensors are arranged in the vertical sections straight above the disposal hole and between the disposal boreholes. The tunnel is filled with bentonite blocks, and pellets are backfilled between the bentonite block and the rock wall. The saturation process of the bentonite pellets can be monitored by measuring swelling pressure, water content, and relative humidity.

Each type of transmitter has one temperature sensor inside for the necessary temperature correction. The life time of each type is expected to be 10 years using lithium batteries inside the transmitter based on a measurement frequency of once a day, and a data transmission frequency of one per week.

Two types of borehole type receiving antennae are shown in Figure 6-8 (Suyama, 2009). They can be selected according to the direction of the magnetic flux and the borehole direction. Antenna A is used for the magnetic flux in perpendicular direction to the axis of the cylinder. Antenna B is used for the magnetic flux in axial direction of the cylinder. Antenna A has a diameter of 89 mm and a length of 260 mm. Antenna B has a diameter of 60 mm and a length of 370 mm.

Type	Short-range	Mid-range 1
Size	Φ : 50mm L :130mm	Φ :216mm L :310mm
Transmi.Test through rock in URL	L=25m Callovo-Oxfordian layer Noise:10mV	L=40m
Transmi. Test on the gorund	L=38m Noise:2.0mV	L=100m Noise:1.5mV

Figure 6-8: Types of transmitters for wireless monitoring

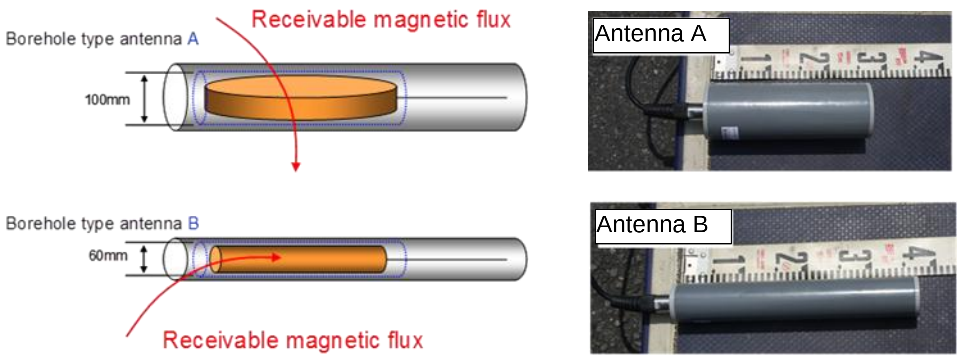


Figure 6-9: Two types of receiving antennae for wireless data transmission

Concluding remarks

Monitoring targets relevant for long-term safety (or the assessment of it) are defined on the basis of process lists compiled for the safety assessment, and the needs of environmental impact monitoring on the basis of potential effects recognised in the Environmental Impact Assessment procedure.

The designed monitoring system in this case study is limited to the development of an example of a near-field monitoring system. A sensor system design has been designed that allows for monitoring the bentonite buffer development in a deposition borehole as well as in the backfilled tunnels. The system is based on individual self-sufficient wireless data transmission systems with an expected lifetime of 10 years.

7 Possibilities to detect sensing system failures

In the geological disposal of radioactive waste, a potentially relevant role in support of decision making and confidence building is attributed to monitoring. The results from monitoring activities support the models and assumptions used to demonstrate safety when they are in agreement with the predicted behaviour of the monitored repository components. It is important to recognise that monitoring outcomes may deviate - for whatever reason - from predicted ones. Such deviation may, for example, be the consequence of a technical failure of one of the many sensors placed and does not necessarily mean that the long-term safety of a repository is impaired. However, if monitoring results are used to support decision making or are part of licence application conditions, it is important to consider how deviating monitoring outcomes have to be handled, and, in order to be able to design a robust implementation process for geological waste disposal, this needs to be done *a priori*.

One important conclusion of current discussions is that it is important to be able to identify why a monitoring outcome deviates from the predicted behaviour. One reason may be that the monitored repository component evolves differently than predicted, but an alternative explanation may be a failure of the monitoring set-up or equipment used. However, in case a monitored deviation indicates that the long-term safety may be impaired in any way, it will be of utmost importance to be able to exclude a failure of the installed monitoring equipment to avoid an incorrect conclusion. Thus, signal diagnostics and failure detection, as discussed in this report, have an essential role in supporting confidence in monitoring results in general and in supporting decision making in case of deviating monitoring results in particular.

The ability to identify failures is an important feature that may even be seen as an additional technical requirement to the ones defined in the technical requirements report (MoDeRn, 2010). The incorporation of such considerations into the selection of monitoring techniques will contribute to the robustness of the implementation process. There is value in considering the installation of additional monitoring equipment that enables potential failures of other monitoring equipment to be identified when developing monitoring objectives.

In the following section, some relevant key terms are introduced which should provide a common understanding. After some basic considerations, failure detection methods will be presented and linked to failure modes and measurement principles relevant for repository monitoring purposes. These links are intended to illustrate the possibilities and limitations of failure detection during repository monitoring. In addition, some application examples for failure detection applications in underground research labs (URLs) are given.

7.1 Basic considerations and definitions

On the one hand, monitoring data is a result of a chain of sensors, cables, connectors, analogue-digital-converters, data-acquisition units, data-processing units, correction and calibration methods, and data transmission units. This means that the "quality" of monitoring data does not only rely on the sensor itself, but also on the proper operation of each of the given components (denoted as *method*). However, these components of the chain and the methods are generally well proven and robust, therefore, the risk of failure is quite low. On the other hand as it is the monitoring results and not the sensor readings that will be used for decision making, statements on "quality" beyond the sensor level are required. Furthermore, aspects like redundancy or the correction for cross-sensitivities are part of a higher-level approach, herein denoted as *procedures*.

In the following section, we first define a number of key terms and concepts used in this report and afterwards discuss them in order to clarify the scope of the work.

7.1.1 Terms and definitions used

Accuracy: indicates proximity of measurement results to the true value. Note that for repository monitoring this can be a rather theoretical issue.
Analytical quality control (AQC): all those processes and procedures designed to ensure that the results of laboratory and in-situ analyses are consistent, comparable, and accurate and within specified limits of precision.
Bias: non-random or directed effects caused by a factor or factors unrelated to the measured parameter. Bias errors are consistent and repeatable (constant offset)
Confounding variable: is an extraneous variable in a statistical model that correlates (positively or negatively) with both the dependent and the independent variable.
Correction: value added algebraically to the uncorrected result of a measurement to compensate for systematic error. The correction is equal to the negative of the estimated systematic error. Since the systematic error cannot be known perfectly, the compensation cannot be complete.
Correction factor: numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error.
Drift: slow changes of an output signal independent of the measured property.
Error (of measurement): result of a measurement minus the true value.
Failure: state or condition of not meeting an intended performance.
Measurement resolution: the smallest change in the underlying physical quantity that produces a response in the measurement.
Method: application of a technique for a specific measurement in a specific environment, including all hardware components necessary to convert sensor signals to (digital) data (wiring, connectors, converters).
Precision of measurement is related to the **repeatability** or **reproducibility** of the measurement. Anyhow, the latter are more accurate expressions that should be preferred.
Procedure: a set of written directions defining how to apply a method to a particular environment, including information on placement of sensors and other hardware, handling of cross-sensitivities, and validating results. A method may have several procedures as it can be adapted to a specific need.
Quality assurance (QA) planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled. It is the systematic measurement, comparison with a standard, monitoring of processes and an associated feedback loop that confers error prevention.
Random error: result of a measurement minus the mean that would result from an infinite number of measurements of the same parameter carried out under repeatability conditions.
Redundancy: the duplication of critical components or functions of a system with the intention of increasing reliability of the system. There are several forms of redundancy, these are:

- Hardware redundancy (duplication, triplication, etc. of systems)
- Distinct functional redundancy, such as both mechanical and hydraulic braking in a car
- Information redundancy, see error detection and correction methods
- Time redundancy, including transient fault detection methods
- Software redundancy

Reliability: ability of a device or system to perform a required function under stated conditions for a specified period of time with low risk of failure.
Repeatability (of results of measurements): closeness of the agreement between the results of successive measurements of the same parameter carried out under the same conditions of measurement.
Reproducibility (of results of measurements): closeness of the agreement between the results of measurements of the same parameter carried out under changed conditions of measurement.
Systematic error: mean value that would result from an infinite number of measurements of the same parameter carried out under repeatability conditions minus the (true) value of the parameter.

Technique: any chemical or physical principle used to measure a parameter. There are often several possible techniques available to measure one parameter.
Uncertainty: A state of having limited knowledge where it is impossible to describe exactly the existing state, a future outcome, or more than one possible outcome. For measurement methods, it defines the confidence interval of the expected outcome. Uncertainty depends on both the accuracy and precision of the measurement instrument. The lower the accuracy and precision of an instrument, the larger the measurement uncertainty is. Expressing the uncertainty of measurement results normally requires the use of the terms *standard uncertainty*, *combined standard uncertainty*, *expanded uncertainty*, or their "relative" forms. Notice that precision is often determined as the standard deviation of the repeated measures of a given value. However, this method is correct only when the instrument is in accordance with its technical specifications. When it is working improperly, the uncertainty is greater than the standard deviation of the repeated measures, and it appears evident that the uncertainty does not depend only on instrumental precision.

Error detection refers to a *failure* of the monitoring system on *method* level, i.e. the method's outcome does not comply with the predicted performance of the *method*. The term *reliability* is linked to the risk that a failure has or will occur in the future. Note that the *failure rate* of a method (i.e. the probability per time interval that a method fails) should be intrinsic part of the *procedures* description. The term "precision" can be divided into *repeatability* and *reproducibility*, and it is worth noting that *repeatability* and *reproducibility* are not abstract entities (as will often be the case for "accuracy" in disposal monitoring), but can be tested experimentally, and may give first evidence of potential failures.

"Compatibility" is a term not used in this report. Instead we recognize here that if a method's or procedure's uncertainty is too large to allow effective evaluation if a component's evolution is within a predicted range, this presents a lack of meaningful input rather than a technical mode of failure. This aspect will not be addressed further here because it does not refer to technical failures as discussed in this report, but mainly has to do with monitoring strategies and its interpretation. The above mentioned "reliable" interpretation of data addresses the same aspect as the "compatibility": the uncertainty of a method or procedure and the range of expected values has to be known in advance. However, additional aspects link this topic to this task, too: for a proper interpretation of data, it is important to understand if a failure has occurred.

"Good" and "bad" signals will be addressed as *valid* sensor responses, measurements or data. Data from a failed sensor or method will be addressed as *invalid*.

Sensor "drift" is a term not defined specifically in this report: if the "drift" is a feature that can be corrected for – either in a predefined manner or by (re)calibration – it should be part of a method's procedure. Where it has been decided that "drift" has not been corrected for within a procedure, this will be reflected in the (increased) uncertainty of the method, i.e. this is rather a feature of the method/procedure than a mode of failure. If unforeseen drift occurs that is not part of the procedure, i.e. resulting in larger uncertainties than the procedure states, this *is* a mode of failure. Likewise, the influence of monitoring on the component being monitored must be defined as part of a method, but is not a mode of failure. The same applies to the fact that most sensors respond to variations in several parameters: this needs to be anticipated in the procedure, either as factors that increase the procedure's uncertainties or as *correction factors*, which can be used to compensate for these cross-sensitivities by applying the correction factors to the sensor readings. Note that unknown cross-sensitivities may influence the procedure's outcomes, but this can hardly be seen as a failure mode, and should be excluded thorough investigations and experiments in advance. This is why external reviews and Quality Assurance systems are essential part of procedures in a lot of technical, physical, or chemical processes.

Following the discussion above, "error detection" should be replaced by *detection of failure (modes)*, and it should be distinguished between *valid* and *invalid* outcomes of a method (the term "reliable sensor" makes only sense when it should be emphasized that the failure rate is low).

In conclusion, although statements on uncertainties and validity should be made on a method or procedure level, it seems appropriate that detection of potential failures should already be performed on sensor-signal level. Two main arguments following the line of this report are:

- sensors provide much more information than the few numbers that are finally envisaged as the outcome of a method, and this additional information can be useful in order to detect failure modes
- it is expected that analysing potential failure modes on the level of sensor technologies will result in some principal guideline for the selection of suitable monitoring equipment

Nevertheless, on the procedure level, additional options are available in order to avoid, detect, and - if possible - correct failure modes:

- by defining proper installation, testing, *QA,* and *AQS* procedures
- by making use of redundancy
- by using cumulated information of different methods

7.2 Failure detection methods

7.2.1 Failure modes

In order to address potential failure detection methods in subsequent sections, an overview of potential failure modes is given in this section. A "failure mode" is defined here as a specific circumstance that results in *invalid* monitoring data, i.e. data values that are influenced by factors other than those described by the method. A failure may result in data that fall outside the range defined by a method’s or procedure’s uncertainty, but it may also be the case that data are still within a predicted range, i.e. a failure does not necessarily mean that monitoring data will fall outside a predicted range of values. In the worst case, it is possible that a failure will mask the fact that a monitored repository component evolves differently than predicted, e.g. if temperature increases faster than predicted, but a failed sensor gives systematically lower readings. Again, the capability to detect failure modes in the monitoring chain is an essential aspect of repository monitoring. The failure modes are addressed in a conceptual way and sorted in a hierarchical manner:

<u>Technical failures</u>

- total or partial sensor failures
- failures of signal transmission
- failures of signal conversion

<u>Methodological failures</u>

- failure of sensor installation and placement
- unidentified cross-sensitivity
- failure of correction methods (drift, cross-sensitivities)

<u>Procedural failures</u>

- loss of redundancy (i.e. simultaneous failure of several sensors)
- failure of any error detection and error correction procedures

In numerous and widely varying safety-relevant areas of applications, different methods have been developed to detect failures, some of which are very specific. They vary with respect to the degree of reliability that can be achieved and, thus, with regard to the technical effort and the special requirements of the particular application. In the following sections, an overview of different failure detection strategies will be given. All these methods focus on failure detection that includes failures of sensor elements and signal/data transmission. These are assumed to be identified as the two main failure modes with regard to the issue in the MoDeRn project and, thus, the following sections will focus on these modes.

7.2.2 Failure of sensors

Failure detection by means of redundancy

Probably the best known method to detect failures is redundancy. A typical area of application for hardware redundancy is the aerospace sector which uses an "*m* out of *n*" redundancy (e.g. "2 out of 3" or "3 out of 5"), where "*n*" is the number of parallel identical functional blocks and "*m*" the number of individual results that have to match in order to arrive at a redundant result. The principle of error/failure detection by means of redundancy is shown in Figure 7-1.

When utilizing redundancy, n matching systems receive an input x and produce n outputs y_1 to y_n. These are transmitted to a voter which compares the output signals and uses signal deviation to detect defective functional blocks. If the output signals y_1 to y_n are analogous, the comparison needs to include a tolerance range within which two analogous values are considered to be equal. With digital signals, there is no such fuzziness. Based on the comparison, the voter determines a failure and, if possible, the accurate output signal y. When minimal redundancy is used, i.e. the number of parallel systems n = 2, the voter can only detect a failure. It is not possible to determine which of the two output signals y_1 or y_2 is the valid signal.

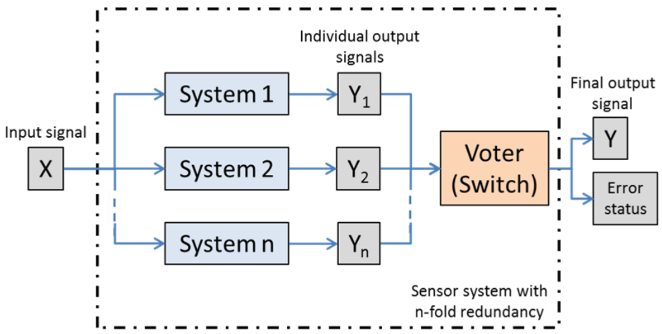


Figure 7-1: Failure detection by means of Redundancy, modified after Weiler (2001)

The advantage of redundancy is that, in principle, it can be applied to any type of system. But it should be noted that redundancy cannot always be realized when monitoring spatially small structures (points).

In addition, it has to be said that redundancy may be easy to apply on the sensor level, but can be more difficult to achieve when thinking of redundancy of systems (e.g. the "monitoring canister" proposed for borehole monitoring in case 1 (Figure 4-6) cannot easily be duplicated). Irrespective of the models used, any type of failure that results in a deviation in any of the output signals y_1 to y_n can be detected. If an "*m*-out-of-*n*"-system is used and n > 2, the comparison coupled with a majority decision of the parallel systems enables the direct correction of a failure. However, a small risk exists that the majority of systems is wrong and the minority not - hence the use of systems with n>3.

A disadvantage of redundancy is that the number of circuits necessary to detect errors increases *n*-fold. If errors have a simultaneous effect on the majority of output signals y_1 to y_n, redundancy fails as the voter can only detect failures via the different outputs. This significantly limits the applicability of redundancy, especially in the field of error detection by means of sensor elements. Under the harsh conditions present in URLs for radioactive waste disposal, it is found that the interface to the sensor elements is the most likely location for a failure. Thus, there is some probability that all redundant sensor elements are destroyed at the same time and by the same cause. In that case, the voter cannot detect any deviation between the sensor outputs. It should be noted that redundancy also increases the precision by averaging out variations in sensors, sensor placement and spatial heterogeneity effects. Thus, redundancy can serve several objectives.

Failure detection by means of known relations

In a strict sense, error detection by means of known relations is a method that is based on diversity. Diversity or *distinct functional redundancy* is a special form of redundancy where multiple components with different designs are used for measuring the same parameter. In sensor systems, this method utilizes the time-invariant relations between independent signals within or outside the system. An error leads to a deviation in the fixed relations, and this inconsistency between independent signals is registered as an error.

An example of error detection integrated in a sensor element is a differential pressure sensor with redundant temperature measurement function according to (Schneider, 1996). This differential pressure sensor consists of two membranes. Each forms an electrode and is impacted/imposed by a pressure p_1 or p_2. Counter electrodes are located at a short distance from the membranes so that two pressure-dependent capacities C_1 and C_2 are generated between the membranes and the counter electrodes. Both membranes are coupled hydraulically by means of a fluid while there is a slight positive pressure. Pressure compensation is effected by means of a hole in the middle of the two chambers. To generate a redundant temperature signal, a temperature sensor (*R*) is attached directly to the differential pressure sensor. The design of a capacitive differential pressure sensor is shown in Figure 7-2.

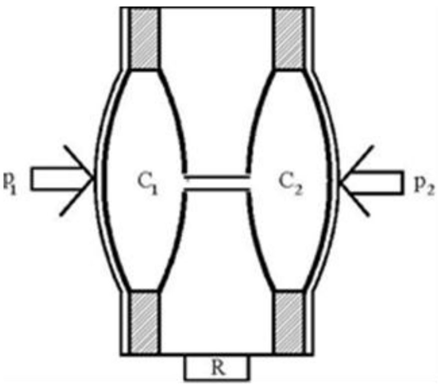


Figure 7-2:
Differential pressure sensor (Schneider, 1996)

If $p_1 > p_2$, the distance between the electrodes of capacitor C_1 decreases while it increases at capacitor C_2. This results in an increase in capacity C_1 and a decrease in capacity C_2. The pressure difference Δp can be calculated by means of the following equation (Schneider, 1996):

$$\Delta p = p_1 - p_2 \sim \frac{1}{C_1} - \frac{1}{C_2}$$

In addition to the change in the capacities C_1 and C_2 due to the pressure difference, there is a secondary influence on the sensor element due to the temperature *T*. The temperature *T* influences the dielectric constant which leads to a change in volume of the hydraulic fluid. This undesirable change in volume is proportional to the temperature and is roughly calculated as follows:

$$T \sim \frac{1}{C_1} + \frac{1}{C_2}$$

Taking into account the temperature measured by an additional temperature sensor at the differential pressure sensor element, two mutually independent temperature signals are available. Both signals are constantly compared by means of the processing unit. Damage to the sensor and the resulting loss of oil in the sensor would imitate a significant difference in temperature. The system identifies this condition and indicates a failure. The difficulty when using diversity for error detection is to select relations that are suitable to reliably monitor the sensor element. Thus, in contrast to redundancy, diversity cannot be used for every sensor system.

In cases where diversity can be used for error detection in the sensor element, a distinct advantage over redundancy is that different, independent signals can be used to check for consistency. Thus, diversity can detect cases where similar errors influence redundant sensor elements.

Failure detection by means of electrical stimulation

For this error detection method, the sensor element is directly stimulated by means of electrical impulses that – together with the measured variable *x* – are processed by all subsequent components of the sensor system. In an accurately working sensor system, the electrical stimulation of the sensor element leads to a known sensor response than can be detected in the output signal *y*. A very basic application is the measurement of the insulation resistance and continuity of thermocouples – the former by applying an elevated voltage (50 to 500 V) between a conductor and the protective sheath, the latter by measuring the resistance (DC or low frequency AC) along the conductors. Also time domain reflectometry (TDR) can be considered as a stimulation technique – in this case in particular to check for cable problems (cuts and short circuits but also less severe interruptions such as cable kinks) as they affect the cable impedance in a more or less pronounced way.

A sophisticated technique for temperature sensors – Resistance Temperature Devices (RTDs) and thermocouples – is the so-called "Loop Current Step Response” (LCSR), a technique which has been applied for in-situ diagnostics in industrial processes, e.g. for inaccessible sensors in nuclear power plants. The LCSR test involves heating the sensing element with an electric current (DC for RTDs – typically 40 to 80 mA, and AC for thermocouples – typically 0.2 to 2 A). The test causes the sensing element to heat up by about 10 to 20°C, depending on the current applied and on the ability of the sensor to dissipate the heat.

A practical set-up for testing RTDs with the LCSR is shown in Figure 7-3. Closing the switch will cause the current to go from typically 1 mA (used for balancing the bridge) to the elevated value required for heating. The resulting signal due to this heating is then further analysed.

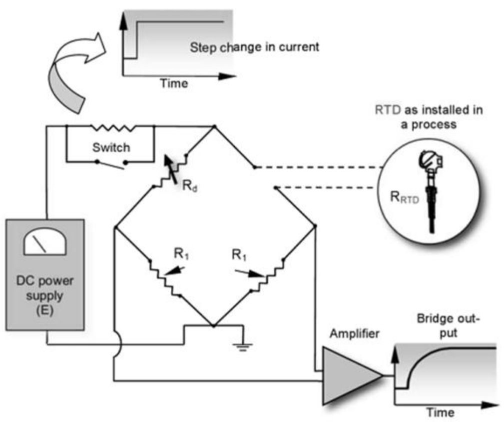


Figure 7-3: Wheatstone bridge for LCSR testing of RTDs (Hashemain, 2005)

Applications of this method potentially relevant for repository monitoring include:

- detection of reverse thermocouple connections (bad polarity);
- detection of cable problems – ideally in combination with TDR (time domain reflectometry). A typical example is the detection of moisture in the RTD: if moisture enters an RTD, both the TDR signature and the LCSR transient are affected. The TDR locates the impedance changes along the cable due to moisture ingress while the LCSR test will pinpoint moisture influence at the sensor itself through smaller response times, detection of affected thermocouple performance due to mechanically or thermally stressed wire; although the LCSR test will not detect subtle inhomogeneities, it can be used as a screening test.

A disadvantage of error detection by means of electrical stimulation is that this method is mainly limited to only a few applications. It can only be applied in sensor elements where the measuring principle can be electrically reversed, i.e. where the stimulations of the sensor element caused by electrical impulses are in the same order of magnitude as the measurand *x*. This is the case in most integrated sensors. Due to the low sensitivity of the sensor element compared with the stimulation signal and the technically limited excitation amplitude, however, it is necessary to use special signal processing methods to detect the superimposed signal in the sensor signal. During diagnosis, proper data recording can be affected by the electrical stimulation so that in this case, continuous monitoring of the operation of the sensor system has to be shortly interrupted for diagnosis. A further disadvantage is the increased power requirement for the stimulation which has a particularly critical impact in transponders or battery powered circuits.

The main advantage of this method of error detection is that not only the sensor element but the complete signal processing chain as well, are subjected to functional testing and that, thus, no additional effort is necessary to detect errors in the individual components. In some sensor elements where direct stimulation is not feasible, indirect stimulation via cross sensitivities may be possible. Thermal stimulation is a very suitable method because it can easily be affected by means of integrated thermal resistors and because many microelectronic sensor elements possess this cross sensitivity. As the cross sensitivity will be compensated in downstream stages, there will be no influence on the measuring results, and a continuous self-monitoring of the system will be possible. A special feature of this method is that sensor sensitivity can be measured at the working point indicated by the measurand *x* and that further knowledge about the current status of the sensor can be gained.

Failure detection by means of reliability indicators

Failure detection by means of reliability indicators uses certain parameters of a circuit/system or sensor to indicate the occurrence and evolution of a failure. These parameters are continuously monitored to detect if they exceed or fall below certain specified ranges/values which are only reached if an error occurs. Examples of reliability indicators are steady-state current measurements in Complementary Metal Oxide Semiconductors, so-called *CMOS* integrated circuits, or temperature measurements using thermocouples inside data acquisition systems to check for any deviating conditions within the system.

This method is based on the principle that after equalizing currents resulting from changes in state or time have subsided, only a small amount of static supply current resulting from leakage flows in a correctly operating digital CMOS circuit. In case of a failure, this steady current can increase significantly. The measuring of the supply current (I_{dd}) in the quiescent state is called internal and external IDDQ-testing. A disadvantage is the relative high capacity of the ampere meter which leads to large time constants and long testing times. Furthermore, in complex circuits, it is possible that failures that concern only a small section of the circuit are only a residual current proportion below the normal range of dispersion of the quiescent current so that they are difficult to detect. In order to compensate for these disadvantages of external IDDQ-tests, built-in current sensors (BICS) are used (Olbrich et al., 1996). In this case, the additional capacity and the voltage drop via the current sensor need to be minimized while the generated circuit overhead needs to be kept to a minimum.

The advantages of this method are easy monitoring and low overhead for testing equipment.

Local sensor validation

The local error detection of a sensor system (also: local sensor validation, LSV) according to (Yung, 1992a) detects errors by analysing characteristic signal components of the unfiltered signal *y*' of the system. This method is based on the assumption that errors or failures may occur at various locations in the system in the form of, e.g., a short-circuit, disruption, or as an overdrive of the operational amplifier, and that it would be highly efficient to monitor all possible sources of errors. The exact sources of the errors can only be determined if all sensor components and their interactions are known in detail. Nevertheless, certain signal characteristics in the unfiltered output signal of a sensor system may suggest a failure (Amadi-Echendu, 1994). According to (Yung, 1992b), a failure can cause eight typical output signals which are shown in Figure 7-4.

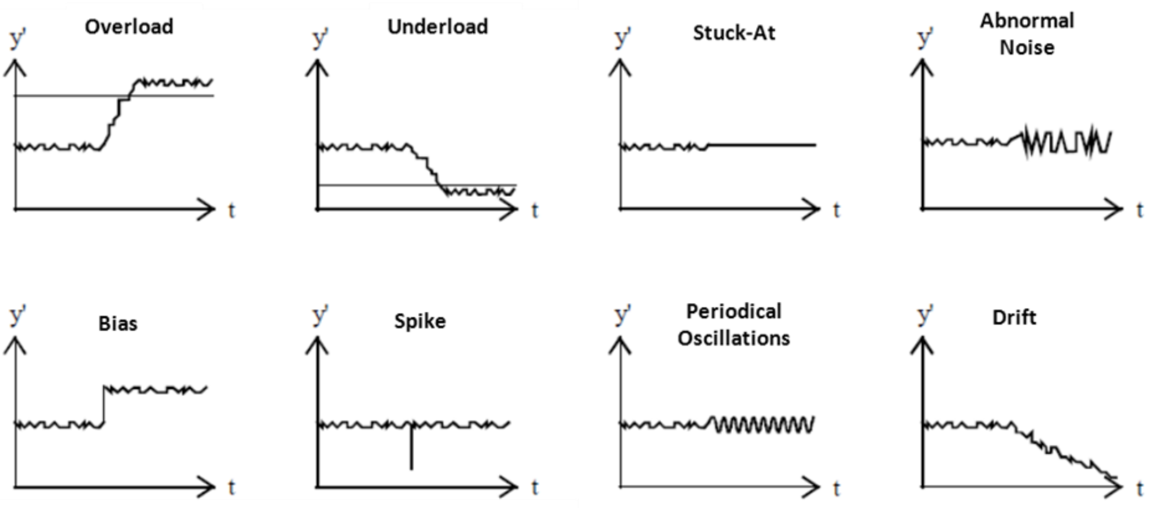


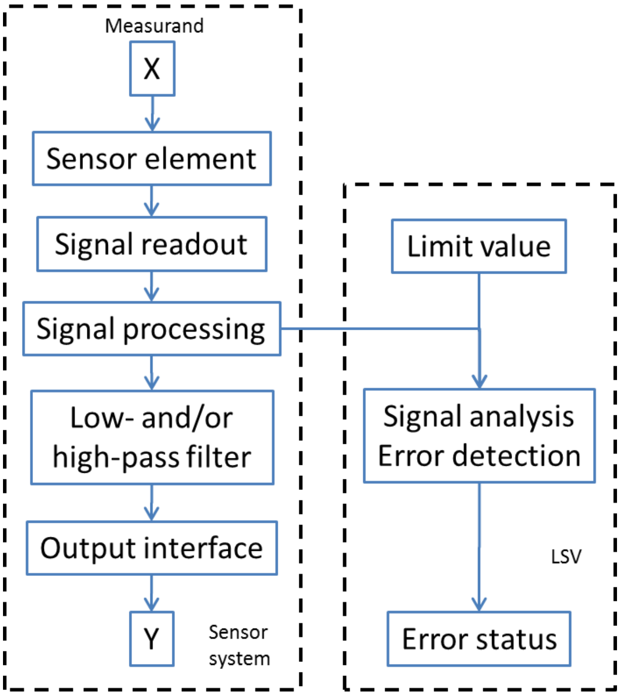
Figure 7-4: Characteristic output signal in the case of a failure (Yung, 1992b)

For a better illustration of the output signal *y*', measurand *x* was kept constant so that changes in the output signal are only caused by an additive noise ratio and the effects of the respective error. A limit error occurs if the output signal exceeds or falls below a specified threshold value. Physically, such output signals are often caused by short-circuits or a disruption in the sensor system. Either process- or sensor-specific parameters are chosen as threshold values. In a sensor with an interface consuming 4-20 mA, the threshold value could be a current consumption exceeding 20 mA.

A bias error causes a shift in the output signal of the sensor system that is significantly faster than a regular change in the measured variable. Such a shift can be caused by an inaccuracy in the current or voltage reference network. A spike is a short-term shift in the output signal *y*' that – like a bias error – is noticeably faster than an acceptable change in the measured variable. Spike errors are caused by short-term failures in the sensor system. When a stuck-at error occurs, the output signal is stuck at a constant value. This failure is usually caused by a loss of sensor sensitivity to the measured variable *x*. An oscillation error is caused by a significant and lasting increase in the noise level. These failures are usually due to external causes, e.g. due to a noisy voltage supply or to a bad contact (inside sensor or between sensor and cable). If the output contains unwanted waves that are not caused by the measurand, this is due to an (unwanted) oscillation or interference with other signals/power lines. When a drift occurs, there is a very slow, continuous increase or decrease in the output signal. The change is noticeably slower than in case of a bias error.

According to Yung (1992b), the eight characteristic output signals *y*' represent most of the potential failures that can occur. However, not each failure type will occur in every sensor system. In many systems, the search for certain signal characteristics is therefore not carried out in order to simplify error detection. Limit and stuck-at errors, however, will occur in most sensor systems.

For LSV, a functional block used for signal analysis is placed as close as possible to the output interface so that all downstream levels of the sensor system can be checked for failures.



The direct use of the sensor output signal *y* is not suitable to detect failures as the output signal is often low-pass filtered due to the use of AD converters so that important frequency components are lost. In most cases, the cut-off frequency of the sensor element is considerably higher and, thus, provides information beyond the low-pass filtered output signal *y*. The principle of local sensor validation is shown in Figure 7-5

Figure 7-5: Principle of local sensor validation

For analysis, the sensor signal *y*' is separated into high and low frequency components by means of two filters. The low frequency component mainly contains the measuring signal while the high frequency component mainly contains the noise. Subsequently, the values for several statistical parameters, e.g. mean, variation, rate of change, are extracted from both signal components. The positions of these extracted values within stored limits are determined. Any deviation from these values indicates a malfunction in the sensor system. To detect malfunctions of the sensor by analysing the unfiltered output signal *y*', four indicators are used:

- **Limit indicator:** Monitors whether the output signal *y*' exceeds the maximum value or falls below the minimum value. As maximum/minimum values either physical limits (operating voltage reached) or application-specific limits (maximum/minimum values of the sensor system) can be used. During initialization, both limit values are stored in the system memory.
- **Shift indicator:** This indicator is used to detect an unusual shift in the output signal *y*'. The triggering threshold has to be fixed to a certain value during initialization of the sensor system.
- **Noise indicator:** The noise variation in the output signal is compared with an upper and lower limit (valid for the selected frequency range) and the indicator is set accordingly.
- **Drift indicator:** This indicator is used to monitor long-term deviations of the output mean value from a nominal value stored in the system.

Each of these indicators can have three possible values. *0* indicates that the system is working properly, while *+1* and *-1* indicate that the output exceeds or falls below the reference values, respectively. These four indicators can be used to detect eight kinds of deviations in the output signal of the sensor system. Each indicator contains certain information about a malfunction of the sensor so that the combination of the indicators triggered determines the type of failure.

A disadvantage of this method is that only locally accessible information, e.g. the output and the corresponding noise, can be used to detect errors. Information from a higher-level system instance (e.g. controlling unit), for example, cannot be considered. Furthermore, it is necessary to store the reference limits that trigger the indicators. Depending on the intended use of the sensor system, these values may have to be adjusted for an optimum error and failure detection. If this method is not intended for a specific use, the limit margins have to be broad enough in order to keep the failure rate low, which reduces the sensitivity of the error detection method. Drift errors can only be detected by observation periods much longer than the expected rate of signal changes.

An advantage is that – via a simple extension close to the system output – this method can be applied in many different types of sensors without the need to develop a detailed mathematical model that is customized to the specific process. It is possible to detect many different types of failures without the need for a special error detection circuit for each possible error. Real-time capability can be achieved without extensive and complex multi-measurements. If the reference limits are set appropriately, failures can be detected reliably with a minimum of incorrect failure messages. The circuit complexity due to additional components necessary for filtering and signal processing is moderate.

Failure detection by correlation

This method can be applied when sensors measure the same physical parameter but are placed in equivalent positions with regard to this parameter (e.g. same distance to a heat source when measuring temperature but in opposite direction). Then, it is possible to evaluate whether the readings of one of those sensors are valid by directly correlating them with the readings obtained from the others. This needs of course expert knowledge about the monitored process in the area.

When sensors measuring different physical parameters are in the vicinity of one another, correlations can also be established if those sensors comprise equivalent auxiliary measures. For example, temperature sensors associated to a pressure cell (used to correct the effect of temperature on its readings) can be correlated with the readings from nearby thermocouples to assess their validity, or vice versa. The readings from the thermocouples can be used to correct the pressure cell readings if the associated temperature measurement is the one that failed.

Finally, indirect correlations can be established between sensors measuring different parameters if they are embedded in media where these parameters are coupled. For instance, humidity and total pressure are coupled in unsaturated confined bentonite. A way of knowing if an increase in the readings from a humidity sensor corresponds to an actual increase of humidity in the bentonite, readings from a nearby total pressure sensor can be checked looking for a corresponding increase. Again, this needs expert knowledge about the monitored process in the area.

7.2.3 Failure of data transmission

Failure modes of data transmission

Assuming that data transmission in case of repository monitoring is limited to the transmission of bit-wise, digital data, "errors" refers in this context to wrongly received bit values (i.e. "*1*" instead of "*0*" and vice versa). Transmission errors can occur as a result of noise and interferences, i.e. by a change in the transmitted signal on its way from the transmitter to the receiver. Other reasons for errors of this kind are transmission channel interferences, signal distortion, or synchronization problems. The following four potential failure modes, which apply to data transmission in repository monitoring in general, have been identified:

- *electro-mechanical unit failure*: no meaningful data will be received due to electrical or mechanical damage of any kind or to a loss of power
- *data errors*: these can appear for many reasons, including partial damage of electrical and mechanical components
- *protocol errors*: data may be misunderstood due to errors in the protocols used. The protocols are based on algorithms that are either coded in hardware or software
- *channel interference*: data may be received that originates from other sources

The relevant indicator to quantify transmission errors of a digital data transmission chain is the "*bit error rate*" (BER), defined as the number of bit errors divided by the total number of bits transferred. While the BER is a measured value, the "*bit error probability*" is the expectation value of the BER, i.e. the BER can be used as an estimate of the bit error probability for a certain transmission system. BER and bit error probability will be used synonymously hereafter. As explained in the next sections, several methods exist that allow the detection and correction of incorrectly received data as part of the data coding scheme applied. Failures in digital transmission are therefore rare, especially in bidirectional systems that allow the receiver to request the transmitter to resend wrongly received data.

Error detection methods for data transmission

For the four failure modes defined in the previous section, the following error detection methods can be applied:

- *General unit failure*: This failure mode is easily identified by the fact that there is a repeated failure to receive meaningful data. An additional scan of the transmission channel may be performed in order to exclude the presence of one of the other failure modes.
- *Data errors*: as will be elaborated in the remainder of this section, data errors can be identified by error detection methods, and the probability of undetected errors depends on the method used.
- *Protocol errors*: the protocols used are based on algorithms, which are either coded in hardware or software. Sufficient testing of the algorithms should avoid this. Self-testing procedures of transmitter and receiver units can be implemented in order to detect if algorithms are modified by any cause.
- *Channel interference*: the spatial origin of a transmitted signal can be estimated by measuring and comparing signal strengths at different locations. In bidirectional systems, the identity of a transmission can be verified by requesting cryptographic keys, combined with (encrypted) checksums.

From the four failure modes defined above, data errors are the most relevant item, and many error detection schemes have been developed in order to detect errors in digital data streams. All these methods have in common that they can be used to detect errors of the overall transmission chain, i.e. they do not depend on the specific localized cause of error. The simplest scheme is the use of a "parity bit" that is added to a group of bits and indicates if the number of "1's" in the group is even or odd. A so-called "checksum" can be added to a data block, and enables the receiver to verify the delivered data block. Data can also simply be sent repeatedly in a predefined pattern.

Errors can have different patterns, depending on their origin: in case of noise (i.e. random perturbations), errors are more or less equally distributed in a data stream, and the signal-to-noise ratio (SNR) of a transmission method can be used to estimate the expected BER. The same kind of analysis can be used to calculate the necessary signal strength in order to optimize the ratio between the probability of undetected errors and the (extra) energy used for the applied error detection code.

In case of interferences, patterns may exist that are difficult to cover by a simple error detection scheme: e.g. in case of "burst errors" (contiguous sequences of errors), a parity bit is not efficient, because the probability that an error is undetected can be as high as 50% if the burst length covers the whole data block. Specific error detection schemes are developed in order to address this specific kind of error, e.g. the so-called "cyclic redundancy check" (CRC) scheme is used in the case of burst errors. It should also be noted that in the case of interferences, an increase in the SNR is not always a useful method to decrease the BER; other strategies may be more efficient.

Because all error detection schemes introduce "redundancy"[1] to the data stream, the redundancy of a scheme should be evaluated against the probability that transmission errors remain undetected. Furthermore, the block size of an error detection scheme needs to be considered for two reasons:

- because of the probability that errors increase with increasing block size, the block size should be much smaller than 1/BER
- a larger block size decreases the redundancy, but in the case of a transmission error, the whole block of data must be considered as invalid

An important error detection method can also be applied on the *procedure* level: because in most cases, monitoring data is expected to evolve rather slowly, incidental spikes in a parameter evolution can easily be identified and filtered by predefined methods. The latter is also important because for all error detection methods, a residual probability that an error remains undetected exits. Thus, instead of choosing "expensive", highly redundant methods on transmission channel level, a filtering of parameter timelines on procedure level may be far more efficient and robust.

<u>Aspects of error detection in low-frequency data transmission</u>
Wireless data transmission of low-frequency electromagnetic signals (<100 kHz) is used to bridge medium to large distances (10 m to >100 m) but may also be applied to smaller distances (1-10 m). The technologies currently used, especially for larger distances, can be marked as "tailor-made" solutions, and conclusions on failure modes are therefore based on "expert judgement" rather than experience. In addition to the error detection methods discussed in the previous section, the following can be noted:

- General unit failure: with respect to possible further analysis, it should be noted that – in order to locate and fix this failure – all potential measures are restricted to the receiver at the earth´s surface.
- Data errors: noteworthy is that strong external interferences (e.g. lightning strikes) may corrupt large sequences of data (burst errors), and suitable error detection methods that anticipate these events need to be chosen. The use of a specific modulation techniques and the effect of non-linear component might also favour certain types of non-random errors that need to be considered when selecting (and testing) error detection codes.
- protocol errors: -
- channel interference: -

<u>Aspects of error detection in high-frequency wireless data transmission</u>
High-frequency data transmission (MHz – GHz) is used to bridge small distances (1-10 m). Its use on larger distances is limited due to the high attenuation of the signal by geologic me-

1 note that the term "redundancy" in this context has a different meaning then in previous sections: it describes the number of transmitted bits minus the number of bits of actual information

dia or by barrier material (e.g. concrete, bentonite, salt grout). In addition to the error detection methods discussed in the previous section, the following can be noted:

- General unit failure: using a single remote device for controlling various sensors and transmitters allows a precise synchronisation of data transmission. By correlation, it is possible to detect missing or corrupted frames that indicate a possible failure in a sensor or transmitting unit. In addition to this, both the battery level and RSSI (received signal strength index) are monitored to have more detailed information about each node in particular.
- Data errors: mainly two different methods are implemented; a framing error detector (hardware) and a simple checksum, as mentioned above. When none of them raise the error flag while a frame is being received, the data is processed by the sensor's coordinator microcontroller. Then, if every field of the frame is understood (and the system is equipped with bi-directional radio transceivers), the coordinator sends an acknowledge message to the remote node to let it know the data has been received correctly. Otherwise, the transmitter will retry a new broadcast to transfer the sensor's data to the receiver correctly.
- Protocol errors: messages are sent both ways (transmitter to coordinator and vice-versa) using a standard format well known by the two parts. This protocol begins with a header sequence and finishes with an end of frame data sequence (EOF). In addition, particular device identification is included in the protocol in a complementary and non-complementary format to avoid possible errors.
- Channel interference: the high frequency bands allow the utilisation of more than one channel in the same frequency with wide enough gaps between them to tolerate the co-existence of various systems in physically closed scenarios, working in different channels. Desensitization is the measure of a receiver's ability to reject off-channel signals. Desensitization of a desired signal at a reference sensitivity level due to an adjacent channel signal is called specifically Adjacent Channel Rejection (ACR).

Error correction methods for data transmission

In addition to error detection, schemes exist that allow the (partial) correction of errors:

- backward error correction schemes can be used for bidirectional transmission lines: in case an error is detected, the transmitter is requested to resend the corrupted data block
- an error correcting code (ECC) can be sent before or after the data block and can be used by the receiver to (partially) recover the original data in case of error

For the latter, many possibilities exist for its implementation that allow specific correction schemes: for example, an ECC may be used to correct the highest bits of a value, while the lowest bits are assumed to be uncritical compared with the uncertainty of a measuring method. In contrast, it can also be the preferred means to correct the lowest bits, resulting in either very precise data or data which can be easily identified as outliers, e.g. by analysing timelines.

Error detection and correction methods are widely used in all kind of applications. However, a number of specific aspects, summarized in the previous section, apply for the cases when wireless transmission techniques are used because wired solution may impair the safety function of a barrier. In this case, energy supply can be assumed to present a limiting factor, which results in the need to search for optimized methods that allow the SNR to be reduced and to keep the data redundancy small.

7.3 Detection methods related to failure modes and measurement principles

7.3.1 Failure detection methods and failure modes

In the previous sections, several failure modes are summarized, and several failure detection methods are identified. Table 7-1 gives a structured answer to the question, which kind of failure detection technique can be used to detect which kind of failure mode. For instance, a technical failure of an individual sensor can be identified by redundancy, but redundancy may not help us if the drift correction procedure does not work properly because this may apply to all redundant sensors. Because the availability of failure detection techniques partially depends on the specific method to be used, such an exercise should be performed for each failure detection technique.

Table 7-1 gives an overview on which failures modes lead to major problems, because they could stay undetected, and which modes are less "challenging" (e.g. a simple sensor breakdown is easily identified by redundancy).

Table 7-1: Failure modes and failure detection techniques

	sensor failures	**failures of signal transmission**	**failures of signal conversion**	**failure of sensor installation and placement**	**distortion of sample environment**	**unidentified cross-sensitivity**	**failure of correction methods**	**loss of redundancy**	**failure of error detection and error correction procedures**
Redundancy	x	x	x	x	x	-	-	-	-
Diversity (hardware)	x	x	x	x	x	x	x	x	x
Electrical stimulation	x	x	x	-	-	-	-	-	-
Reliability indicators	-	-	x	-	-	-	-	x	-
Local sensor validation (LSV)	o	o	o	?	-	-	-	x	-
Correlation	o	o	o	x	x	o	o	?	?

In the same way, Table 7-1 shows us which techniques are effective in addressing failure modes. The table may also help to select techniques that are favourable with respect to failure detection, and it may help to identify additional monitoring techniques or measures that can be applied in order to be able to address most failure modes. Redundancy, for instance, seems to be already quite efficient, and together with "diversity", it can address almost all failure modes.

7.3.2 Failure detection methods and measurement principles

Table 7-2 gives an overview of measurement principles of geotechnical sensing systems that can be applied within repository monitoring programmes.
In total 18 relevant principles have been identified, 13 electrical and 5 optical ones. Table 7-3 relates the measurement principles to the failure detection methods given in the previous section.

Looking at Table 7-3 it is obvious that not all failure detection methods are applicable to all measurement principles. But at least for most of the principles, there are individual failure detection methods available (marked in yellow).

For some principles, like piezo-electric effect or chemical effects (especially with regard to fibre optic sensors), none of the failure detection methods can be applied.

Generally, it can be stated that (automatic) failure detection without access to sensors is limited.

Table 7-2: Measurement principles of geotechnical sensing systems

No	Measurement principle
1	Thermocouple
2	Electrical resistance variation RTDs and Thermistors Strain gauge (including piezoresistive effect in semiconductor Resistance block (soil moisture) Potentiometer
3	Piezo-electric effect
4	Magnetic induction based
5	Vibrating wire • Static measurements • Dynamic sustained vibration
6	Capacitive systems • Displacement • Hygrometer (electric permittivity)
7	Electro-magnetic wave propagation • TDR, TDT (Time Domain Reflectometry and Transmissometry) • FDR, FDC (Frequency Domain Reflectometry and Calibration) • Phase transmission
8	Heat dissipation • Thermal conductivity • Thermal diffusivity
9	Neutron moderation (neutron gamma probe)
10	Psychrometer (soil suction)
11	Tensiometer (water potential)
12	Nuclear radiation • Gas-filled ionization chamber, gas-filled proportional chamber • Geiger-Müller counter • Scintillation detector • Semiconductor detector
13	Electrochemical systems • Potentiometric electrode for pH measurement (also Eh) • ISFET (Ion-Sensitive Field-Effect-Transistors (pH)) • Potentiostat (corrosion)
	Optical principles
14	IR detection (can also be considered as a semiconductor detector)
15	Fiber optic (FO) chemical sensors • Active core • Active coating • Dye on fibre end (optrodes) • Refractometer • Evanescense spectroscopy
16	Fabry-perot interferometer
17	Bragg-gratings
18	OTDR (Optical Time Domain Reflectometry) backscattering (Raman, Rayleigh, Brillouin)

Table 7-3: Failure detection methods related to the measurement principles identified

No.	Measurement principle	Redundancy	Diversity	Electrical stimulation	Reliability indicators	Local failure detection	Corre-lation	Comment
1	Thermocouple	"Multicouples" several hot junctions one cable/package	Different types of thermocouples (different metals)	"Loop Current Step Response"	Continuity – often incorporated in data-acquisition equipment; isolation resistance			
2	Electrical resistance variation	X						
	RTD-thermistor	X		Loop current step response				
	Strain gauges	Typically several gauges are combined in one wired set-up		Output proportional to input		Long-term drift		
	Full-bridge transducers	X	e.g. pressure sensors: output signal proportional with pressure, but input impedance changes with temperature		Input and output impedance			
	Potentiometer	X		Output proportional to input		Performance of contact point – when long time no movement: burn-in of contact – or mech. blocking		
3	Piezo-elect. effect	X						
4	Magnetic induction	X		Impedance meter				
5	Vibrating wire	X	Thermal influence					
	Discontinuous	X		The excitation to remagnetize a	Continuity; decay ratio, spectral			

No.	Measurement principle	Redundancy	Diversity	Electrical stimulation	Reliability indicators	Local failure detection	Corre-lation	Comment
				sensor	analysis of signal - incorporated in newest VW condi-tioning			
	continuous	X						
6	Capacitive systems	X		impedance meas-urements		impedance meter		
7	Electromagnetic wave propagation	X	real (travel time) and imagi-nary (energy loss) of EM wave	inherent to measurement principle				
8	Heat dissipation	sophisticated models incorpo-rate several tem-perature sensors		inherent to measurement principle	stable temperature required prior to measurement			
9	Neutron moderation	X						usually only through mobile probe – with calibration prior to each measurement campaign
10	PsychRometer	X		inherent to measurement principle				cf. thermocou-ple (measure-ment principle based on this sensor)
11	Tensiometer	X				drift due to loss of vacuum		correct func-tioning re-quires regular maintenance (degassed wa-ter, …)
12	Nuclear radiation	X						
13	Electrochemical systems	X				drift		regular cali-bration re-quired
	Optical principles			*Optical stimulation*				***OTDR** can be used for all fibers to de-*

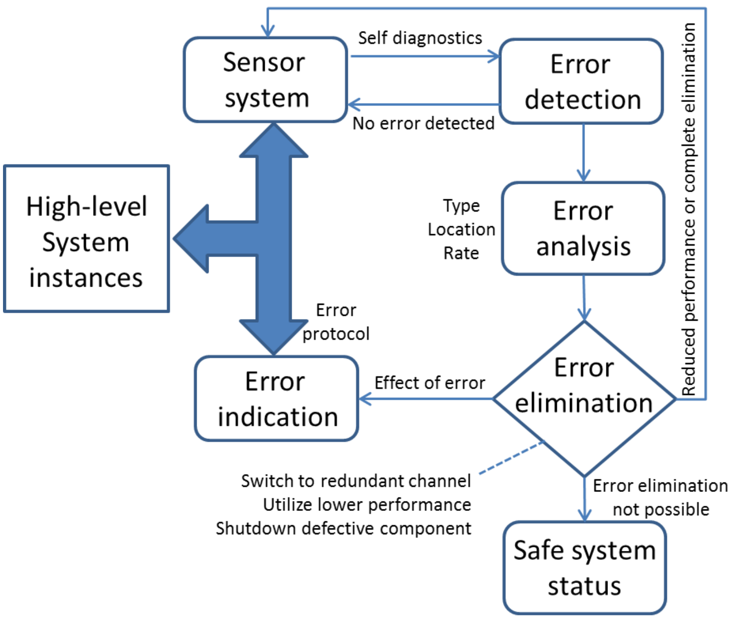
No.	Measurement principle	Redundancy	Diversity	Electrical stimulation	Reliability indicators	Local failure detection	Corre-lation	Comment
								tect cable failures
14	IR detection	X						
15	FO chemical sensors	X						
16	FP interferometer	X			Amount of light energy required; presence of “secondary” peaks in spectrum			
17	Bragg-gratings	X	Thermal influence					
18	Distributed monitoring							Failures affect all measurements in optical fibre
	Brillouin	X	Strain and temperature		Brillouin spectral	OTDR		
	Raman	X				OTDR signal decreasing with length that must be compensated		
	Correlation Rayleigh (OTDR)	X	Strain and temperature			intrinsically		

For all electrical measurement principles, the following applies:
- Reliability indicators on signal cable performance: continuity, isolation resistance, TDR
- Local failure detection: abnormal noise due to inadequate contacts of connectors or wiring pads

7.4 Fail-safe sensor system including diagnostics

In industry, the operation of sensors and electronics in hazardous environments requires the use of intrinsically safe systems that are rated and approved for the specific environment. Since sensors will be implemented for repository monitoring purposes, especially for long-term monitoring of disposal cells after their closure, the focus could be on the use of fail-safe sensors. These systems make use of error detection methods described in the previous section and apply these methods in a predefined, automated manner. An existing sensor system is supplemented with four functional blocks for error detection, analysis, indication, and elimination in order to achieve intrinsic safety. Figure 7-6 shows a principle block diagram of a fail-safe sensor system.

The data processing unit is continuously in self-diagnostic mode, i.e. the functionalities of the sensor element as well as of all downstream components are continuously monitored. Failure detection in sensor elements is a special case. Standard self-diagnostic methods cannot be applied because sensor elements convert non-electrical (physical, chemical, etc.) quantities into electrical quantities and usually, there is no other access from the sensor system to the non-electrical quantities. A further difficulty is that internal signals are superimposed by other signal processing levels and can, thus, not contribute to failure detection. Methods to detect failures must not have a significant impact on data acquisition.



When a failure is detected, the error analysis function is activated. This function determines the type of failure (distinguishing between permanent or short-term failures) and possibly the failure rate and the location of the failure. This information is processed by the error elimination function. The aim of a fail-safe sensor system is continuous data acquisition even if an error occurs. During error elimination, the defective functional block has to be shut down while the system works either via a redundant functional block or while the performance of the sensor system is reduced.

Figure 7-6: Block diagram of a fail-safe sensor system

If error elimination is not possible, the sensor system must be put into “safe system status”, i.e. data transmission to the next system level needs to be interrupted so that output signals from the defective block are not mistakenly interpreted as measurement results. The latter is the most important topic for repository monitoring.

The error elimination status has to be transmitted to the next system level. The signalisation possibilities of the error elimination level are determined by the output interface used. When analogous interfaces are used, the possibilities for error signalisation are limited. Only allocated parts of the output voltage can be used to indicate errors. By comparison, digital interfaces provide enhanced possibilities due to the use of error logs. In addition to the measuring results, the error value can be transmitted. Measuring results and corresponding measuring errors are independent of the system and the manufacturer and are a measure for the quality of the measurement. They are, thus, more suitable than error codes, which are customized to the respective sensor system. The latter can be transmitted in addition to the sensor-specific error description.

7.5 Examples of failure detection application in URLs

7.5.1 Failure detection at the Meuse/Haute-Marne URL

SAGD (*Système d'Acquisition de Gestion de Données*) is a data acquisition system used by Andra and provides a well-established example of an automated failure detection system that has been used for more than ten years. It is aimed at managing the monitoring data at Andra's Meuse/Haute-Marne URL. In order to provide useful information, the system software Geoscope integrates many functions, such as:

- automatic conversion of data into parameter values,
- use of maximum and/or minimum threshold values for triggering alarms and/or for automated disqualification of the data.

When data exceeds the threshold, an alarm is triggered and can be visualized in the list of alarms, and an acknowledge action is requested. An email alert can be set up to send a warning message to the person in charge of the measurements. The SAGD process can also be programed to send an email alert to a mailing list.

A different threshold can be set for automatic disqualification. Disqualification does not obliterate the data but only puts a flag on it. Disqualified data do not appear on the plotting window. Disqualification can also be done manually by authorized users.

The automatic data disqualification is currently used in the Bure Underground Laboratory to discard any “invalid” measurements. In this case, invalid measurements are typically readings recorded before the actual connection of the sensors. Two examples of Bure measurements are presented below:

- In case the data from temperature probes are required as soon as the sensors are connected, the acquisition is started before the sensors are connected (because people installing the sensors are not the ones dealing with the acquisition system). The readings obtained prior to the connection yield absurd measurement values (e.g. 8000°C). So, the disqualification threshold is set above 200°C, for instance. By clicking on the sensor name in the software, only “real” measurements (when the sensors are connected) are plotted.
- With vibrating wire sensors, it appears sometime that the frequency recorded is not the fundamental frequency but harmonics, for example. If the disqualification thresholds are correctly defined, this measurement will be discarded from the plot.

Currently, there is no criterion for the number of disqualified data that may indicate a sensor failure. The current approach for failure detection in the Bure URL is mainly based on the functionalities for giving alarms (this covers sensors and system issues). To track the number of disqualifications for a sensor will be helpful during the operational phase (but Bure URL is focused on independent experiments). Because the Geoscope software is also used to monitor structures such as the Barcelona metro or Monte Carlo building, maybe this idea has already been implemented in a functionality not yet used in Bure URL.

For important measurements, an operator is needed to plot the data weekly and check visually if the data are valid according to the established instructions: abrupt changes, noise or similar observations are currently not handled automatically. The current planning for future development includes that, for example, alarms be sent when there are 5 consecutive measurements automatically disqualified or absent. Furthermore, if there is no value for a given period, an alarm should be sent as well as when there is an abrupt change in the data or trends. Currently, alarms are only sent if thresholds are exceeded.

7.5.2 Failure detection at the MOL URL

In the Mol URL, a system quite similar to the SAGD system described in the previous section is used: each measurement channel can contain a lower and upper limit, and also a limit on the maximum change between two measurement intervals. Furthermore, a minimum measurement interval is specified (to allow timely detection when no new data enter the system). At regular times, the responsible persons get an email with the status of the data.

Currently, an extension is planned to handle the analysis and interpretation of the measurement data in a structured way. Different levels (raw data, first check for disturbances, sensor failure etc. by the principal investigator, up to clearing of the data to the public domain) are defined and will be implemented in a so-called GSIS (geo-scientific information system). In the end, one should be able to retrieve from this system all data required for reports, publications, licence applications etc.

7.5.3 Failure detection in the FEBEX experiment at the Grimsel URL

The FEBEX SCADA (Supervisory Control and Data Acquisition) is almost entirely redundant for quality assurance reasons. Therefore, it comprises two linked computers, configured as master and slave, and double data acquisition units for most of the sensors, so a set of SCADA proprietary data files is independently generated in each computer.

During most of the operational phase, data processing in the FEBEX experiment has been performed every three months. It is basically a manual procedure that starts with the data dumping from the master computer's data files into a master MS ACCESS dedicated database with custom tools to help process them. One reading per sensor and day is included in the master database. Data plots are automatically generated within the database, and a visual revision of the curves is carried out by trained staff.

Any unusual behaviour of a sensor as well as a lack of data of any of them is revised in detail by checking the original readings stored every half hour in the SCADA computers and by correlating doubtful data directly with data from other similar sensors or indirectly with sensors if their measuring parameters are coupled. If possible, data from the slave computer is used to compare it with the wrong readings detected. Eventually, single data points are replaced when the failure is located in the acquisition chain or in the master computer rather than in the sensor itself. If it is not possible to replace data, the wrong data are removed from the data plots, and the sensor status is changed from “good” to “potentially failed”. Unusual behaviours detected so far are mainly spikes, stuck-at, abnormal noise, overload, underload and drifts.

During the maintenance visit carried out every six months, all sensors are revised in-situ by operators using portable reading units. One by one, each sensor is disconnected from the SCADA and connected to those units, and a reading is registered. Any sensor in status “potentially failed” whose signal is not considered correct in this revision is changed to status “out of order”.

All sensors are revised during the data processing, so if a sensor in status “potentially failed” or “out of order” starts providing good readings again, its condition is changed to “good” and its readings are included again in the data plots. A sensor will recover from “out of order” to “good” when the readings can be related to those readings before failure, taking account of any expected evolution during the period that it was “out of order”. An example of this would be where a total pressure sensor was showing increasing readings before the failure and these reading could be correlated with readings from other pressure sensors measuring the same parameters. An example of a similar correlation could be applied to thermocouples located at a similar distance from a heater albeit in different measuring sections

7.5.4 Failure detection in the field experiments at the Äspö HRL

Intelligent datascan units have been used for collection of measured results in most of the field experiments (BaPT, LOT, CRT, PROTOTYPE and TBT) at Äspö HRL. The sensors are connected directly to datascan units. A PC is used to communicate with the datascan system. The software, Orchestrator (SCADAPRO), is used for storing and presenting measured results. The raw data stored with Orchestrator are checked, processed, and (for some data) converted to calibrated values every month. The results are presented as plots and checked for overload, underload, abnormal noise, drift, stuck-at, bias, and loss.

The authorized staff at the Äspö HRL are informed of any failure so that they can try to identify the reasons for failure in a sensor or in other components of the data acquisition system. Most failures have been caused by problems with datascan units or other loggers. The humid environment in the tunnel is the main reason of failure in data acquisition units.

The raw data measured can also be checked directly with online displays on a computer, using dedicated software. The alarm function in the software is used for detecting failure of e. g. heater power in some of the experiments. An alarm is sent to the staff at the Äspö HRL if the power is below or above certain limits.

After the in-situ tests had been dismantled, all the sensors were checked and recalibrated if possible. The results show that the movements in the buffer during the experiment have affected many of the sensors since the welds and connections to the tube are sensitive to movement. The weld between the housing and tubing and coupling was broken in several sensors.

7.6 Discussions and recommendations

An overview of potential failure modes was given above. The numerous and widely varying safety-relevant areas of applications have enabled development of different methods to detect errors and failures, some of which are very specific. These vary with respect to the degree of reliability that can be achieved and thus, with regard to the technical effort and the special requirements of the particular application. An overview of different error and failure detection strategies was given, focussing on failure detection that includes failures of all parts of the monitoring chain including signal/data transmission. Then, these failure detection methods have been related to failure modes and measurement principles.

The relation of detection methods to failure modes gives some idea of which failures modes are leading to major problems, because they may stay undetected and which modes are less "challenging" (e.g. a simple sensor breakdown is easily identified for example by redundancy). It also shows what measures/techniques are effective in addressing failure modes. It may help to select techniques that are favourable with respect to failure detection, and it may also help to identify additional monitoring techniques or measures that can be applied in order to address as many failure modes as possible.

One possibility to increase the reliability of sensor readouts is the use of fail-safe sensors. Since sensors will be implemented for repository monitoring purposes, especially for long-term monitoring of disposal cells after their closure, the focus could be put on the use of fail-safe sensors. These systems make use of error detection methods described in the previous section and apply these methods in a predefined, automated manner.

When monitoring, data should be used as part of decision-making; robust methods and procedures that ensure a good performance of the applied monitoring systems are essential. Due to the long timeframes and the fact that sensors or other components of the monitoring equipment are in many cases inaccessible, monitoring of geological disposal is challenging, and the possibility of failure detection will be an important aspect of the robust methods that need to be developed. Looking at the examples of the failure detection methods and detection procedures applied at the different underground research laboratories in Europe, it is clear that the opportunity for focussed development and application of such methods and procedures is currently limited. This is due to the fact that monitoring techniques are generally applied as part of research projects, with experiments performed often limited in time and, thus, no real long-term monitoring over several decades is possible. Under these circumstances, there will always be the possibility to recover the implemented sensors and check for any performance changes or failures. So, there is no absolute need for a fail-safe sensor to be used in the short-term experiments. However, when it comes to the detection of failures, several specific features of monitoring in waste disposal can be used:

- Evolution of parameters is usually slow, enabling efficient criteria to be defined for local failure detection systems.
- Redundancy can be applied easily and on different levels:
    - redundant sensors in the same disposal component
    - sensors at different locations/distances of/to a disposal component
    - repetitive monitoring of the same component in different parts of the disposal system
    - distinct functional redundancy
- Correlations can be used because in most cases more than one parameter is measured, and these parameters often have a constitutive relationship with each other

With regard to long-term monitoring, this study suggests that when designing the monitoring programme, fail-safe sensors should be considered where possible since these kinds of sensors incorporate a couple of (automatic) failure detection and compensation features.

8 Monitoring deviating repository evolution

8.1 Scenario Development

The following sections provide a qualitative and, for one example, a quantitative evaluation of the ability of a monitoring system, as foreseen to be installed in a salt-based repository for the disposal of radioactive waste, to detect potential scenarios of the repository's evolution. The present assessment applies to "Case 1", where the German disposal concept has been taken as a reference.

8.1.1 Scenarios and scenario development

When assessing the safety of a radioactive waste disposal facility, it is important to consider the performance of the disposal system under both present and future conditions. This means that many different factors (e.g. future human actions, climate and other environmental changes as well as events or processes that could affect the performance of the disposal facility) need to be taken into account. This can be achieved through the formulation and analysis of a set of so-called "scenarios". In this respect, development of scenarios constitutes the fundamental basis for the quantitative assessment of the safety of a repository.

Scenarios are descriptions of possible evolutions of the disposal system. The scenarios are used to identify and define 'assessment cases' that are consistent with the assessment context. Each assessment case may represent or include a range of similar possible evolutions of the disposal system. The selection and the rationale for the selection of an appropriate set of scenarios and associated assessment cases determine the subsequent assessment of the performance of the waste disposal system. In simple words it can be stated that scenarios aim at defining "the broad range of possible future developments to be considered in the subsequent modelling and consequence calculations"..."Scenario development is concerned with the identification, broad description, and selection of potential future scenarios relevant to safety assessment of radioactive waste repositories" (NEA, 1991).

Scenarios represent structured combinations of features, events, and processes (FEPs) relevant to the performance of the disposal system. Different types of scenarios are usually considered including the ***'reference scenario'***, which may also be referred to as the 'base case scenario', 'expected evolution', 'normal evolution' or 'undisturbed performance'. In addition, so-called ***'alternative scenarios'***, which may also be referred to as 'alternative evolution scenarios', are usually considered which include disturbing processes and events. The various *alternative scenarios* considered in an assessment would have most FEPs in common with the *reference scenario*. However, some particular FEPs will differ between the *reference* and the *alternative scenarios*, and these would characterize each particular scenario that deviates from the *reference* one.

Often scenarios are not designed with the aim of illustrating the possible evolution of the disposal system and its surroundings, but rather in order to illustrate the properties of one or more of the natural or engineered barriers (Prij, 1993). For this purpose, parameter values or other properties are assigned to parts of the barrier system so that the barrier under consideration is influenced in an exaggerated way. The aim is then to show that even extreme conditions are not detrimental to the overall safety of the repository. By assuming conditions that are more extreme than what can be expected in reality, the robustness of the various natural and engineered barriers can be more clearly evaluated. Scenarios of this sort are often called 'what if' scenarios to distinguish them from scenarios that are based on more realistic assumptions and parameter values.

Two methods are generally used for constructing scenarios. The method described for example in the IAEA ISAM project (IAEA, 2004), and in the Dutch PROSA project (Prij, 1993), may be described as a 'bottom-up' method and is based on screening of features, events, and processes. When using this method, a comprehensive list of FEPs is developed as starting point. This may involve the use of generic lists of FEPs (internationally agreed lists, regulations, etc.) and the determination of site-specific and system-specific FEPs. This is followed by a screening process to exclude FEPs from further consideration that would have either a very small impact on the disposal system or a very low probability of occurrence. For the relevant FEPs, a thorough examination of interactions between them and their combination in relevant scenarios is performed. Criteria for screening FEPs may include rules relating to regulations and/or to the probability or consequences of FEPs.

The extended PROSA method (Grupa, 1999) has been applied to the safety study underlying the license application for the closure of the Asse salt mine (Germany), including the experimental disposal facilities, and for a review on behalf of the Ministry of Agriculture and Environment of Sachsen-Anhalt (MLU) of two supporting reports issued in 2002 in preparation for the licensing process for the Morsleben Repository for radioactive waste (Endlager für radioaktive Abfälle Morsleben - ERAM) (Grupa, 2003).

An alternative, 'top-down' method for developing scenarios is based on an analysis of how the safety functions of the disposal system may be affected by possible events and processes (e.g. ONDRAF/NIRAS, 2002). This analysis is followed by a process of auditing the scenarios developed against an appropriate list of FEPs.

Regardless of the method used for developing the scenarios, all features, events, and processes that could significantly influence the performance of the disposal system should be addressed in the assessment. In addition, explanations and justification should be provided for those scenarios that are considered to represent the normal or expected evolution of the system, and for those scenarios that address events and processes that have a low or particularly uncertain probability of occurrence. If possible, an indication of the likelihood of each scenario considered should be provided to help with the assessment of risk.

Moreover, it is important to identify how the probabilities of occurrence of events and processes and/or scenarios were assessed, how the uncertainty associated with each scenario was dealt with, and which scenarios were included in the risk evaluations. If probabilities of occurrence of events and processes are integrated in risk calculations, the calculation outcomes can be added up relative to their expected change of occurrence and compared with risk criteria, for example dose limits. If the probability of occurrence of a scenario is not used – so that only doses or risks of each scenario are calculated – an explanation should be provided to clarify how the assessment results from various scenarios are compared to any regulatory criteria on risk.

In safety studies, some events are judged to disturb the evolution of the repository significantly, so additional calculation cases (*alternative scenarios*) are performed next to the *reference scenario*. Examples are (Beuth, 2008):

- Brine intrusion scenario for a repository in rock salt: groundwater intrudes into the repository as a result of, for example, undetected fracturing or water-permeable inclusions in the rock salt. Radionuclides and salt dissolve in this water. Subsequently, convergence of the disposal chambers in the salt can force the brine, contaminated with radionuclides, out of the salt formation into the groundwater or overlying aquifers.
- Poor sealing scenario for a repository in clay: This scenario treats the fictional case where at least one disposal gallery and an access shaft have been poorly sealed during closure of the facility. The possible consequence is the presence of a preferential flow path for radionuclide transport in the case of flooding of the excavated volumes to the biosphere.

- Human intrusion scenarios: Various forms of mining engineering activities (exploratory drilling, construction of a mine) may bring future generations into involuntary contact with the waste.
- Abandonment scenario: Large scale social events during the operation of the facility, e.g. economic crisis, (civil) war, or large natural disasters, could lead to an abandonment of the repository without proper closure. Upon a subsequent flooding of the mine, radionuclides could be released from the waste packages and eventually transported to the biosphere by advective flow and diffusion through the remains of the underground infrastructure.

In general, the scenario development has to indicate in a reasonable manner that all relevant FEPs have been taken into account. Furthermore, compliance with the regulations has to be shown.

8.1.2 Scenarios developed within the Dutch PROSA project

In the Netherlands, the feasibility and safety of deep geological disposal in rock salt was assessed in the past. This section provides a condensed overview of the Dutch methodology to develop scenarios as part of the long-term safety assessment.

Key terms and concepts used in PROSA

<u>Scenario</u>: Considering the set of all possible future repository developments, a scenario is a subset that contains similar future occurrences, i.e. can be covered by the same model calculation. A scenario provides a broad-brush description of the relevant events and processes and their sequencing.

- In the *reference scenario* all barriers, either man-made or natural, are functioning as foreseen (note that this includes a conservative representation of natural decay processes).
- In *alternative scenarios* one or more barriers are compromised.

The probability of the *reference scenario* is practically one, while *alternative scenarios* have small probabilities.

Method adopted in PROSA

An important aim of the PROSA study was the determination of the sensitivity of the radiological consequences on selected system parameters and selected scenarios and the derivation of safety relevant characteristics of a disposal concept. A systematic procedure to account for the variability and uncertainty was used to fulfil this objective.

The starting point of the scenario development was the compilation of a comprehensive list of potentially important FEPs. A screening procedure was applied in order to compile a manageable number of representative scenarios. This screening of FEPs was considered a crucial step in the procedure for scenario selection. As the screening of all FEPs (several hundreds) is time-consuming and complicated to perform on the repository system as a whole, it was proposed to perform this screening process for a number of well-defined states of the barriers in the multi-barrier system. In a particular “state” (e.g. intact, degraded, or absent) of the multi-barrier system, it is easier to screen the FEPs for several reasons:

- In absent barriers (PROSA used the term: “bypassed”), transport related FEPs can be neglected;
- Each multi-barrier state can be linked to a particular time scale in which radionuclides released from the waste packages pass the barrier on their way into the biosphere. If, for instance, the isolation shield in the salt formation is not bypassed, i.e. it maintains its intended safety function, it takes a very long time for the nuclides to leave the salt formation and consequently, short-term FEPs can be neglected accordingly.

Having defined the possible states of the multi-barrier system, the subsequent screening consists of identifying the relevant FEPs for each of the multi-barrier states. Not only the FEPs which can affect the state of the barriers but also the FEPs which affect the transport of nuclides in that state of the barriers have to be identified. The methodology proposed to select the scenarios and to find the processes needed in the consequence analysis contains the following steps:

1. Identification of FEPs that might influence the state of the subsequent barriers as well as the release and transport of radionuclides. The list should be comprehensive and not be restricted to FEPs induced by nature or components of the disposal concept but also contain human-induced FEPs.
2. First screening of the list of FEPs. The first screening of this list is performed with respect to the type of host rock (repository in a rock salt formation) and the probability of occurrence.
3. Classification into so-called “primary” and “secondary” FEPs. A primary FEP is assumed to directly attack or bypass one or more of the barriers of the multi-barrier system. The primary FEPs consequently define the state or evolution of the repository. In particular they lead to a change in the size or the short-circuiting of the barriers. The remaining FEPs are defined as the secondary FEPs. These FEPs relate to the transport and the state of the nuclides for a given state or evolution of the repository and should be included in the transport model.
4. Definition of possible multi-barrier states (MBS). In the definition of the state or evolution of the barriers in the multi-barrier system, a simple and straightforward division into attacked or by-passed was proposed. In addition, a relatively small number of barriers was proposed to limit the number of possible MBS.
5. Assignment of the primary FEPs to each of the multi-barrier states taking into account that some processes attack more than one barrier.
6. Screening of the FEPs for each of the multi-barrier states. In this screening a classification of FEPs with respect to time is very helpful.
7. Definition and selection of the scenarios to be analysed further. This step also includes the selection of the processes to be taken into account in the consequence analysis.
8. Determination of the secondary FEPs for each of the multi-barrier states.

A total of 22 scenarios have been identified (Table 8-1) that were further developed and evaluated. The PROSA method leads to three families, or distinct grouped sets, of scenarios: (i) Subrosion scenarios, (ii) Flooding scenarios, and (iii) Human intrusion scenarios.

For the following reasons, only the flooding family seems of interest:

Subrosion scenarios are relevant only on a geologic timescale.
Human intrusion scenarios: during the period of institutional control, access control should prevent human intrusion. In the post-closure phase, surface-based technologies will detect human intrusion.
Flooding scenarios are of interest since they may occur on a shorter timescale (Table 8-2).

With respect to Scenarios Id. 14 and Id. 17, it was concluded in PROSA that at that time, no accurate models existed to analyse the consequences of very high gas pressure. A sudden release of stored energy (Scenarios Id. 15 and Id. 18) was assumed to be not relevant based on first model calculations, but if future studies show otherwise, it was noted that this scenario has to be analysed in more detail. In conclusion, four flooding scenarios where distinguished in PROSA.

Table 8-1: Summary of scenarios identified
(X: barrier impaired; EB: Engineered barrier, Is: Isolation Shield, Ob: Overburden)

MBS Nr.	State of Barriers			Scenario	
	EB	Is	Ob	Dominant primary FEPs	Id.
1	X	X	X	Subrosion, diapirism, denudation	1
2	X	X		Subrosion, diapirism, fault in overburden Subrosion, diapirism, glaciation	2 3
3	X		X	Flooding Flooding, large brine pocket	4 5
4	X			Flooding, fault in overburden Flooding, large brine pocket, fault	6 7
5		X	X	Subrosion, high gas pressure Subrosion, release of irradiation induced energy	8 9
6		X		High gas pressure, fault in overburden Release of stored energy, fault in overburden High gas pressure, glaciation Release of stored energy, glaciation	10 11 12 13
7			X	Flooding, very high gas pressure Flooding, release of stored energy Leaky storage cavern	14 15 16
8				Flooding, very high gas pressure, fault Flooding, release of stored energy, fault Reconnaissance drilling Solution mining Conventional mining Archaeological investigation	17 18 19 20 21 22

Table 8-2: Family of flooding scenarios
(X: barrier impaired, EB: Engineered Barrier)

MBS Nr.	State of Barriers			Scenario	
	EB	Is	Ob	Dominant primary FEPs	Id.
3	X		X	flooding flooding, large brine pocket	4 5
4	X			flooding, fault in overburden flooding, large brine pocket, fault	6 7
7			X	flooding, very high gas pressure flooding, release of stored energy	14 → 4 15 → 4
8				flooding, very high gas pressure, fault flooding, release of energy, fault	17 → 6 18 → 6

8.1.3 Scenarios considered in the generic German disposal concept

In the German Safety Case for geological disposal in rock salt, sets of alternative scenarios have been developed in addition to a normal evolution scenario that each represents sequences of less likely and unlikely events (Buhmann et al., 2008). These scenarios were subdivided into three classes of scenarios:

- The "altered premises" group: this “A group” covers scenarios where realistic but less likely deviations from the premises used for the reference scenario are considered;
- The "less likely evolution" group: this “B group” of scenarios covers less likely evolutions of a likely FEP directly related to barrier functions;
- The "less likely FEPs" group: this “C group” of scenarios covers elements of the FEP catalogue that are considered to be less likely.

The procedure to develop the reference scenario and the alternative scenarios in the German safety concept is shown in Figure 8-1. This procedure is also adopted for the present study.

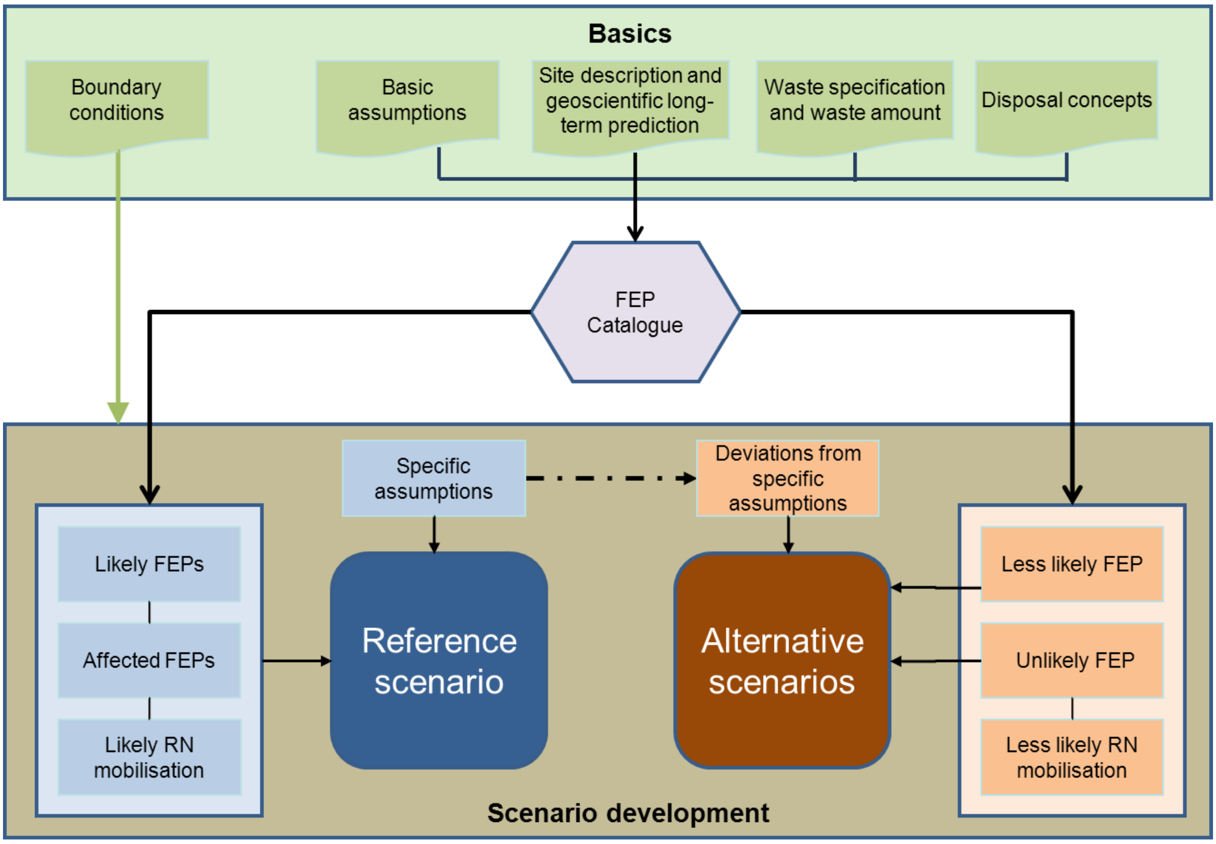


Figure 8-1: Schematic representation of the elements and methodology used for the development of scenarios

The next section describes the three different classes of scenarios in more detail.

"Altered premises" group

The "altered premises" group covers scenarios where realistic but less likely deviations from the premises (assumptions) used for the *reference scenario* are considered.

Two scenarios were defined with respect to the future evolution of the geosphere:

A.1) Two glacial channels will develop within the next 1 million years

A.2) A glacial channel will develop at a greater depth (600 m) within the next 500,000 years

Two potential scenarios were identified with respect to the performance of seals and dams:

A.3) Early failure of the shaft seal

A.4) Early failure of dams that seal connecting galleries

Three scenarios were identified with respect to (undetected) presence of potentially water-conducting geologic features as anhydrites or Carnallite in the vicinity of disposal cells/galleries (<50 m):

A.5) Presence of undetected geological features in the vicinity of disposal cells/galleries in (>20 m)

A.6.) Presence of brine inclusions in the vicinity of connecting galleries (<100 m³)

A.7.) Presence of fissures between potentially water conducting layers and galleries

"Less likely evolution" group

The "less likely evolution" group of scenarios covers less likely evolutions of a likely FEP which is directly related to barrier functions.

B.1.) Subrosion: higher subrosion rates are always considered to be connected to the development of glacial channels and are treated in conjunction with glacial scenarios (B.2).

B.2.) Development of glacial channels: this scenario is comparable to the glacial scenarios A.1/A.2 of the "*altered premises*" group and includes scenario B.1.

B.3.) Early failure of disposal container: early failure of one or more waste disposal containers would lead to the mobilisation of volatile radionuclides and subsequently - when a solute phase is present - corrosion of the waste matrix and mobilisation of soluble radionuclides.

B.4.) Impairment of performance of shaft seals: this may alter the permeability, porosity, and air entry pressure of the seals. As a consequence, modified migration properties of the seals may lead to the increased transport of gas and solutions.

B.5.) Convergence: altered convergence rates of open or backfilled spaces in the repository (disposal cells, galleries, shafts) may alter the geomechanical evolution of the repository, e.g. the healing of the EDZ or the compaction of seals and dams. This may affect the radionuclide release from the repository.

B.6.) Displacement of (parts of) shaft sealing: This scenario will be covered by scenario C.2 of the "*less likely FEP*" group (see below).

B.7.) Swelling behaviour of bentonite in the shaft seal: This scenario will be covered by scenario C.2 of the "*less likely FEP*" group (see below).

B.8.) Metal corrosion: Higher corrosion rates will result in higher gas generation rates and - in the case of activated metals - to increased radionuclide mobilisation. In addition, higher corrosion rates of waste containers may lead to earlier container failure. This may affect the radionuclide release from the repository.

B.9.) Degradation/corrosion of cementitious materials: Degradation/corrosion of cementitious materials may affect the properties and performance of shaft seals, dams, and other sealing elements. As a result, the transport of gas and solutions and eventually radionuclides through the seal may increase, or a potential transport in the repository may be modified. This scenario will be covered by the accompanying scenarios C.2, C.3, and C.4 of the "*less likely FEP*" group.

B.10.) Degradation of mechanical strength of metals due to inclusions of H_2 gas: This scenario will be covered by scenario B.3 (early failure of a disposal container) and addressed in scenario C.2 of the "*less likely FEP*" group.

B.11.) EDZ: the appearance of the EDZ alters the properties (e.g. permeability) of the host rock that directly encloses sealing elements in the repository and may alter the sealing performance of shaft seals, dams, or other sealing elements. This scenario will be covered by scenarios C.2, C.3, and C.4 of the "*less likely FEP*" group.

B.12.) Fissures and inhomogeneities in the host rock: Undetected fissures and inhomogeneities in the host rock may influence the barrier performance or may lead to inflow of solutions. The first aspect is covered by C.2 of the "*less likely FEP*" group, the latter by B1.4, "presence of fluid in the host rock".

B.13.) Altered stress conditions in the host rock: Altered stress conditions in the host rock may affect several FEPs related to fluid pressure (and movement) and the performance of barriers. This needs to be assessed in an alternative scenario.

B.14.) Presence of fluid in the host rock: The presence of larger amounts of (undetected) fluids in the host rock need to be assessed in an alternative scenario. This scenario is comparable to A.1/A.2 of the "*altered premises*" group

B.15.) Presence of carbohydrates in the host rock: the presence of carbohydrates in the host rock is considered to be only relevant in relation to the thermochemical reduction of sulphates and addressed in B.16 (see below).

B.16.) Thermochemical reduction of sulphates: potential effects of thermochemical reduction of sulphates need to be assessed in an alternative scenario.

B.17.) Infiltration of gases into the host rock: It is presently unclear if gas can permeate into the host rock under the prevailing conditions. Permeation of gas into the rock may alter the latter's permeability and needs to be assessed in an alternative scenario.

"Less likely FEPs"-group

The "less likely FEPs" group of scenarios covers elements of the FEP catalogue that are considered to be less likely.

C.1.) Potential flow path in former exploration drill holes: In this scenario, a flow path between parts of the repository or between parts of the repository and the enclosing geosphere may exist in a borehole that was used for geological exploration. Due to the presence of a flow path that connects the repository with the enclosing geosphere, solution may enter the repository, which in turn may lead to an early contact to the waste containers and, consequently, to the mobilisation and transport of radionuclides. If the flow path exists between parts of the repository only, it may allow an increased transport of solutions and gases inside the repository, while a transport of solution to the enclosing geosphere can occur through the shaft seal only.

C.2.) Early failure of shaft seal: An early failure of the shaft seal may shift the radionuclide source term upfront; it can be represented in PA model calculations by assuming an increased permeability of the shaft.

C.3.) Early failure of a dam in the connecting galleries: The early failure of a dam may shift the radionuclide source term upfront; it can be represented in a PA model by assuming an increased permeability of the dam. It is noted that due to the low probability of a simultaneous failure of both shaft seal and dams, this will not be assessed in a separate scenario.

C.4.) The early failure of sealing elements without barrier function: The early failure of sealing elements used to seal connecting galleries but have no barrier functions may alter the transport of gases and solutions in case of flooding.

C.5.) Preferential flow paths in seals, dams, or other sealing elements: The occurrence or development of preferential flow paths in seals, dams, or other sealing elements can increase the porosity and permeability of these barriers or sealing elements. This scenario will be covered by C.2 to C.4, depending on the particular element.

The scenarios described are the basis of the scenarios considered in this case study

8.1.4 Selection of alternative scenarios

Table 8-3 gives an overview of the scenarios considered for the generic German disposal concept in rock salt. The selection of scenarios results in 13 different scenarios, 12 of which are considered to be of potential interest for this case study.

Table 8-3: Potential scenarios to be considered

Nr	Name	'Premises' group	'Less likely FEP' group	'FEP' group	MoDeRn WP4.5
1	Development of glacial channels	A.1, A.2	B.1, B.2		-
2	Early failure or reduced performance of shaft seal	A.3	B.4, B.6, B.7, B.9, B.11, B.12	C.2, C.5	+
3	Early failure or reduced performance of dams	A.4	B.4, B.6, B.7, B.9, B.11	C.3, C.5	+
4	Presence of undetected geologic features	A.5	B.12, B.14		+
5	Presence of brine inclusions	A.6	B.12, B.14		+
6	Presence of fissures	A.7	B.12, B.14	C.1	+
7	Early failure of container		B.3, B.10		+
8	Altered convergence behaviour		B.5		+
9	Metal corrosion		B.8		+
10	Failure of other sealing elements		B.9, B.11	C.4	+
11	Altered stress conditions in the host rock		B.13		+
12	Thermochemical reduction of sulphates		B.15, B.16		+
13	Infiltration of gases into the host rock		B.17		+

One scenario, i.e. scenario Nr.1 “development of glacial channels”, is judged to be of no importance in the context of MoDeRn due to the very long time scale (several hundred thousand years), which makes the evaluation of monitoring results unfeasible. The second scenario, “*early failure or reduced performance of shaft seal*”, is analysed in a quantitative manner in section 8.3.

The scenarios described above and summarized in Table 8-3 have been developed for the German safety concept, which is also adopted for the case study.

8.2 Qualitative assessment of the scenarios against monitoring results

The aim of this study is to assess how the scenarios outlined above would impact the readouts of the monitoring devices as described in a previous section. The respective scenarios will be described shortly and for each scenario it is discussed how the measured parameters in the different sections of the repository are expected to evolve as a result of the investigated scenario.

8.2.1 Scenario 1: Development of glacial channels

The timing of the development of glacial channels is far beyond the foreseen institutional control period, including monitoring, of 500 years. Therefore, this scenario is not assessed in this evaluation.

8.2.2 Scenario 2: Early failure or reduced performance of shaft seal

The safety function attributed to the shaft seal is “sealing against water” (Figure 4-3). This function is intended to hold in both directions:

- 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.
- The shaft seal is to retain radionuclides in the repository in the event that nuclides are mobilised during the post-closure phase.

In both cases, an early failure or reduced performance of the shaft seal is only of concern in case brine is present inside the repository. Otherwise, there will be no radiological consequences in the biosphere. If a shaft seal is in place, the repository is already in a closed state, i.e., the drifts and boreholes are backfilled and the drifts and boreholes are sealed. In this scenario, it is assumed that the shaft seals will not fail simultaneously with the drift and borehole seals (VSG, 2011). As a consequence, the drift seals and borehole seals will maintain their safety functions, and failure of the shaft seal in combination with the presence of brine inside the repository is only of concern for the backfilled drifts which are directly connected to the shaft. Early failure or reduced performance of a shaft seal can manifest itself in the following features (VSG, 2011):

- Increased permeability of the sealing elements
- Increased permeability of the periphery of the sealing elements
- Decreased stability of the structures involved
- Reduced retardation capability of the sealing elements
- Reduced lifespan of the sealing elements

If the repository is in a dry condition, it is assumed that an early failure or reduced performance of the shaft seal cannot be detected by monitoring equipment which is installed inside the drifts or adjacent to or inside the disposal boreholes (Table 8.4).
A failure or reduced performance of a shaft seal is of special concern when brine is present. In this case, the safety function “sealing against water” is affected. A failure or reduced per-

formance of the shaft seals can be indicated by an inflow of brine through the shaft into the repository. In this case, alternative readouts of the proposed monitoring equipment can be expected:

- The distribution of stresses and pressures will differ on opposite sides of drift seals, which are assumed to meet their intended safety functions.
- 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 will be detected at various locations.

Table 8-4: Overview of sensor readouts in relation to scenario 2 *"early failure or reduced performance of shaft seal"*

Parameter - Indicative for Scenario	(detectability: + high, o medium, - low)			
	Module 1: borehole (backfill) and liner/cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		-
Radial pressure	-	-		
Pore pressure		-		
Total pressure				-
Rock stresses			-	
Displacements				-

More direct evidence of the performance of the shaft seals can be provided by pressure sensors that are installed inside the shafts and adjacent to the seals. The evolution of the pressure over time will provide an indication of the convergence rate of the shaft seal. The porosity and permeability of the shaft seals, which are indicators of their performance, can be estimated subsequently. The readouts of the monitoring equipment installed at the designated locations may develop as indicated in the table below. This scenario will also be analysed in a quantitative manner in section 8.3.

Table 8-5: Overview of sensor readouts in relation to scenario 2 "*early failure or reduced performance of shaft seal"* – assuming the presence of brine

Parameter - Indicative for Scenario	(detectability: + high, o medium, - low)			
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		+
Radial pressure	+	+		
Pore pressure		+		
Total pressure				+
Rock stresses			+	
Displacements				+

8.2.3 Scenario 3: Early failure or reduced performance of drift seals

The safety function attributed to the drift seals is "sealing against water" (Figure 4-3). Drift seals form an integral part of the overall closure concept of the final repository, and – in case of disturbance – are to prevent or impede fluids that have penetrated the system via the shaft seals from entering into the rest of the mine workings. During a disturbed repository development (brine inflow), they are also to prevent fluids from leaving the emplacement area. Early failure or reduced performance of drift seals can be caused by e. g. unsound construction design, use of defective or unsuitable materials, and shortcomings in the implementation planning, and may be revealed by the following features (VSG, 2011):

- Increased permeability of the sealing elements
- Increased permeability of the periphery of the sealing elements
- Decreased stability of the involved structures
- Less retardation capability of the sealing elements
- Reduced lifespan of the sealing elements

An early failure or reduced performance of drift seals is of concern in the case of the presence of brine inside the repository. In the case of a "dry" repository, an early failure of the drift seal does not lead to any transport of soluble radionuclides into the biosphere. In addition, the safety function attributed to the drift seals does not include sealing against released gases or the reduction of gas pressure. In case gaseous, volatile products are released from the boreholes, these gases may permeate into the overlying drifts and pass the drift seals. In this scenario it is assumed that failure of the drift seals will not occur simultaneously with failures of other sealing elements (VSG, 2011). As a consequence, the shaft seals and borehole seals will maintain their intended safety functions.

If a drift seal is in place, the repository is already in a closed or partially closed state, meaning that (part of) the drifts and boreholes are backfilled with crushed salt and sealed with plugs. If the shaft is also backfilled and sealed, no brine will be able to enter or leave the repository, as the shaft seal would maintain its intended safety function. In the case of an open, unsealed shaft (i.e. during the operational and pre-closure phase), an affected drift seal will constitute a potential flow path to the biosphere.

In this scenario, it is assumed that the borehole seals maintain their intended long-term safety functions. As a consequence, no brine would be able to enter or leave the boreholes after the borehole plugs are sufficiently compacted ("closed") due to the convergence of the open spaces of the repository. Upon their instalment, the borehole plugs remain slightly permeable for an extended period of time, i.e. for several hundred years. During this time frame, radionuclides could be carried out of the boreholes by the transport of brine, if present, and pass the failed drift seal. It should be noted that this implies the failure of canisters (scenario 7) within the borehole during this time frame, which is not likely since the lifetime of the canisters covered by the liner is 500 years minimum as required by the Safety Requirements issued by the BMU (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) in 2010 (BMU, 2010). It is reiterated that the drift seal does not have a safety function with regard to delaying or restraining gaseous or volatile matters that may be released from the waste canisters.

It is assumed that under normal, dry conditions of the repository, an early failure or reduced performance of drift seals can be detected by equipment monitoring the pressure or displacements in, near, or adjacent to the drift seals. The evolution of the pressure may provide indirect information about the porosity and permeability of the drift seal. The water content or humidity will affect the convergence of backfilled spaces and compacted salt seals, and, in relation to the pressure evolution, may provide indirect information about the state of compaction of the drift seal. However, these parameters do not provide information about the presence and status of EDZs adjacent to a plug.

The temperatures and rock stresses measured in the host rock do not provide direct information about the state of the seals. The readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-6: Overview of sensor readouts in relation to scenario 3 "e*arly failure or reduced performance of dams"*

Parameter - Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		0
Radial pressure	-	-		
Pore pressure		-		
Total pressure				+
Rock stresses			-	
Displacements				+

A failure or reduced performance of a drift seal is of special concern when brine is present in the repository. In that case, the safety function "sealing against water" is affected. This situation will likely lead to deviating readouts of the proposed monitoring equipment:

- The distribution of stresses and pressures will level off at opposite sides of the affected drift seals.
- The convergence of backfilled drifts will likely slow down due to the backpressure of brine-filled drifts, resulting in measured displacements which may differ from the expected values or which may differ significantly for "dry" locations in the repository.
- The presence of water/humidity will be detected at various locations.

Table 8-7: Overview of sensor readouts in relation to scenario 3 *"early failure or reduced performance of dams"* – assuming the presence of brine

Parameter - Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		+
Radial pressure	-	-		
Pore pressure		-		
Total pressure				+
Rock stresses			+	
Displacements				+

8.2.4 Scenario 4: Presence of undetected properties

This scenario comprises the potential presence of undetected features in the vicinity of the disposal cells and galleries and of fissures and inhomogeneities in the host rock.

In this scenario, the different repository components are assumed to maintain their intended safety functions (VSG, 2011). The presence of undetected properties (e.g. anhydrite) or fissures may lead to the intrusion of brine into the disposal cells and the formation of potential pathways for radionuclide transport out of the disposal cell to the enclosing geologic particularities if they are located in the vicinity of the disposal cells (and galleries). As per design, a minimum safety distance of 50 m is generally maintained between disposal cells or disposal galleries and the particularities mentioned above. Based on the site characterization techniques used, it can be assumed that the presence of undetected features, brine inclusions, or fissures are within a distance of at least 30 m to the disposal cells and are most likely to appear at the interface of the Zechstein host rock.

By monitoring the temperature evolution in the undisturbed host rock as a function of time and space, it may be possible to detect the presence of (larger) disturbances in the host rock when the measured values are compared with the results of model simulations. Openings in the host rock, e.g., fissures, inhomogeneities, or undetected brine pockets, are less efficient heat conductors than undisturbed salt bodies. As a consequence, these features would act as local heat isolators, which lead to increased temperatures in between the disturbances and the heat-generating canisters. However, because it is assumed that disturbances are located at a large distance to the emplacement areas, it is very unlikely that this scenario can be directly detected by temperature or stress monitoring.

Indirect evidence[2] for the occurrence of such a scenario can be given by the presence of brine, which can be detected under certain circumstances, e.g.:

- brine intrusion happens in a monitored borehole
- the amount of brine intrusion is large enough to trigger the humidity sensor at the top of the borehole, where the sensors are situated.
- brine intrusion happens during the monitoring phase

It can be argued that the presence of undetected particularities can only impair the safety of the repository if brine intrudes into the disposal cells. A monitoring set-up that allows measuring the presence (or absence) of brine at the bottom of *all* boreholes would allow to detect the presence of brine intrusions.

Table 8-8: Overview of sensor readouts in relation to scenario 4 "*presence of undetected geologic features"*

Parameter - Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		-
Radial pressure	-	-		
Pore pressure		o		
Total pressure				-
Rock stresses			-	
Displacements				-

8.2.5 Scenario 5: Presence of brine inclusions

This scenario relates to the presence of brine inclusions (<100 m^3) in the vicinity of connecting galleries. In this scenario the different repository components are assumed to maintain their intended safety functions. The presence of undetected brine inclusions, including the

[2] Note that the presence of undetected geologic features must not necessarily lead to brine intrusion into the disposal cell. Evaluating the conditions under which such intrusion may happen is beyond the scope of this study.

presence of hydrocarbons, in the vicinity of the connecting galleries could lead to a release of radionuclides in the disposal facility, as brine is capable of serving as a transport medium.

The safety function attached to the host rock is "tightness against fluids" (Figure 4-3). Two processes may impair this safety function as natural geologic barrier: excavation activities and the local heat input by HLW in the emplacement area. For both processes, the thermo-mechanical impact on the host rock must be assessed, since they may result in the generation of open, connected pore volumes. The formation of micro fissures may lead to the formation of pathways that allow the intrusion of brine solutions into the emplacement area. Relatively small brine pockets will most likely be present – if at all – in the vicinity of stratigraphic interfaces. It is therefore unlikely that such a feature can be detected by temperature sensors or stress sensors at any of the monitoring locations or by the displacement sensors at the barriers. As in the previous section, indirect evidence may be given if brine is present in the connecting gallery, which can be detected under certain circumstances:

- brine intrusion happens in the vicinity of a (monitored) drift seal[3]
- brine intrusion happens during the monitoring phase

The presence of brine inclusions in the vicinity of the connecting galleries only impairs the safety of the repository if brine actually enters the galleries and subsequently, the disposal cells. Depending on the amount of brine and the compaction state of the backfill, brine intrusion into connecting galleries can be measured by humidity sensors at the barriers. A quantitative assessment is necessary in order to assess under which specific conditions this applies. A monitoring set-up that allows the measurement of the presence (or absence) of brine at the bottom of *all* boreholes would enable the presence of such a condition to be monitored. In case the compaction of the disposal cell sealing progresses quickly enough to achieve a complete sealing of the disposal cell (i.e. the seal is impermeable) during the monitoring period, an intrusion of brine in the period thereafter can be excluded.

Table 8-9: Overview of sensor readouts in relation to scenario 5 "p*resence of brine inclusions"*

Parameter - Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		+
Radial pressure	-	-		
Pore pressure		-		
Total pressure				-
Rock stresses			-	
Displacements				-

8.2.6 Scenario 6: Presence of fissures

This scenario comprises the presence of fissures between potentially water conducting layers and galleries.

[3] The repository concept anticipates that all drift seals are monitored.

In this scenario, the different repository components are assumed to maintain their intended safety functions. Only the presence of undetected water in the vicinity of the disposal cells and galleries could lead to a release of radionuclides into the biosphere, as brine is capable of serving as a transport medium. Fissures in the host rock can serve as a potential brine flow path into (parts of) the repository and subsequent outflow of contaminated brine and release into the biosphere. Parameters that characterize these features are (cf. section 4.3):

- the temperature evolution, i.e., the rock temperature in the vicinity of canisters and the underground openings, and
- the stress evolution in the geologic barrier

The temperature evolution, resulting from the heat output of the emplaced radioactive waste, is a process that provides indirect information about the stress evolution due to the thermally induced stresses and the thermally accelerated creep behaviour of the rock salt. The procedure to verify the geomechanical integrity of a geologic barrier is based on calculations. These calculations rely on the correct representation of the temperature evolution for calculating the long-term stress evolution. By comparing the temperature evolution in the undisturbed host rock as a function of time and extent into the host rock with measured values, it should be possible to detect the presence of disturbances or open spaces in the host rock. Openings in the host rock – in the current concept assumed to be fissures – conduct the heat propagation into the host rock less efficiently than the undisturbed salt bodies. As a consequence, these features would act as a local heat isolator, leading to increased temperatures in between the disturbances and the heat producing canisters. If the disturbances are located at one side of a module of the repository, this would mean that at this side the measured temperatures would be systematically higher than at the undisturbed side. Information about the presence of inhomogeneities could be obtained from a comparison of the corresponding readouts from local groups of temperature sensors, and confirmed by an analysis of 3D heat conduction models assuming discontinuities (yes or no).

Table 8-10: Overview of sensor readouts in relation to scenario 6 “*presence of fissures”*

Parameter - Indicative for Scenario		(detectability: + high, o medium, - low)		
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	o	-	o	
Water content		-		-
Radial pressure	-	-		
Pore pressure		-		
Total pressure				-
Rock stresses			o	
Displacements				-

Determining the stress evolution in the geologic barrier can also be an indication of the presence of disturbances in the host rock. In an undisturbed situation, the local stresses in the host rock are expected to develop in a more or less isotropic manner. If, however, disturbances in the host rock exist at one side of the repository, this may lead to anisotropic rock stresses in the vicinity of the underground openings. As a consequence, a systematic deviation in one direction of rock stresses measured near the excavated parts of the repository can be an indication of the presence of local disturbances in the host rock. However, to be able to assess if it is likely that fissures are detectable by the methods mentioned, the location and extend of fissure in the host rock need to be known (and assessed).

8.2.7 Scenario 7: Early failure of container and liner

The safety functions attributed to the container are “confinement/immobilization of radionuclides”, and “sealing against fluids”.

An early failure of disposal containers would lead to the mobilization of volatile radionuclides and subsequently, when a solute phase is present, corrosion of the waste matrix and mobilization of soluble radionuclides. In addition, the metal parts may lose their mechanical strength due to the inclusion of hydrogen gas. Mobilized volatile components can only escape from already sealed boreholes if the borehole seals are not yet sufficiently compacted due to the pressure of the overburden. Within the scope of the PAMINA project (Becker et al., 2009), the associated “time to closure” against liquids has been estimated at several hundred years. The “closure” of the plugs against the transport of gases should be evaluated separately. For both liquids and gases, potentially hazardous releases may occur if the disposal containers fail only a few hundred years after their emplacement.

The presence of volatile radionuclides, which is an indirect indication of container/liner failure, cannot be detected with the equipment currently available. The measured parameters temperature, pressure, stresses, displacements, and water content are not, or perhaps only to a minor extent, affected by this event. The readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-11: Overview of sensor readouts in relation to scenario 7 “*early failure of container and liner”*

Parameter -Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		-
Radial pressure	-	-		
Pore pressure		-		
Total pressure				-
Rock stresses			-	
Displacements				-

An early containment failure is of special concern if brine is present in the repository. In this case, radionuclides may be mobilized by the brine and transported away from the affected containers and boreholes. However, this situation would only be possible as long as the borehole seals have not been compacted to their “closure state” as a result of the on-going convergence of the open and porous spaces. The consequences in terms of dose rates released to the biosphere as a result of such a scenario must be assessed separately. If brines are present, the readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-12: Overview of sensor readouts in relation to scenario 7 “e*arly failure of container and liner”* – assuming the presence of brine

Parameter -Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geo-logic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		+
Radial pressure	0	+		
Pore pressure		+		
Total pressure				+
Rock stresses			+	
Displacements				+

8.2.8 Scenario 8: Altered convergence behaviour

When all waste canisters are emplaced, the entire void volume of all mine workings in the repository will be backfilled with crushed salt, and the various seals will be put into place. Upon convergence by the pressure forces of the overburden, the backfill and seals will be compacted further. During compaction, the porosity and permeability of the backfill and seals decrease until, in the long run, they exhibit the same barrier properties as rock salt. From that time on, the compacted volumes are virtually impermeable for fluid flow. The safety barriers that are affected by the FEP convergence are the drift seals and the shaft seals (Rübel, 2011).

An altered convergence behaviour may affect a variety of features, processes, and parameters, such as pressures, stresses, porosities, EDZs, potential flow paths, displacement of material, volume changes, etc. It is, however, assumed that altered convergence rates of open or backfilled spaces in the repository (disposal cells, galleries, shafts) do not alter the fundamental processes themselves, but rather the evolution over time of the relevant processes. As a result, any excavation damaged zones, faults, and fractures in the host rock may heal more slowly or faster, and the compaction rates of (compacted) crushed salt may change. These processes may affect the release of radionuclides from the repository (Rübel, 2011).

A faster than normal convergence rate may have two implications:

- Seals and backfill will be compacted faster, resulting in an earlier “closure” of the repository. This effect may accelerate safe confinement.
- When already present in the repository, any contaminated brine will be forced out faster from the repository, which may lead to an increase of the dose rate in the biosphere.

A slower than normal convergence rate may have two implications, too:

- Seals and backfill will be compacted more slowly, resulting in a later “closure” of the repository. This effect may postpone safe confinement.
- When already present in the repository, any contaminated brine will be forced out more slowly from the repository, which may lead to a lower dose rate in the biosphere.

In the PA model assumptions currently utilized, there is a direct relation between the temperature and the convergence rate in a salt-based repository (Buhmann et al., 2005). A higher temperature, due to the heat input from the radioactive waste, increases the convergence rate, and a lower temperature decreases it. However, the temperature is not an indication of the convergence rate. An alternative and unforeseen situation arises when at a given temperature the convergence rate increases or decreases faster than anticipated by the prevailing relationship between temperature and convergence rate.

In addition to the temperature, the presence of brine in backfilled volumes affects the convergence rate. As a result of the backpressure exerted by the brine, the convergence rate slows down significantly. In general, altered convergence behaviour can be detected with devices measuring pressure-related properties, i.e. pressures, stresses, and displacements. The readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-13: Overview of sensor readouts in relation to scenario 8 "*altered convergence behaviour"*

Parameter -Indicative for Scenario		(detectability: + high, o medium, - low)		
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		+
Radial pressure	+	+		
Pore pressure		+		
Total pressure				+
Rock stresses			+	
Displacements				+

8.2.9 Scenario 9: Metal corrosion

From a chemical point of view, corrosion occurs by a chemical or an electrochemical reaction of a metal with substances from the environment. In the case of steel corrosion, the corrosion reaction is influenced by the pH and the availability of oxygen (aerobic corrosion / acid or hydrogen corrosion). In a sealed repository, the available atmospheric oxygen is rapidly consumed by aerobic corrosion reactions of container materials and other mining materials. Subsequently, only anaerobic corrosion processes will occur to form hydrogen gas. In this case, water is consumed and salts crystallize (Rübel, 2011).

For repository safety assessments, metal corrosion rates are modelled which are usually based on average values obtained from a variety of samples under different conditions and temperatures. As an alternative, it may be assumed that metal corrosion occurs faster than assumed in a *reference scenario*. Actual values for less likely corrosion rates should be determined based on dedicated analyses of processes and available data (Rübel, 2011).

A variety of FEPs are influenced by corrosion, such as radionuclide mobilization, sorption and desorption, the repository's geochemical environment, etc. An increased corrosion of metals results in an increased formation of hydrogen gas and larger volumes of corroded metals. It may also lead to earlier waste containment failure and increase the mobilization of radionuclides. No significant corrosion of the iron insert and the fuel assembly is conceivable before the overpack has been breached and moist air intrudes into the canister. Internal corrosion products, which have a lower density and, therefore, occupy more space than the original metallic components, may cause deformation of the canister or clogging of pathways.

Before the radioactive material in the canister can start to migrate after failure of the overpack, it has to dissolve into the groundwater, a process that depends on radionuclide solubility and speciation. Inside the canister, radionuclide retardation by iron corrosion products is an important factor. The outflow of corrosion products from the disposal boreholes will be terminated when the borehole seals are sufficiently compacted by the on-going convergence and the seals have become impermeable for fluid flow.

In general, temperatures will not be affected by changed corrosion rates, since this process is very slow. However, pressure-related parameters are considered to be affected to a minor extent. The readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-14: Overview of sensor readouts in relation to scenario 9 "*metal corrosion*"

Parameter -Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geo-logic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		-
Radial pressure	0	-		
Pore pressure		0		
Total pressure				-
Rock stresses			-	
Displacements				-

8.2.10 Scenario 10: Failure of other sealing elements

Other sealing elements than the shaft seals and drift seals are elements whose function is to close cross-cuts between adjacent drifts (Buhmann, 2011). An early failure of these sealing elements has no direct effect on the other isolating barriers. However, the flow resistance to fluid flow in the repository, if occurring, and thus the potential radionuclide transport can be affected significantly. Due to the early failure of this type of sealing element, the porosity and permeability in this location will increase. In addition, but to a lesser extent, the failure of the sealing elements may also affect the stress distributions in the vicinity of the sealing elements. These processes can result in a dispersion of the relatively large amounts of moisture present in the backfill of the drifts towards the disposal boreholes. This may lead to an increase in the mobilization of radionuclides. The early failure of sealing elements used to seal connecting galleries that have no barrier functions may alter the transport of gases and solutions in case of flooding.

In the German scenario assumptions (VSG, 2011), no multiple failures are assumed so that the borehole seals maintain their intended long-term safety functions. As a consequence, no brine, if present, could enter or leave the boreholes after the borehole plugs are sufficiently compacted ("closed") due to the convergence of the open spaces of the repository. However, upon their instalment, the borehole plugs remain slightly permeable for a certain period of time. During that time frame, radionuclides could be carried out of the boreholes by the transport of brine. Since this type of sealing element is not equipped with monitoring devices, their failure cannot be detected directly. It is assumed that under normal, dry conditions of the repository, an early failure of these seals may be detected by equipment monitoring the pressure or displacements at locations near the seals. The evolution of the pressure may provide indirect information about the porosity and permeability of the connecting seals.

The water content or humidity will affect the convergence of backfilled spaces and compacted salt seals, and, in relation to the pressure evolution, may provide indirect information about the state of compaction of the seals. These parameters do, however, not provide information about the presence and status of EDZs adjacent to the plugs. The temperatures and rock stresses measured in the host rock do not provide direct information about the state of the seals. The readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-15: Overview of sensor readouts in relation to scenario 10 "*failure of other sealing elements"*

Parameter -Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		-
Radial pressure	-	-		
Pore pressure		-		
Total pressure				-
Rock stresses			-	
Displacements				-

A failure or reduced performance of a sealing element is of special concern when brine is present in the repository. Although no safety function is attributed to the "other sealing elements", failure of these structures will likely lead to deviating readouts of the proposed monitoring equipment.

- Stress and pressure distribution will level off at opposite sides of the affected seals.
- The convergence of backfilled drifts will likely slow down due to the backpressure of brine-filled drifts, resulting in measured displacements which may differ compared with expected values or which may differ significantly for "dry" locations in the repository.
- The presence of water/humidity will be detected at various locations.

If brine is present, the readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-16: Overview of sensor readouts in relation to scenario 10 "*failure of other sealing elements"* – assuming the presence of brine

Parameter -Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		+
Radial pressure	0	+		
Pore pressure		+		
Total pressure				+
Rock stresses			+	
Displacements				+

8.2.11 Scenario 11: Altered stress condition in the host rock

The excavation of underground repository structures inevitably leads to a re-distribution of stresses in the vicinity of the cavities, which may result in the formation of Excavation Damaged Zones (EDZ) or fissures surrounding the open spaces (Rübel, 2011). This may affect the hydraulic conductivity in the near field. In addition, the emplacement of canisters containing heat-generating waste leads to a heat-up of the host rock, followed by a gradual cool-down as a result of the decaying heat input. As a result, a thermal expansion and subsequent contraction of the host rock induces changes in the rock stresses near the excavated zones. In addition, the potential presence of fluids during the post-closure phase of the repository may affect the pressure distribution in the host rock. The strain gauge system may detect altered stress conditions in the host rock. Also, the pressure and displacement measurement devices installed at different locations may indicate altered stress conditions or unexpected convergence of the open spaces.

The safety function attributed to the host rock, “sealing against water”, could be detected by applying water/humidity sensors. Such sensors are already foreseen in the present set-up, although the emplacement of additional water sensors inside the boreholes would provide a direct indication of the presence of brine inside the boreholes. For this scenario, the readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-17: Overview of sensor readouts in relation to scenario 11 “*altered stress condition in the host rock”*

Parameter -Indicative for Scenario		(detectability: + high, o medium, - low)		
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geo-logic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		0
Radial pressure	0	0		
Pore pressure		-		
Total pressure				+
Rock stresses			+	
Displacements				+

Table 8-18: Overview of sensor readouts in relation to scenario 11 “*altered stress condition in the host rock”* – assuming the presence of brine

Parameter -Indicative for Scenario		(detectability: + high, o medium, - low)		
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geo-logic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		+		+
Radial pressure	0	+		
Pore pressure		+		
Total pressure				+
Rock stresses			+	
Displacements				+

The situation of altered stress conditions in the host rock could be of concern if brine was present in the repository. Due to the possible formation of EDZs or fissures surrounding the open spaces, the assumed evolution of an EDZ has to be re-evaluated. If brine is present, the readouts of the monitoring equipment installed at the indicated locations may develop as indicated in Table 8-18.

8.2.12 Scenario 12: Thermochemical reduction of sulphates

A natural constituent of the host rock is anhydrite, or calcium sulphate $CaSO_4$. The concentration of anhydrite in rock salt can range from about 2-8% by volume (Rübel, 2011). In the case of a temperature increase to up to about 80-100 °C, and in the presence of hydrocarbons or molecular hydrogen, the anhydrite may undergo a chemical reduction, with the possible formation of gaseous hydrogen sulphide (H_2S) and calcite ($CaCO_3$). This process will likely lead to a change in the composition of the salts present in the host rock and also to a thermally induced volume change of the host rock.

So far, the impact of the thermochemical reduction of sulphates is still an open question. The extent of the impact of this process can only be determined by a detailed process analysis. In case it can be shown that the integrity of the host rock will remain intact, no deviation from the *reference scenario* needs to be assumed. If the integrity of the host rock does not remain intact, the impacts identified have to be taken into account. In this case, the safety function of the geological barrier, “sufficient tightness against fluids”, may be affected.

In the present assessment, it is assumed that the thermochemical reduction of sulphates will induce only a volumetric change of the host rock. The safety function “sufficient tightness against fluids” cannot be detected directly with the monitoring equipment installed in the geologic barrier, i.e. the temperature and stress sensors. A direct determination of this safety function would be possible by installing humidity sensors at various locations. Such sensors are already foreseen in the present set-up, although the emplacement of additional water sensors inside the boreholes would provide a direct indication of the presence of brine inside the boreholes.

For this scenario, the readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-19: Overview of sensor readouts in relation to scenario 12 “*thermochemical reduction of sulphates”*

Parameter - Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	?	
Water content		-		-
Radial pressure	?	?		
Pore pressure		-		
Total pressure				?
Rock stresses			+	
Displacements				+

8.2.13 Scenario 13: Infiltration of gases into the host rock

At present, it is unclear if gas can permeate into the host rock under the prevailing conditions. Permeation of gas into the host rock may alter, i.e. likely increase, the latter's permeability, resulting in an increased transport of fluids and release of any radionuclides from the repository. This process has been discussed during a Workshop in 2007 (Rübel, 2008) and may be caused by the formation of gases in the repository. If the gas pressure exceeds the rock pressure, the local permeability of the rock salt may increase by either the formation of cracks or by the widening of the surroundings on the crystal boundaries without destroying the crystal structure. In the latter case, the permeability increases until equilibrium between gas production and gas permeation is reached. When the gas pressure falls back below the rock pressure, the original permeability of the undisturbed rock salt is restored.

Currently, there is no detailed understanding of the gas transport process into the host rock and the range of the gas dispersion into the salt rock. It is expected that the penetration depth of the gases in the salt depends on the spatial permeability distribution (homogeneity) and on the gas storage capacity (porosity). It is likely that the infiltration of gases into the host rock is a local process and will be limited to the vicinity of the repository; the amounts of gases produced are likely insufficient for an infiltration of gases on a more global scale.

Taking the above-mentioned considerations into account, it is unlikely that the safety function attributed to the host rock, "sufficient tightness against fluids", will be endangered. This safety function cannot be detected directly with the monitoring equipment installed in the geologic barrier, i.e. the temperature and stress sensors. A direct determination of this safety function would be possible by installing humidity sensors at various locations, especially inside the boreholes.

For this scenario, the readouts of the monitoring equipment installed at the indicated locations may develop as indicated in the following table.

Table 8-20: Overview of sensor readouts in relation to scenario 13 "*infiltration of gases into the host rock"*

Parameter -Indicative for Scenario			(detectability: + high, o medium, - low)	
	Module 1: borehole (backfill) and cask	Module 2: borehole and plug	Module 3: Monitoring cross-section A (geologic barrier)	Module 4: Drift seal - cross section B
Temperature	-	-	-	
Water content		-		-
Radial pressure	?	?		
Pore pressure		-		
Total pressure				-
Rock stresses			?	
Displacements				?

8.3 Quantitative example of alternative scenario detection

As already indicated in chapter 4.2, 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. In the framework of the "preliminary safety assessment of the Gorleben site", a shaft closure concept has been developed that meets these requirements. This concept takes into account the occurrence of three main discontinuities by properly locating sealing elements as well as the occurrence of different kinds of brine present at the site at different depth levels by using suitable materials to avoid material corrosion. Müller-Hoeppe, (2012) shows the composition of the shaft sealing system developed to seal the shaft area below a depth of 350 m, i.e. within the salt dome. The upper sedimentary layers have not yet been considered. The system consists of three different kinds of plugs, one bentonite plug in the upper part to stop the inflow of fresh water from the groundwater system. Below this plug, there is a long column of gravel as a support to keep the bentonite plug in place as well as a reservoir to take up and, thus, store water that may flow in through the bentonite plug. The two other plugs are located in the lower part of the shaft to seal the discontinuities. They consist of salt concrete and MgO concrete to take care of the different brine solutions NaCl and $MgCl_2$ in order to avoid material corrosion.

In chapter 4.3.3, it was also indicated that measuring points within the sealing elements of a shaft seal are to be avoided in order to avoid impairing the sealing function of individual sealing elements. As is done in the case of the borehole and drift seals, the proper functioning should be monitored by measurements on both sides of sealing elements. The preliminary monitoring concept considers this by designing so-called monitoring levels, ML-1 to ML-9, between different sealing components (Figure 4-7). As mentioned in section 4.4.3, each monitoring level is equipped with total pressure and porewater pressure sensors as well as a transmission unit consisting of a wireless transmitter and a long-life battery (Figure 4-13).

One important process that influences a sealing construction in a shaft and that is relevant regarding the safety assessment concept is the hydraulic load development on one or on both sides (top and bottom) of the sealing elements of the shaft seal system. As an example, scenario 2 "*early failure or reduced performance of shaft seal*" (group B4, C2, Table 8-3) was chosen to investigate the possibility of detecting *alternative scenarios*, especially with regard to the process mentioned above.

Performance assessment calculations have been performed by GRS for the *reference scenario* as well as for an *alternative scenario* assuming a reduced shaft sealing performance (Müller-Hoeppe, 2012). The reduced performance has been simulated based on increased permeabilities of the three sealing elements. For the bentonite plug, the permeability increase was half an order of magnitude, for the salt concrete plug, the permeability was increased by four orders of magnitude, and for the MgO concrete plug, the permeability increase was two orders of magnitude. This "high permeability scenario" covers the issue of improperly built plugs which is assumed to be a less likely scenario.

Within the scope of performance assessment calculations, the pore pressure development as a result of the hydraulic load development has been recorded at the different monitoring levels. The results are shown in Figure 8-2 for the upper part of the sealing system and in Figure 8-3 for the lower part. The continuous curves represent the evolution for the reference case and the dashed curves are the results of the increased permeability (alternative) scenario. A vertical line has also been drawn into the figure at a time point of 100 years, which is assumed to be a reasonable monitoring period after closure of the repository. The results show that during the first 100 years, a small pore pressure evolution is to be expected at ML-2 and ML-5 only, but nowhere else. Significant changes in the pore pressure development will take place 300 years after closure at the earliest. A full saturation of the complete sealing system and, thus, water penetration into the repository will occur after about 1700 years, which is beyond any realistic monitoring period.

In the case of the *alternative scenario*, things are different. In this case, the pore pressure starts to evolve within the first 10 years at almost all monitoring levels except the lowest one, ML-9, where there is no reaction for almost 100 years. The results also indicate that in case of a proper implementation and thus proper functioning of the very first plug, the bentonite plug, the pore pressure increase will be close to 0 at the lower monitoring levels during the assumed monitoring period of 100 years.

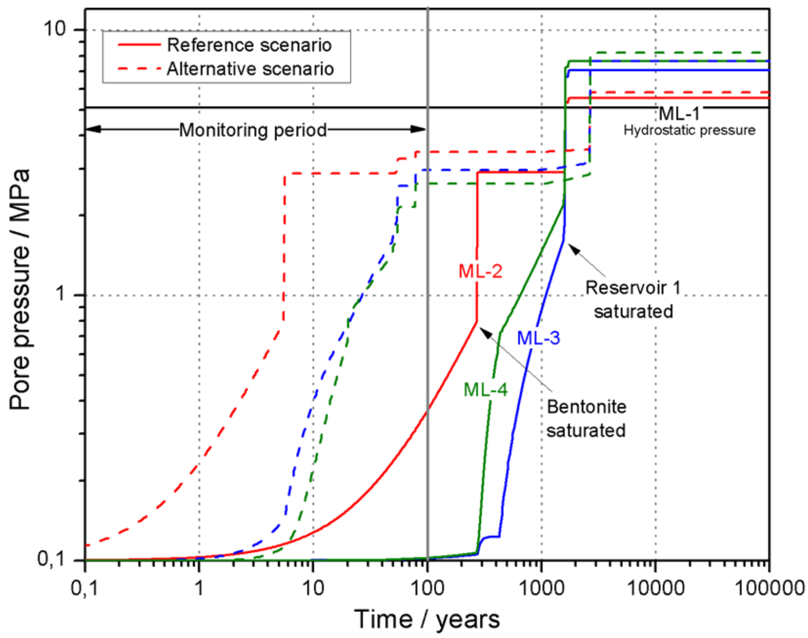


Figure 8-2: Evolution of pore pressures at the monitoring levels 1 to 4 (upper part)

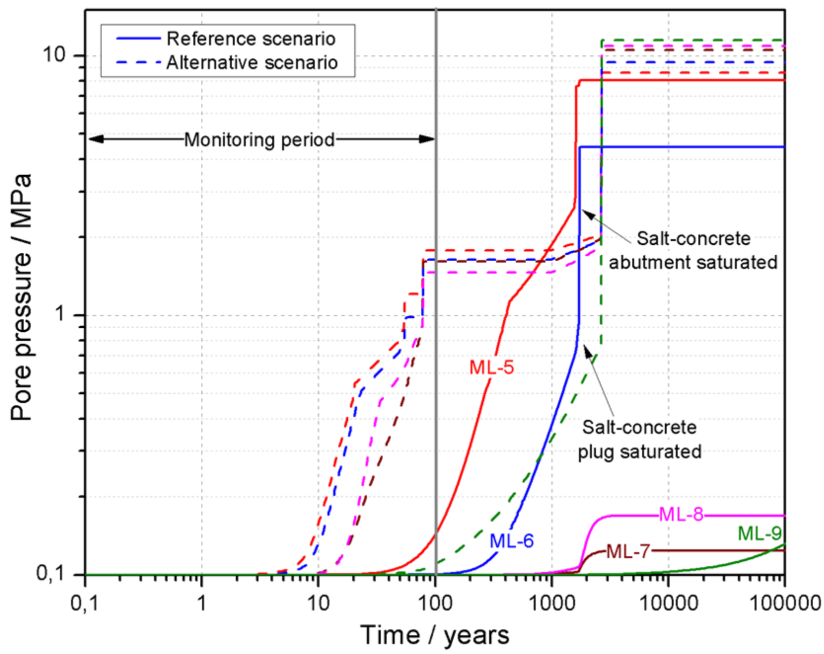


Figure 8-3: Evolution of pore pressures at the monitoring levels 5 to 9 (lower part)

This example shows that it is generally possible to detect the alternative scenario and, thus, an improper implementation of a sealing element by simply monitoring at both ends of the element. An installation of sensors within an element is not necessary. This means that monitoring can be done without impairing the safety function of a barrier element. It has to be noted that the monitoring concept assumes a proper wireless data transmission over the given distances between the monitoring levels and to the earth's surface at the end. Considering the current developments in the area of wireless data transmission, this seems reasonable.

8.4 Discussions on detectable alternative scenarios

This part of the case study treats the impacts of *alternative scenarios* on the readouts of monitoring equipment in a generic repository design in rock salt in a qualitative, and for one example, in a quantitative manner. The scenarios have been derived from the German Safety Case. By combining the readouts obtained from the different devices installed at different locations in the repository, indications could be derived as to whether the evolution of the repository is in line with the *reference scenario* or in line with one of the *alternative scenarios*. The following table provides an overview of scenarios which may be detected with the designed monitoring modules, assuming that no brine is present in the repository.

Table 8-21: Overview of detectable alternative scenarios

No	Scenario name	Detectable	Representative parameter
1	Development of glacial channels	N/A	-
2	Early failure or reduced performance of shaft sealing	Yes	pore pressure, total pressure
3	Early failure or reduced performance of dams	Yes	Water content, pressure, displacement
4	Presence of undetected geological features	Yes	Water content
5	Presence of brine inclusions	Yes	Water content
6	Presence of fissure	No	-
7	Early failure of container and liner	No	-
8	Altered convergence behaviour	Yes	Pressure, displacement
9	Metal corrosion	?	Radial/pore pressure
10	Failure of other sealing elements	No	-
11	Altered stress condition in the host rock	Yes	Pressure, displacement
12	Thermochemical reduction of sulphates	?	Temperature, pressure, displacement
13	Infiltration of gases into the host rock	?	Pressure, displacement

N/A: Not Applicable

The implications of the assumed scenarios are of special concern when brine is present in the repository. In that case, the safety function “sealing against water” is affected. This situation will likely lead to deviating readouts of the proposed monitoring equipment:

- The distribution of stresses and pressures will level off at opposite sides of affected seals.
- The convergence of backfilled drifts will likely slow down due to the backpressure of brine-filled drifts, resulting in displacement measurements that may differ from expected values or which may differ significantly for “dry” locations in the repository;
- The presence of water/humidity will be detected at various locations.

Table 8-22: Overview of detectable alternative scenarios, assuming the presence of brine

No	Scenario name	Detectable	Representative parameter
1	Development of glacial channels	N/A	
2	Early failure or reduced performance of shaft sealing	Yes	Water content, pressure, displacement
3	Early failure or reduced performance of drift seals	Yes	Water content, pressure, displacement
4	Presence of undetected geological features	Yes	Water content
5	Presence of brine inclusions	N/A	
6	Presence of fissure	N/A	
7	Early failure of container and liner	Yes	Water content, pressure, displacement
8	Altered convergence behaviour	Yes	Water content, pressure, displacement
9	Metal corrosion	N/A	
10	Failure of other sealing elements	Yes	Water content, pressure, displacement
11	Altered stress condition in the host rock	Yes	Water content, pressure, displacement
12	Thermochemical reduction of sulphates	N/A	
13	Infiltration of gases into the host rock	N/A	

Table 8-22 provides an overview of *alternative scenarios* that may be detected with the equipment installed, assuming that brine is present in the repository. The presence of brine inclusions in the vicinity of the repository only impairs the safety of the repository if brine actually enters the connecting galleries and thereafter, the disposal cells. Depending on the amount of brine and the state of compaction of the backfill, intrusion of brine into connecting galleries can be measured by humidity sensors at the different barriers and seals. A monitoring set-up that allows measuring the presence (or absence) of brine in *all* boreholes would directly indicate failures of the different safety functions.

9 Conclusions and lessons learned

For the three cases under study (1) salt rock, German concept, (2) clay rock, French concept, and (3) granitic rock, Finish/Swedish concept, lists of parameters have been identified that are able to characterize relevant processes in and around a repository. Monitoring these parameters provides the possibility to support the basis for the long-term safety case as well as to support the pre-closure management and thus decision making processes.

Regarding the method used to determine the relevant parameters, the study showed several similarities between cases 1 and 3 and a slightly different way in case 2. The difference is illustrated in Figure 9-1.

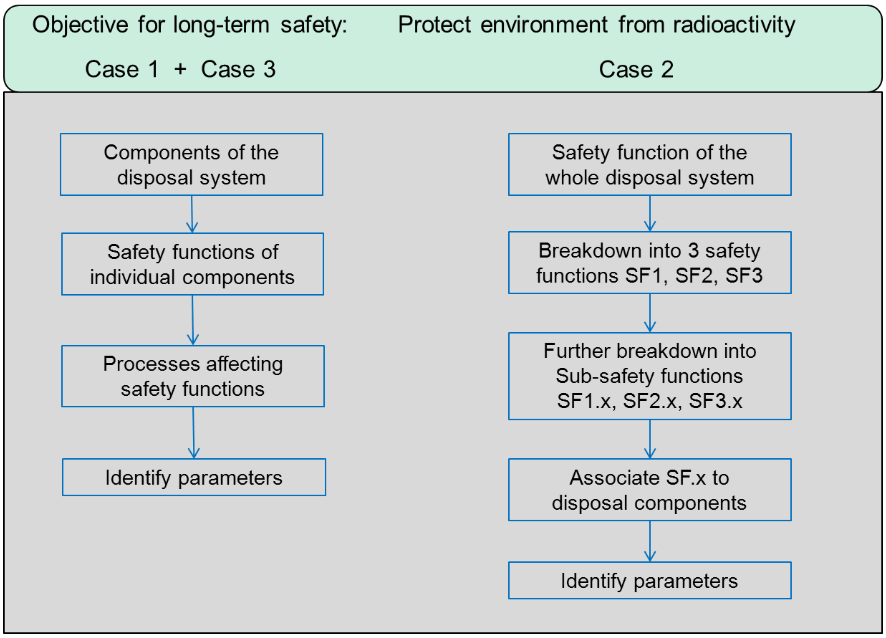


Figure 9-1: Different ways of parameter identification

Cases 1 and 3 start with the description of the disposal system, followed by an allocation of safety functions to individual components of the disposal system. The next step is then to select those processes in and around the repository that might affect one or more of the safety functions. Finally, parameters are identified that are able to characterize the relevant processes and, thus, are worth monitoring.

The method of identification in case 2 is slightly different. Case 2 starts with the definition of an overarching safety function to be met by the whole disposal system. Then, there is a breakdown into three main safety functions, followed by a further breakdown into sub-safety functions to which then individual disposal components are allocated prior to parameter identification. In cases 1 and 3, the reasoning to monitor specific parameters is to characterize processes that may affect a safety function of a disposal component, whereas in case 2, there is a more direct association of parameters to a very specific safety function of a disposal component.

Common to all cases is the consideration of safety functions of repository components as a basis for the identification of parameters worth monitoring, which seems reasonable and should be seen as a recommendation for designing monitoring programmes.

For case 1 (salt host rock, German concept), a system design has been developed that allows the monitoring of a representative area of a high level waste repository after its closure.

The system is based on long-term wireless data transmission and on the principle of "no sensor installation within sealing elements to avoid any weakening". For case 2 (clay host rock, French concept), a strategic design is proposed for monitoring a complete disposal cell with special focus on the requirement of waste reversibility. In case 3 (granite host rock, Swedish/Finish concept), the designed system is limited to the development of an example of a near-field monitoring system. A sensor system configuration has been designed that allows the monitoring of the bentonite buffer development in a disposal borehole as well as in the backfilled tunnels. The system is based on individual, self-sufficient wireless data transmission systems with an expected lifetime of 10 years.

Common to all three cases is the idea of using something like a "pilot facility". In case 1, there is a specified "monitoring field", in case 2, a specified "disposal cell" is chosen, and in case 3, a "demonstration facility" is planned to apply monitoring for process understanding. The idea of establishing some form of "pilot facility" would enable not only increased process understanding during repository operation and to evaluate and update monitoring programmes prior to final closure but would also be a useful tool for stakeholder confidence building.

A potentially relevant role in support of decision making and confidence building is attributed to monitoring. The results from monitoring activities support the models and assumptions used to demonstrate safety when they are in agreement with the predicted behaviour of the monitored repository components. It is important to recognise that monitoring outcomes may deviate – for whatever reason – from predicted ones. This deviation may, for example, be the consequence of a technical failure of one of the many sensors placed and does not necessarily mean that the long-term safety of a repository is impaired. However, if monitoring results are used to support decision making or are part of licence application conditions, it is important to consider how deviating monitoring outcomes have to be analysed, and, in order to be able to design a robust implementation process for geological waste disposal, this needs to be done a priori.

The ability to identify equipment anomalies or failures is an important issue that may even be seen as an additional technical requirement (not yet seen as such) to the monitoring requirements defined in the "monitoring requirements report". The incorporation of such considerations into the selection of monitoring techniques would be a relevant contribution to the robustness of the implementation process. The installation of additional monitoring equipment that enables the identification of potential failure of other monitoring would be useful as well. This could lead to an additional objective for monitoring.

When assessing the safety of a radioactive waste disposal facility, it is important that the performance of the disposal system is considered under both present and future conditions. This can be achieved through the identification and analysis of a set of so-called "scenarios". In this respect, development of scenarios constitutes the fundamental basis for the quantitative assessment of the safety of a repository. Scenarios are descriptions of possible evolutions of the disposal system and represent structured combinations of features, events, and processes (FEPs) relevant to the performance of the disposal system.

Different types of scenarios are usually considered, including a *'reference scenario'*, which represent the assumed normal repository evolution and the so-called *'alternative scenarios'*, which represent disturbing processes and thus a deviated repository evolution.

All FEPs that could significantly influence the performance of the disposal system are to be addressed in the assessment. In addition, it is to be addressed, which scenarios are based on processes having a low probability of occurrence.

One new element in the overall strategy appears to be the use and role of safety functions as high-level principles guiding repository design and siting and used to identify key issues in a safety evaluation. The concept of safety functions, the use of qualitative arguments in addition to quantitative assessment, and the notion of integrated analysis have not only influenced the methods used to describe the disposal system and to develop scenarios, but also to identify the parameters relevant for monitoring. Thus, safety functions are the linking elements between the safety case and monitoring.

This underpins the importance of a clear identification of the safety functions of each disposal component. The introduction of the use of safety functions brings in a new basis for scenario development and also for the overall safety analysis. It relies on the profound knowledge and understanding of processes and phenomena that are likely to evolve in the disposal system and its environment. This knowledge and the clear defined safety functions become a basis for uncertainty analyses, and derivation of *reference scenario* and *alternative scenarios* and their sensitivity analyses. Generally, it can be stated that consensus exists concerning the role of scenario development in safety assessments. In this context, scenario development constitutes the fundamental basis for the further work, e.g. consequence analysis.

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