D1.1 BEACON Bentonite Mechanical Evolution

Beacon - Bentonite Mechanical Evolution
State-of-the-Art Report

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Summary

The “Beacon” (Bentonite Mechanical Evolution) project will address key technical issues that must be tackled in order to support the implementation of planned geological disposal projects for high-level radioactive wastes across the EU. The overall objective of the project is to evaluate the performance of an inhomogeneous bentonite barrier. Since the safety-relevant performance of the bentonite is mainly defined by its chemical, mineralogical and physical properties, comprehensive sets of requirements regarding the chemical, mineralogical and physical characteristics of bentonite have been developed by the different waste management organizations (WMOs) for their concepts. The present report was compiled from the answers to a questionnaire that was distributed to the different WMOs or their representatives. The role of uncertainties related to the heterogeneities of bentonite is, in most repository concepts, addressed using a deterministic approach defined with a preferred density value. There are several natural properties of bentonite that may impact the degree of homogenization. Most waste management organizations considered water content, original exchangeable cations, bulk density, swelling pressure and hydraulic conductivity as relevant natural properties for the bentonite regarding heterogeneity, while organic carbon and thermal conductivity appear to be incidental for the homogenization process. All participating waste management organizations agree that the most valuable output from Beacon would be material models that are accurate enough to be used as a tool for design and engineering purposes, i.e. to assess the behavior and performance of the bentonite-based EBS both on the short-term and long-term under variable design and environmental conditions. It is expected that, if the preparation of the sealing material (e.g. pellets) and the emplacement method are performed properly, heterogeneity will not be problematic for safety cases and that the buffer material can be represented in the safety assessment by a well-chosen homogeneous material.

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1. Introduction

The "Beacon" (Bentonite Mechanical Evolution) project will address key technical issues that must be tackled in order to support the implementation of planned geological disposal projects for high-level radioactive wastes across the EU. The overall objective of the project is to evaluate the performance of an inhomogeneous bentonite barrier. This will be achieved by cooperation between design and engineering, science and performance assessment. The evolution from an installed engineered system to a fully functioning barrier will be assessed. This will require an increased understanding of material properties and fundamental processes that lead to homogenization as well as improved capabilities for numerical modelling. The output will be a verification of the performance of current designs for buffers, backfills, seals and plugs and an improved handling of mass losses in long-term assessments.

The overall objective of the project is to develop and test the tools necessary for the assessment of the mechanical evolution of an installed bentonite barrier and the resulting performance of the barrier. For some repository designs, mainly in crystalline host rock, the results can also be used for the assessment of the consequences of mass loss from a bentonite barrier on the long term.

The driver for this project is repository safety, and the demands of waste management organizations to verify that the material selection and initial state design fulfil the long-term performance expectations. For this project, the initial state refers to the period during installation of the barrier, while long-term performance refers to the period for barrier saturation and evolution of the hydro-mechanical properties, which could range from 10s to 1000s of years. In current and future applications for repositories, the regulators will expect the applicants to have a sufficient predictive capability of the barrier evolution from the installed to the final state.

Beacon is focused on direct application to real assessment cases in actual repository systems. A few cases from relevant repository systems have therefore been selected as test examples. The systems to be evaluated in Beacon include three cases: 1) a tunnel plug based on the Andra design, 2) a disposal cell from the Nagra concept, 3) the KBS-3 deposition tunnel backfill. These are representative of the primary areas of uncertainty in density homogeneity. These examples cover a broad range of issues and the results should also be applicable to other concepts and systems.

The scientific-technical work in Beacon is structured into five work packages (WP1-5), WP6 is for civil society interaction, dissemination as well as training is handled in work package 7, while coordination and project management are covered in one single work package (WP8). The interconnections between the work packages are illustrated in the technical annex of the Beacon proposal (Beacon, 2016).

The present report forms the basis for the products foreseen in WP1, which is the main driver for the entire project. The national programs involved are all represented in WP1, through the implementer or equivalent organization. The objective of WP1 is to define the important issues concerning the mechanical properties of bentonite and to define how these should be treated. This will result in a number of specified assessment cases with the focus on long-term performance and/or repository engineering. When the quantitative results from the assessment cases are available from WP5, WP1 will evaluate the findings with respect to the design and/or performance of the bentonite barriers.

1.1. Description of work in WP1

Since the safety-relevant performance of the bentonite is mainly defined by its chemical, mineralogical and physical properties, comprehensive sets of requirements regarding the chemical, mineralogical and physical characteristics of bentonite have been developed by the different waste management organizations for their concepts. In most cases, these requirements assume a bentonite density as a boundary condition for the requirement to be fulfilled.

In the framework of WP1, the needs of safety assessment regarding the evaluation of non-homogeneous backfill properties are addressed, in particular to what extent non-homogeneous material property distributions comply with safety requirements. The outcome of this work package is planned to be a (hydro)-mechanical assessment of the case studies, given a range of uncertainties in the boundary conditions based on empirical and numerical evidence, that, based on a probabilistic approach, would ultimately result in a set of requirements under consideration of the host rock and the repository design. For this work package, three case studies were defined: the Andra tunnel plug, the Nagra disposal cell and the KBS-3 deposition tunnel backfill.

Based on the outcome of the assessment cases and the evaluation method and uncertainties, the end-user may formulate design-specific requirements that can be used for the safety case in a final workshop.

The present report was compiled with the answers to a questionnaire (Appendix A) that was distributed to the different WMOs or their representatives. The questionnaire aimed at reflecting the state-of-the-art regarding the treatment of heterogeneous bentonite density distribution and properties in the safety case.

1.2. The questionnaire

The WMO's involved in BEACON could report based on a questionnaire (see Appendix A) the treatment of uncertainties related to the emplacement of bentonite for their specific technical barriers design. The questionnaire was compiled under the lead of WP1 with the input of all the other work packages as well.

The returned questionnaires were checked for consistency and plausibility. The following steps consisted in writing out the returned questionnaires and a first review of the text by the original authors. The texts were compiled to a report which was reviewed by the BEACON partners before publishing.

The questionnaire consisted of three different parts: (1) application of bentonite in the specific design (2) the required performance of bentonite (3) detailed characterization of the required properties of the bentonite.

2. Role of bentonite in the repository concepts

2.1. Nagra, Switzerland

2.1.1. Bentonite components in the repository concept

After transport to the underground facilities, the disposal canisters are emplaced in 300 to 600 m long drifts with an inner diameter of about 2.5 m. In the reference configuration, the canisters are emplaced coaxially and centralized within the drifts, requiring a pedestal of compacted bentonite blocks (Na-Bentonite from Wyoming, dry density 1,450 kg m^{-3}) to support the canisters prior to the backfilling of the remaining spaces with highly compacted bentonite granules (comprising ~ 80% by volume of dense granules ~ 2,100 – 2,200 kg m^{-3} and 20% powder). The bentonite blocks and granules together form a protective mechanical and chemical buffer around the canisters. A spacing of ca. 3 m is foreseen between individual canisters to limit the temperature increase in the surrounding buffer and rock due to heat generation in the canisters from radioactive decay. The current repository concept, published in Nagra (2011), uses a cementitious liner to support the walls of the emplacement rooms and access tunnels, designed to withstand the highest mechanical loads expected to arise during the construction and operational phases. To avoid any hydraulic shortcuts along the walls of the SF/HLW emplacement drifts that could arise from the degradation of the liner, and to comply with the principle of compartmentalization, sealing sections comprised of granular and preformed bricks of buffer material (1,650 – 1,750 kg m^{-3}) are emplaced at regular intervals along the drifts, about one for every 10 canisters, to provide a hydraulic barrier (Nagra, 2014a). There is no liner where these sealing sections are emplaced, so that bentonite forms a watertight contact directly with the Opalinus Clay. The concept is illustrated in (Fig. 1). ILW is packaged in concrete emplacement containers of standard size in the surface facility. After transport to the underground facility, the containers are stacked in dead-end emplacement caverns about 8 m in width and up to 200 m in length, which are supported by concrete liners. The remaining void spaces are backfilled with specifically designed mortars and finally the caverns are sealed with a gas-permeable sand-bentonite mixture and a cementitious abutment (Nagra, 2016a).

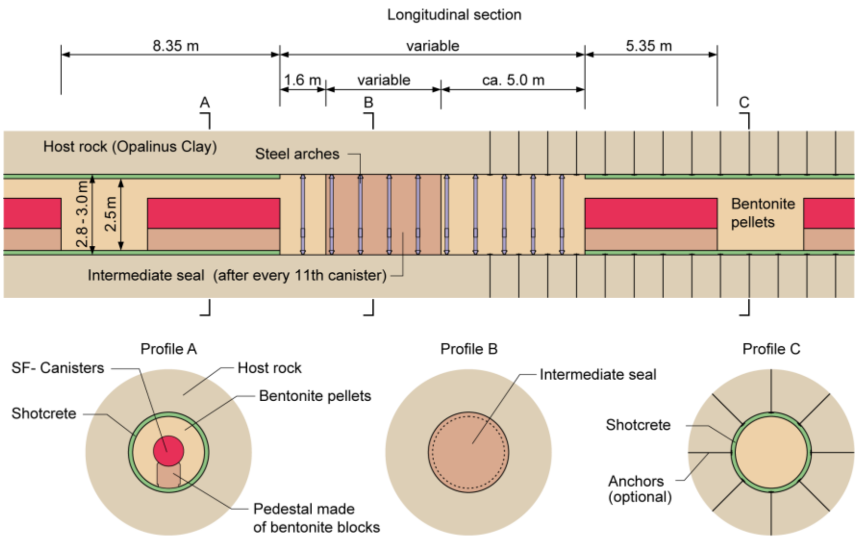


Fig. 1: Schematic diagram of the near-field design of the Swiss SF/HLW repository based on Nagra (2016a) that was used in this study as a conceptual basis for investigating the long-term evolution of the safety-relevant functions of the bentonite buffer.

2.1.2. Safety-relevant properties of bentonite

To safely contain the waste and to comply with the overriding safety principles, the key requirements for a buffer material in the case of high-level radioactive waste disposal independent of the host rock are: (1) a low hydraulic permeability/conductivity; (2) a self-sealing ability; and (3) durability of properties in the very long-term.

- The safety-relevant properties of bentonite are:
- Swelling capacity providing mechanical stabilization of rooms and hence avoiding significant extension of the EDZ
- Chemical retention of radionuclides by retarding transport from the buffer
- Low hydraulic conductivity for ensuring diffusive transport
- Sufficiently high viscosity for mechanical support of the canister
- Sufficient gas transport capacity for ensuring gas transport without compromising the hydraulic barrier
- Minimizing microbial corrosion to ensure conditions favorable to slow corrosion (of the canister)
- Resistance to mineral transformation ensuring longevity of other safety-relevant attributes of the buffer
- Suitable heat conduction ensuring favorable maximum temperature conditions

2.2. SKB, Sweden

2.2.1. Bentonite components in the repository concept

Repository for spent fuel

A combination of high density blocks and pellets in all components consisting of pure bentonite will be used in the repository for spent fuel. The reference buffer geometry is presented in Fig. 2. The buffer consists of one solid bottom block, six ring-shaped blocks around the canister and three solid blocks on top of the canister. The buffer ends and the backfill commences at the top of the third block on top of the canister. The center line of the buffer blocks coincides with the center line of the deposition hole. The gap between the block and the rock surface of the deposition hole is filled with pellets. The thickness around the canister will, for the installed buffer, deviate from the nominal thickness, i.e. 35 cm. The installed buffer thickness will depend on the diameter of the deposition hole and its variation along the hole and on the position of the ring-shaped blocks within it. The buffer thickness will also be affected by the position of the canister within the ring-shaped blocks and the diameter of the canister. The canister will be guided so that it is placed centered within the buffer ring. Additionally, the deposition tunnel backfill, the backfill of other tunnels and shafts to a level of about 200 m above the repository and possibly investigation borehole seals are also bentonite-based components in the repository.

Low- and intermediate level waste repositories

In the low- and intermediate-level waste repositories, some buffer components and tunnel seals are bentonite-based. The bentonite components for low- and intermediate-level waste repositories of the SKB concept are not further discussed in this document.

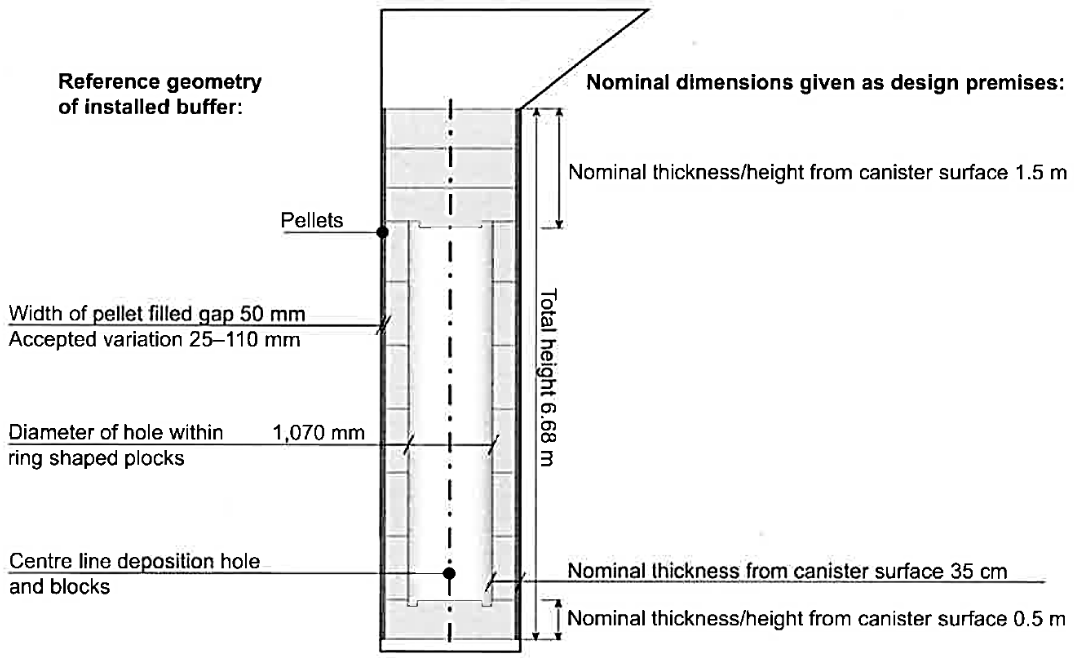


Fig. 2: Reference geometry of the installed buffer (SKB, 2011).

2.2.2. Safety-relevant properties of bentonite

The overall safety functions of a radioactive waste repository are generally confinement and retardation. Confinement is defined as the complete isolation of the waste, while retardation slows down any releases in the case of failed confinement. Safety-relevant properties of bentonite are specified for each component:

Buffer surrounding canisters in deposition holes

- Limit advective mass transfer
- Limit microbial activity
- Filter colloids
- Protect the canister from detrimental mechanical loads – rock shear load
- Protect the canister from detrimental mechanical loads – pressure load
- Resist transformation
- Keep the canister in position
- Retain sufficient mass over life cycle

Deposition tunnel backfill

- Keep the buffer in place
- Limit advective mass transfer

Other tunnels and shafts backfilled to a level of about 200 m above the repository

- Avoid the formation of new preferential flow paths

Investigation borehole seals

- Avoid the formation of new preferential flow paths

2.3. Posiva, Finland

2.3.1. Bentonite components in the repository concept

Posiva's bentonite-based engineered barrier system (EBS) consists of a buffer and backfill that are emplaced in deposition holes and deposition tunnels, respectively, according to the KBS-3V repository concept. Bentonite might also be applied to deposition tunnel plugs as a hydraulic sealing layer behind the plug and as bentonite tape ensuring the contact between concrete cast and host rock. Closure of the underground disposal facility outside the repository (deposition holes and deposition tunnels) and other excavated tunnels, shafts and boreholes will also use bentonite as part of different backfilling structures.

The buffer and backfill are composed of compacted bentonite blocks and pellets which fill the gap between the blocks and the host rock walls. In the latest design of the buffer (work in progress), the gap between canister and blocks is also filled with pellets. The blocks in the buffer are cylindrical in shape, whereas rectangular blocks separated by an installation gap are used in the backfill. Specific rectangular blocks are used to construct the sealing layer for the plug. In the closure structures, bentonite may also be mixed with crushed rock or sand.

2.3.2. Safety-relevant properties of bentonite

The role of bentonite in the EBS is to ensure that the safety functions of the EBS are maintained on the long-term while not impairing the safety functions of other barriers. The safety functions of the bentonite-based EBS are to

Buffer

- protect the canister from detrimental mechanical processes
- limit transport of corroding substances in the buffer volume
- maintain chemically favorable conditions in the buffer volume
- transfer the heat from the canister sufficiently effectively to resist mineral alteration
- limit and retard radionuclide release in the event of canister failure

Backfill

- keep the buffer in place
- limit advective mass transfer in the deposition tunnels
- maintain chemically favorable conditions for the barrier system

Closure

- reduce the risk of unintentional human intrusion through the closed volume
- keep the deposition tunnel backfill in place
- avoid the formation of new preferential flow paths

- maintain chemically favorable conditions for the barrier system

These safety functions are further divided into performance targets (which are requirements arising from long-term safety), design requirements and design specifications in Posiva's requirements management system. In addition, different requirements are also applied, but in this report the descriptions are related to the performance-based ones.

2.4. SÚRAO, Czech Republic

2.4.1. Bentonite components in the repository concept

The deep geological repository (DGR) concept is based on the Swedish KBS concept with certain modifications – it will be constructed in crystalline host rock using steel-based disposal canisters and bentonite as the buffer material (Fig. 3). The direct disposal of SNF (spent nuclear fuel) is anticipated and the encapsulation plant will be located within the DGR complex (Pospiskova et al., 2017). It has not yet been decided if disposal will be horizontal or vertical, currently both options are being considered.

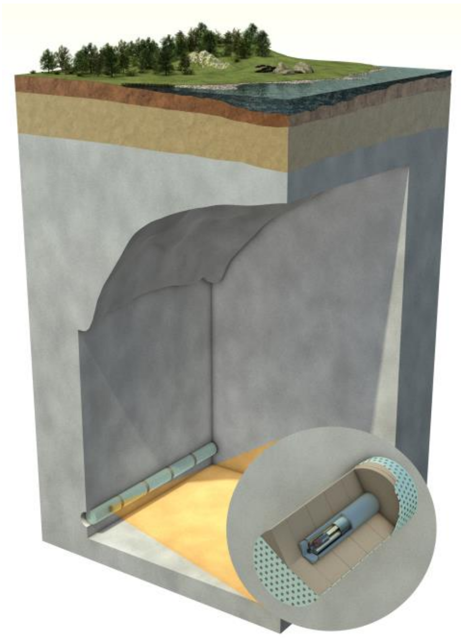


Fig. 3: Visualization of the DGR (SÚRAO).

The basic concept for the buffer is based on the KBS-3 concept where blocks and pellets are planned. An alternative option uses only bentonite pellets. The backfill concept is open and currently a mixture of bentonite and crushed rock from the DGR is preferred.

It is planned that Czech bentonite will be used as the buffer and backfill material. This bentonite is mined in the western part of the Czech Republic and is of the Ca–Mg type with a higher amount of iron in the octahedral positions (Franče, 1992).

2.4.2. Safety relevant properties of bentonite

The properties of the bentonite to be used were verified in the project preparation stage. Low hydraulic conductivity (limiting advective transfer), permeability for gases and the swelling capacity are important geotechnical properties of the bentonite layer as far as the reduction of the migration of radionuclides and limitation of microbial activity is concerned. Sufficient thermal conductivity of the bentonite is also significant for the removal of heat from the container. Bentonite barriers should also provide stabilization and mechanical protection of the container (shear and pressure load). Sorption capacity is important to retard/limit the radionuclide transport.

2.5. Enresa, Spain

2.5.1. Bentonite components in the repository concept

The Spanish repository concept in granite is based on the disposal of spent fuel in carbon steel canisters in long horizontal disposal drifts. Canisters are disposed of in cylindrical disposal cells constructed with pre-compacted bentonite blocks of 1,700 kg/m^3 dry density (in order to achieve a final dry density of 1,600 kg/m^3). The blocks are initially non-saturated (degree of saturation of 66%). The disposal drifts of 500 m in length and 2.4 m in diameter (

Fig. 4) are located at a depth of 500 m in the host formation. The separation between canisters is determined mainly by thermal constraints. Separations of 2 m between canisters and 35 m between disposal drifts have been established, in order not to exceed a temperature of 100 ºC in the bentonite. Actual separation is a function of the properties of the host rock. The detailed dimensions of an individual cell are shown in Fig. 5.

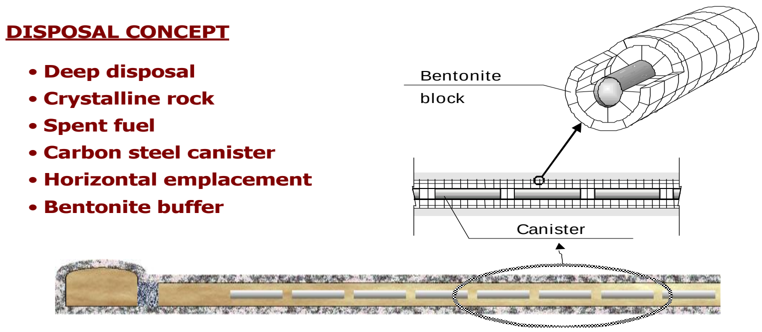


Fig. 4: Longitudinal section of a disposal drift.

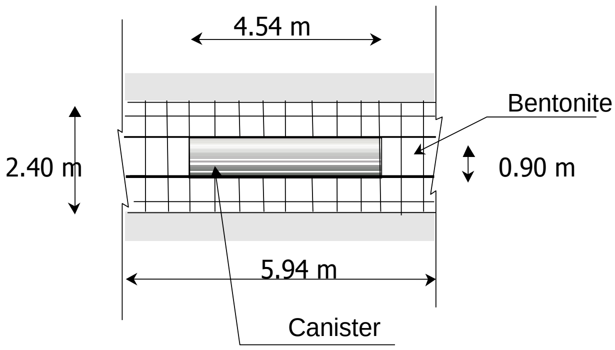


Fig. 5: Dimensions of an individual disposal cell.

Once a disposal drift is completed, it is sealed with a 6 m long seal made of bentonite blocks and closed with a concrete plug at its entry. After completion of all the disposal drifts, the main drifts, ramp, shafts and other remaining rock cavities will be backfilled with a mixture of bentonite and natural sand or an appropriate crushed material. The backfill material will consist of 10 % bentonite (increasing up to 20 % at the top of the drifts) and suitably graded sand.

2.5.2. Safety relevant properties of bentonite

The bentonite buffer is required to maintain a large diversity of safety functions, which can only be fulfilled once the bentonite saturates and swells, tightly closing the construction gaps between the bentonite blocks and the drift wall or the canister wall on the one hand and between the blocks themselves on the other. The gaps will close quickly upon contact with groundwater; in the case of the outer gaps, this will happen shortly (weeks or months) after buffer emplacement. Nevertheless, there are no safety functional requirements applicable during the time when the canister provides absolute containment. During the re-saturation of the buffer, the main concern is the preservation of the favorable properties of the buffer material. As the safety functions assured by the buffer are assumed for the full duration of the quantitative safety assessment (on the scale of a million years), its properties have to be preserved at a sufficient level for commensurate periods of time.

The long-term safety functions of the bentonite buffer are to:

- Isolate the waste package from the geosphere by limiting advective transport of corroding agents to the canister.
- Mechanically isolate the canister from limited shear displacements in the disposal drift walls. In the reference case, shear faults are not expected, so this is a reserve function.
- Avoid canister sinking in the disposal drift that could result in direct contact of the canister with the rock, hence short-circuiting the buffer.
- Avoid excessive swelling pressures that could contribute to total pressures that the canister cannot withstand.
- Avoid excessive temperatures (>100 ºC) that could result in chemical alteration of the bentonite, by transferring radiogenic heat from the waste package to the host rock.
- The buffer is a containment barrier by itself, as it retains radionuclides based on its properties:
    - Low hydraulic conductivity, which makes radionuclide transport by advection negligible
    - Sorption of many radioelements, especially actinides
    - Filtration of colloids and large complex molecules because of the small size of the pores
- Avoid the build-up of excessive gas pressure in the near-field, without undue impairment of the safety functions.

2.6. Andra, France

2.6.1. Bentonite components in the repository concept

In Andra's concept, a repository installation would consist of disposal cells (underground caverns) excavated in a claystone (Callovo-Oxfordian) formation; these cells contain the waste packages. The architecture envisioned by Andra includes disposal cells for various categories of waste within specific repository zones.

An example of the layout of the cavern for ILLW waste can be found in Fig. 6. (Andra, 2005). The range of primary packages in terms of conditioning, geometry, and radiological and chemical content in the ILLW waste category is highly diverse. The concern with simplifying operating methods has led to the design of standardized disposal packages which group together one to four primary packages in a parallelepipedial concrete container weighing ~6 to 25 tons and measuring from 1.2 to 3 m. The disposal cells are sub-horizontal tunnels limited in length to ~500 m for the useful part. The concrete drift liner gives the engineered structure mechanical stability (Andra, 2005). In the reference concept, both ends of the disposal cells are backfilled with the same type of crushed host rock and bentonite mixture put in place in all repository galleries at closure.

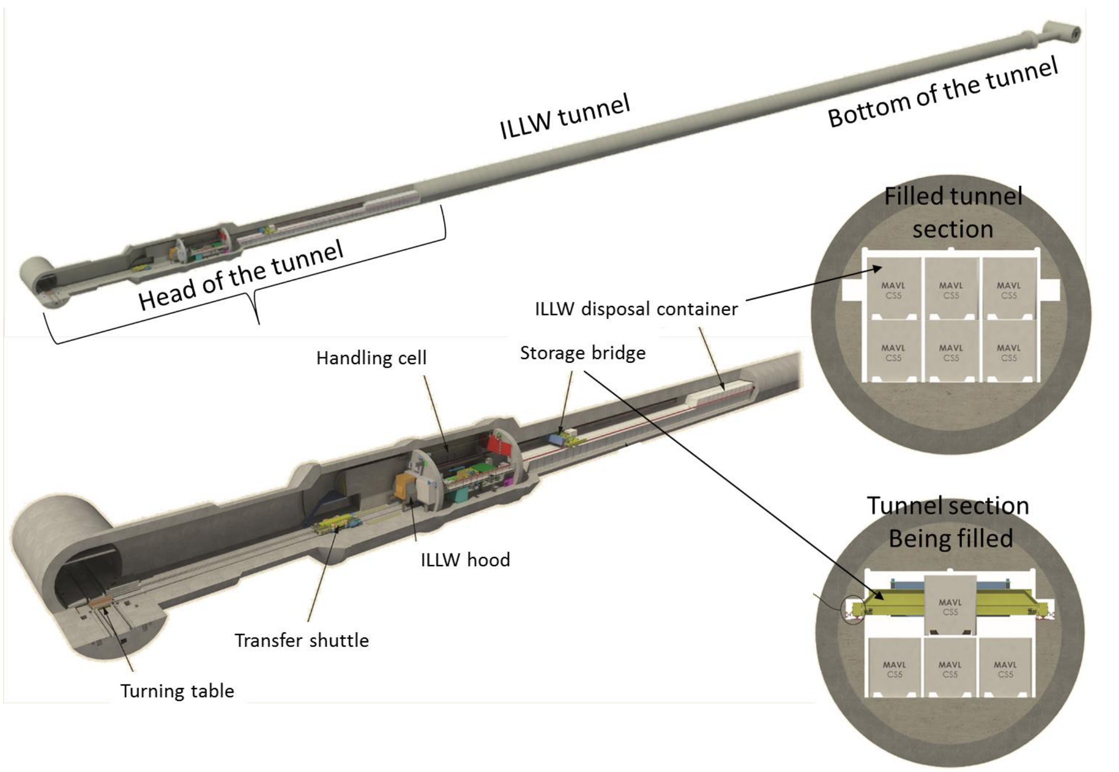


Fig. 6: ILLW disposal cell in the French disposal concept.

In the case of HLW, the disposal cells are micro-tunnels, around 1 m in diameter and up to 150 m in length (Fig. 7). To prevent the inflow of water to the waste during the thermal phase, each primary package of vitrified waste is placed in a watertight overpack. This overpack is made of non-alloy steel with an effective thickness of 55 mm, dimensioned very conservatively to withstand corrosion for 1000 y (Andra, 2005). The French concept does not rely on a bentonite buffer surrounding the waste packages. However, bentonite plugs are used to separate the disposal cells from the transfer drifts (Sellin & Leupin, 2013). These plugs consist of blocks of bentonite embedded in a metallic sleeve or granular bentonite mixture. The bentonite can optionally be mixed with sand or host rock.

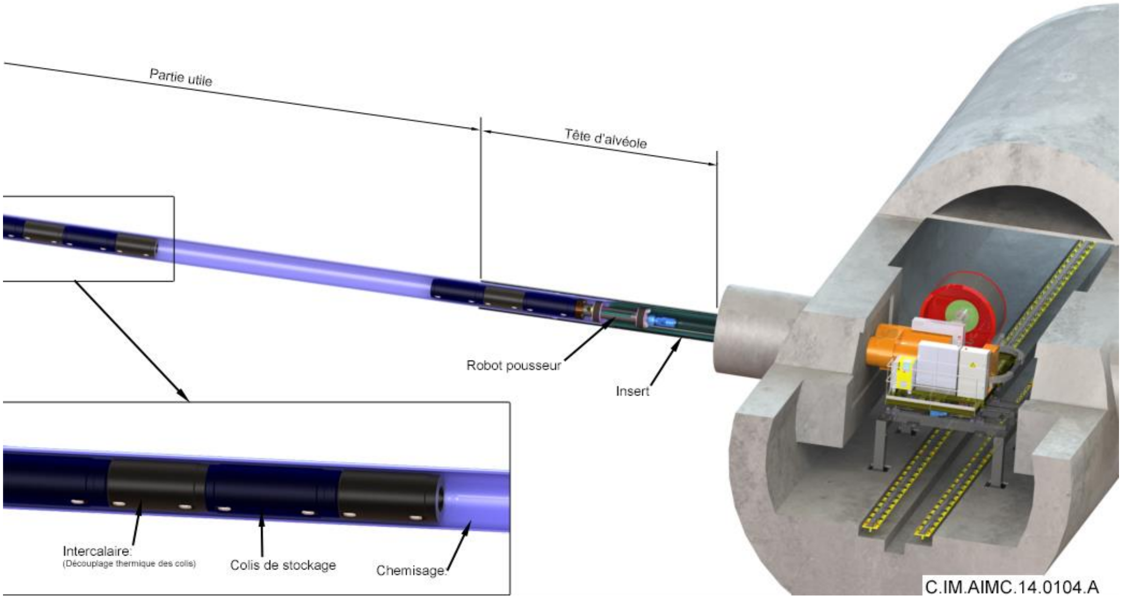


Fig. 7: HLW disposal cell in the French disposal concept.

The reference version of a seal at repository level *(in the main galleries and possibly at the entrance/bottom of some ILLW deposition cells)* consists of a bentonite core in contact with the host rock over only part of its length (parts of the concrete liner are maintained for mechanical stability), kept in place by concrete plugs at both ends (Fig. 8). The bentonite core is a mix of pellets and powder. The material is pure bentonite possibly mixed with sand or host rock. If necessary, shotclay can be used to fill part of the "off-profiles" in the contact zone between host rock and bentonite core.

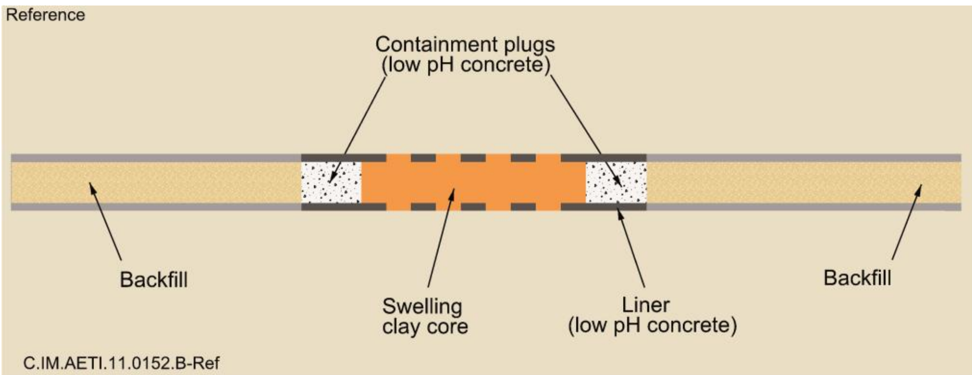
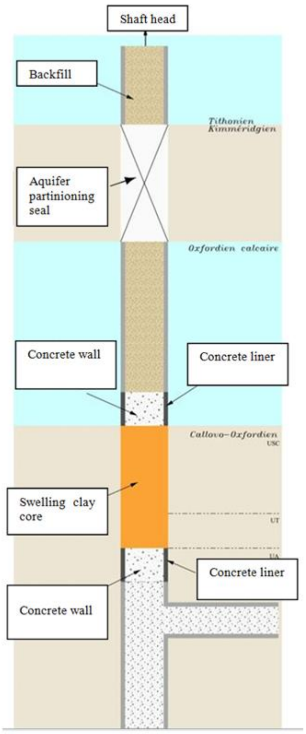


Fig. 8: Schematic representation of a reference design for a repository-level seal.

In the access shafts and ramps, the sealing concept is the same except that, in the upper part of the host rock, mechanical stability is higher and the concrete liner can be removed along all of the bentonite core length (Fig. 9).



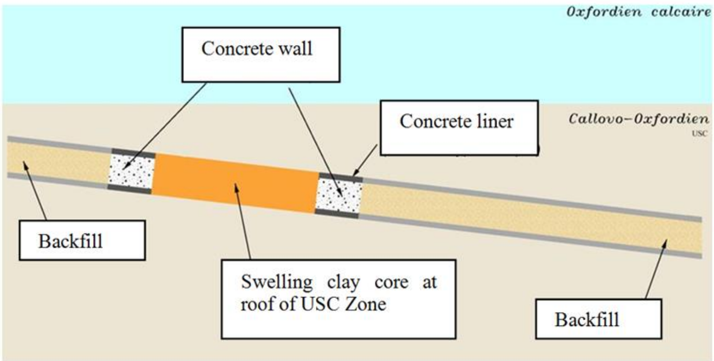


Fig. 9: Schematic representation of the reference design for acces seals.

2.6.2. Safety relevant properties of bentonite seals and plugs

Seals:

The fundamental safety objective assigned after repository closure (protection of human health and of the environment) implies that the repository:

- Can isolate the nuclear waste from surface phenomena and human intrusions, function mainly based on the site geological characteristics (absence of exceptional resources, low permeability, etc.) and the depth of emplacement;
- Can limit the transfer to the biosphere of radioactive and toxic substances contained in the waste by gaseous or aqueous channels. Gas transport phenomena are not studied here (in particular the generation and transport of H_2).

To reduce the transfer of radioactive and toxic substances by water, Andra assigns the following three post-closure safety functions to the repository:

- Counteract water flow: This function consists of greatly limiting the advection phenomena in the repository and justifies the choice of the low permeability clayey Callovo-Oxfordian formation as a host rock for the siting the repository. After repository closure, during the transitional phase of re-saturation, the limitation of water flow from overlying geological formations helps to delay the saturation of underground works and therefore the arrival of water at the waste packages. Saturation is then mainly controlled by the water flux coming from the Callovian-Oxfordian formation, whose flows are low and well controlled in terms of chemistry. After total re-saturation, the objective is to limit the renewal of water flow in the vicinity of the waste and to limit the advective transport of solutes in the disposal cells / vaults, in their access drift and in the underground structures connecting to the shafts (and ramps), to promote the two functions below.

- Limit the release of radioactive and toxic substances and immobilize them in the repository: This function relies on the hydraulic conditions prevailing in the vicinity of waste (low water renewal and slow solute transport) and on prevailing chemical conditions that favor the retention of radionuclides and toxic substances, which themselves depend in part on hydraulic conditions and on temperature.
- Delay and reduce the migration of radioactive and toxic substances that may be released outside the repository cells / vaults: This function mainly concerns the transfer pathways via the Callovo-Oxfordian (COX) clay rather than through the cells / vaults, their access drifts and the connecting drifts. This allows benefiting from (i) the diffusive transport of solutes in the Callovo-Oxfordian, (ii) the delay due to the retention of most of the chemical species in clay and (iii) the large-scale dispersion provided by a thickness of at least 60 meters of argillites between the cells / vaults and by the surrounding over- and underlying geological formations.

In fact, the limited convective velocity of the solutes in the cells / vaults, their access tunnels and the connecting structures on the one hand and the transport distance in these underground works on the other hand contribute to the transportation of the majority of radionuclides and toxic substances (released by the waste packages) through the Callovian-Oxfordian clay rock.

The seals are involved in the fundamental safety objectives after repository closure, mainly by counteracting the flow of water in the repository:

- By limiting the amount of water likely to come from the overlying transmissive formations down through the shafts and ramps during the re-saturation phase.
- After saturation of underground structures, by limiting the flow of water in the repository mainly linked to water exchange with the host formation. The hydrogeological characteristics of the site and architecture of the underground facility are mobilized to achieve this function. The aim of seals is to contribute to the flow limitation thanks to their low hydraulic transmissivity.

The shaft seals make the greatest contribution by limiting water flow between the underground facility and the surrounding formations. Seals installed in the drifts connecting each repository zone to the shafts or ramps increase the hydraulic resistance of these drifts. The drift seals (and possibly some ILLW disposal vault seals) ensure very slow flow conditions in the system and their positions close to the cell contribute to closer confinement of the waste.

Tab. 1: Variation of the safety function "limit water flow" as per the different seal types.

<table>
<tr><th>Safety function</th><th>Objectives</th><th colspan="2">Type of seal</th></tr>
<tr><td rowspan="2">Limit water flow from overlying transmissive formations toward the repository through the shafts</td><td>During resaturation period, limit water flow from the overlying formations</td><td rowspan="2">Shaft and ramp seals</td><td></td></tr>
<tr><td>After total repository resaturation, limit water flow from the host formation drained by the repository</td><td rowspan="2">Horizontal drift seals and IL-LLW vault seals</td></tr>
<tr><td>Limit water flow in the repository drifts</td><td>Reduce water head gradient in the repository</td><td></td></tr>
</table>

HLW cells Plugs:

After several performance assessment evaluations, Andra has reached the conclusion that, due to the relatively small hydraulic impact of a HLW cell, HLW seals are not relevant for the function „limit water flow in the repository drift ".

Thus, the function of the HLW cell closure component is reduced with respect to long-term safety to "limiting the release of radioactive and toxic substances" by „limiting chemical interaction between concrete gallery liner and HLW glass".

This component is therefore no longer termed a seal, which implies a water limitation function, but a plug.

2.7. GRS; Germany

2.7.1. Bentonite components in the repository concept

Seven different bentonite components are considered in the repository concept (Fig. 10): *(1) Shaft seals*, for example, are currently foreseen to be composed of a mix of bentonite briquettes (with a volume of 10 cm³) and granular bentonite (grain size fraction 0-3 mm) with a final bulk dry density of >1.6 g/cm³. An addition of 20% sand to the bentonite is considered as an option. *(2) Drift seals* between main drifts and infrastructural area, as well as *(3) drift seals* between access drifts to emplacement fields and main drifts, which are planned as bentonite blocks and also an addition of 20% sand to the bentonite is considered as an option. Similar to the shaft seals, *(4) emplacement borehole seals* – in the borehole emplacement concept only – consist of the same mixture of bentonite briquettes and granular bentonite. The use of bentonite is currently considered as optional for *(5) exploration borehole seals*, therefore no details on the bentonite emplacement is available yet. For the *(6) buffer* blocks with a dry density of 2 g/cm³ and pellets with a dry density of 2.2-2.3 g/cm³ (drift emplacement) or bentonite slices and rings with a dry density of 2 g/cm³ (borehole emplacement) prepared from the milled clay quarried from the claystone during the mining of the drifts with an admixture of bentonite are currently foreseen to be used. In the case of *(7) backfill*, the use of bentonite is currently considered as optional, i.e. it is currently foreseen for bentonite, if used, to be milled and mixed with the milled clay quarried from the claystone during the mining of the drifts.

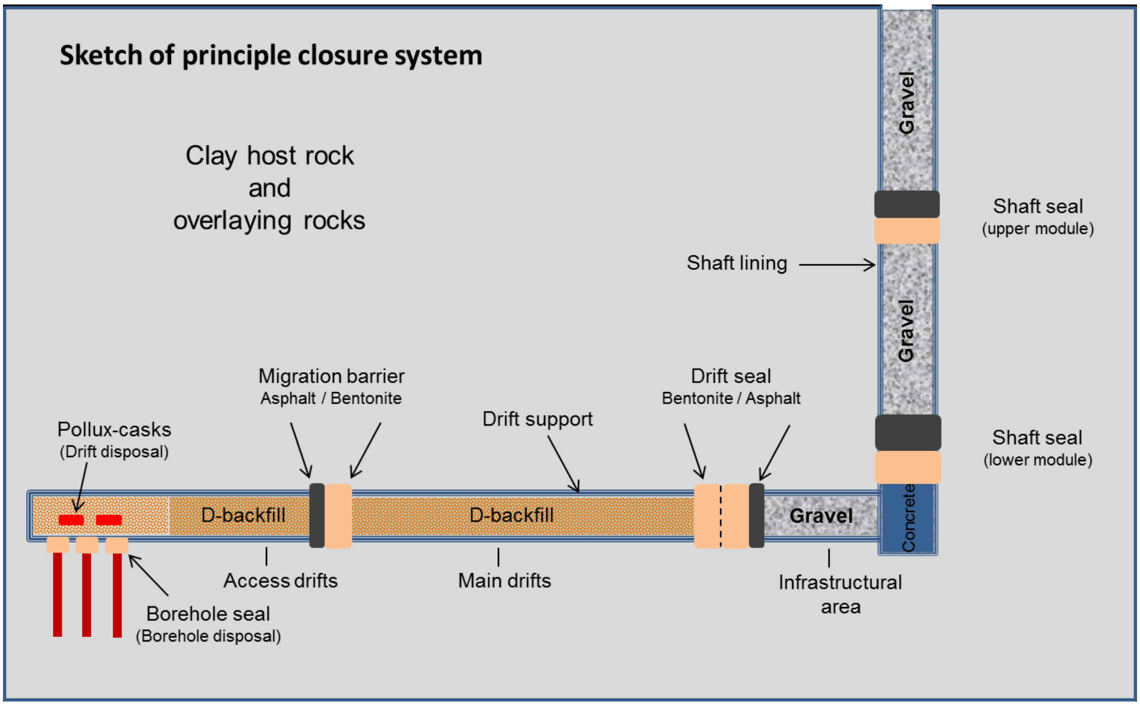


Fig. 10: Schematic outline sketch of the closure system.

2.7.2. Safety relevant properties of bentonite

Based on the geological, and particularly the hydrogeological, settings as well as the emplacement concept and site-specific repository design, a backfilling and sealing concept describes the measures for backfilling and sealing the underground excavations in such a way that only minor radionuclide release is to be expected even via the drift and shaft system. To fulfill this repository safety objective, the backfilling and sealing concept currently foresees extensive use of bentonite in seals. A further safety objective to be fulfilled by bentonite relates to a build-up of the supporting pressure against the converging rock in the buffer and backfill.

(1) Shaft seals:

(i) retardation of pore-water solution inflow from the adjoining rock area during the early phase after repository closure,

(ii) retardation of the outflow of potentially contaminated solutions from the repository following (i).

(2) Drift seals (between main drifts and infrastructural area):

(i) retardation of solution inflow from the infrastructural area during the early phase after repository closure until the hydraulic driving force in the direction of the emplacement fields no longer acts,

(ii) retardation of the solution outflow from the main drifts following (i).

(3) Drift seals (between access drifts to emplacement fields and main drifts):

(i) sealing the emplacement fields,

(ii) minimization of the transport of contaminated solutions through the excavation damaged zone (EDZ) of emplacement fields, which can potentially not be healed during the early phase after repository closure.

(4) Emplacement borehole seals (in the borehole emplacement concept only):

(i) preventing advective solution transport from and into the boreholes,

(ii) partial sealing of the EDZ of the boreholes,

(iii) radionuclide sorption.

(5) Exploration borehole seals (use of bentonite here is currently considered as optional):

(i) minimization of the transport of contaminated solutions through exploration boreholes.

(6) Buffer:

(i) build-up of the supporting pressure against the converging rock,

(ii) increased gas absorption capacity during the early phase after repository closure,

(iii) radionuclide sorption.

(7) Backfill (use of bentonite here is currently considered as optional):

(i) stabilization of the host rock after the corrosion of the drift lining,

(ii) radionuclide sorption,

(iii) hydraulic barrier in the long-term.

2.8. Swedish NGO Office for Nuclear Waste Review, MKG

This report provides additional statements on the heterogeneities of bentonite in the context of the KBS-3 method. These inputs are based on the personal view of Professor Roland Pusch and can be found in Appendix C.

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4. Occurrence of heterogeneity in the repository

4.1. Nagra, Switzerland

Material

The bentonite material has to be produced and stored such that, during the emplacement procedure, the target dry density can be achieved everywhere in the emplacement tunnel. Care must be taken, for example, to ensure that the difference in water content between ambient air and solid material does not exceed 5 -10% during storage to avoid the disintegration of the block material (Müller et al., 2017).

Emplacement

A ‘backfilling machine’ is needed to backfill a horizontal disposal tunnel with granulated bentonite mixture as tightly and homogeneously as possible. Based on the experience from the EB experiment (Kennedy and Plötze, 2004) and the ESDRED project (Plötze and Weber, 2007), the decision was made to design and fabricate a backfilling machine with five screw conveyors for the FE experiment. The aim of using five screw conveyors was to improve the backfilling quality in terms of homogeneity, since segregation effects had been observed during previous projects. It was found that, without additional measures (such as slope coverage), small material avalanches occur at the front of the slope, resulting in ‘fir tree like’ segregation effects in the backfilled material. A staggered alignment of the screw conveyors was therefore chosen with respect to the expected slope angle of the backfilled material. Moreover, an increased compaction was expected as each screw conveyor was designed to remain within the material bulk, building up a conveyance pressure (Müller et al., 2017).

Re-saturation process

Independent of application, the buffer and backfill, which are inhomogeneous after emplacement, will take up water and swell. This will cause the voids in the buffer, between rock and buffer and between canister and buffer, to disappear and it is expected that the buffer will homogenize. In a deep geological repository built in Opalinus Clay, a diffusive, radially-symmetric re-saturation is expected, i.e. re-saturation that should not result in additional heterogeneities within the buffer.

After complete saturation of the near-field

After complete saturation of the near-field, the EDZ is expected to be largely self-sealed, although increased gas pressures may keep some pathways open. The pore-water pressure in the rock will increase again slightly in the near- and far-field as the canister corrosion continues, until corrosion is complete after about 60,000 years.

4.2. SKB, Sweden

Heterogeneity is expected to occur in the buffer surrounding the canisters in the deposition holes: heterogeneity in the radial direction due to the difference in initial density of blocks and pellets, heterogeneity in the axial direction due to expansion of the buffer into the tunnel, and possibly heterogeneity due to mass loss from erosion. In the deposition tunnel backfill, heterogeneity could occur in the radial direction due to differences in initial density of blocks and pellets or due to mass loss from erosion. Heterogeneity of the backfill in other tunnels and shafts to a level of about 200 m above the repository and borehole seals is of minor concern.

4.3. Posiva, Finland

The heterogeneities in the initial state, i.e. after installation of the EBS, are mainly due to density differences in the high(er) density and low(er) density bentonite volumes. Specifically, density differences exist between

- blocks and pellets
- blocks and installation gaps
- buffer and backfill

Spatial variations that may affect the degree of density differences in the initial state are

- unevenness in the walls of the deposition hole and deposition tunnel
- variation of the deposition holes within the acceptable tolerances
- uncentered installation of the buffer blocks or deposition of the canister

Some density differences may also be expected due to block manufacturing and pellet fill emplacement.

During the early evolution of the bentonite-based EBS, processes due to groundwater flow into the repository may produce additional density differences, even if no initial heterogeneities exist by design. These processes include

- saturation and swelling of bentonite under various groundwater compositions, inflow rates, inflow locations and temperatures
- mechanical piping and possible erosion due to advective groundwater flow, which may transfer bentonite mass within the repository or transport bentonite mass into open fractures
- expansion of the buffer up into the backfill
- rock fallout in the wall of the deposition hole
- swelling of bentonite into open fractures

Finally, there is a hypothetically foreseeable scenario for the long-term evolution of the EBS, where some bentonite may be eroded into the open fractures due to interaction between bentonite and dilute groundwater. If this bentonite erosion process is continuous over long time periods, density differences in the form of a density gradient might develop in the system.

The density differences are expected to homogenize ("self-heal") to a considerable degree due to the swelling potential of bentonite.

4.4. SÚRAO, Czech Republic

Given the fact that the Czech DGR concept is based on the Swedish KBS concept, similar heterogeneities are expected. The focus will be on mineralogical heterogeneity, such as smectite content variations, and density heterogeneity. Nevertheless, this is not specified for the Czech reference design.

4.5. Enresa, Spain

The sources of bentonite heterogeneity can be diverse. The following can be mentioned:

- Combination of pellets and blocks in the same section
- Geometric features of the barrier
- Non-uniform hydration
- Presence of construction gaps and voids that are filled with the expansion of unsaturated bentonite
- Requirement for self-healing of the saturated bentonite after erosion and/or colloid formation

Although bentonite exhibits a natural tendency towards homogenization, observations at the end of very long-term tests such as EB (isothermal) and FEBEX (non-isothermal) have revealed that, even when the barrier has reached a saturated or near-saturated state, a degree of heterogeneity persists. In addition, there is the possibility that heterogeneity will continue to evolve in the long term due to creep phenomena.

4.6. Andra, France

Various kinds of heterogeneity are expected in Andra's repository concept:

- Linked to the use of different types of material in the same bentonite component. For example, pure bentonite shotclay in the bottom of an off-profile in contact with a sand/bentonite pellet/powder mixture in a disposal-level drift seal.
- Linked to some differences in initial emplaced density. In the seals, the reference design foresees filling the bentonite core with a pellet and powder mixture and feedback from the FSS demonstrator shows that the initial emplaced density is higher at the bottom of the core than at the top (10 m diameter galleries).
- Linked to possible initial technological voids that could stay open after emplacement and before re-saturation of the swelling component. This possibility is also a feedback from the FSS demonstrator where voids were present in off-profiles near the downstream face of the bentonite core.
- Linked to the possible heterogeneous temporal evolution of re-saturation implying compression or expansion of some parts of the bentonite core at a given time.
- Linked to the chemical evolution of the bentonite core due to heterogeneous chemistry of re-saturation water, part coming directly from the host rock (where direct contact exists), and part having percolated through remaining concrete liner. This heterogeneity is not so much linked to density effects as to swelling pressure differences at the same density due to chemical changes in the bentonite structure.

4.7. GRS, Germany

The German repository concept has not yet advanced to the stage where consideration is given to the topic of heterogeneity.

5. Role of uncertainties related to the heterogeneity of bentonite

5.1. Nagra, Switzerland

The emplacement density is the most important indicator of bentonite heterogeneity. The heterogeneity is addressed using a deterministic approach, defined with a preferred density value and a minimum lower density (an upper limit for the density is not specified). Based on several experiments, it was investigated whether these values could be achieved (Müller et al., 2017). Homogeneous initial conditions are expected in the assessment and the boundary conditions are fixed values based on the Neumann-Dirichlet boundary condition. Two main parameters are specifically considered regarding variability in space and time: heat source and gas transport (more detailed information in Nagra, 2014b).

5.2. SKB, Sweden

Heterogeneity is addressed using a deterministic approach in the SKB concept. No heterogeneities are considered in the assessment for material properties, although initial conditions show variability in installed mass and density, as well as in boundary conditions, in particular hydraulic boundary conditions such as inflow rates, inflow locations and geometries. Heterogeneity in source terms is also considered, especially as mass loss.

5.3. Posiva, Finland

In Posiva's repository concept, heterogeneity is addressed using a deterministic approach. In the first iteration of the safety case (Poteri et al., 2014), density differences in the bentonite were assumed to homogenize during early evolution of the EBS along with water uptake and swelling. Additionally, work is in progress concerning probabilistic assessments accounting for spatial and temporal distributions.

Different types of heterogeneities are considered in Posiva's assessments, however it has to be mentioned that all considerations presented below are work in progress.

For the material properties, density differences due to EBS components (blocks, pellets and gaps) will be assessed. Variability in bentonite characteristics, especially between buffer and backfill, will also be considered. Initial conditions could show variability in the EBS components due to the design and geometry of the deposition tunnels/holes and these will be included in the assessment. Additionally, deviations from the design requirements due to quality non-conformities (e.g. installation or manufacturing problems) may be investigated. Environmental conditions that cause variability are to be considered over space and time. These may include groundwater composition, inflow rate and locations. The effect of temperature is also of interest. Addition and/or inclusion of source terms and/or perturbations that may affect the behavior or evolution of the EBS may be implemented in the assessment, possibly involving a scenario where some of the buffer is eroded.

5.4. SÚRAO, Czech Republic

Due to the fact that SÚRAO has no detailed concept, heterogeneity has not yet been addressed. Therefore, no heterogeneities have been considered for material properties, initial conditions, boundary conditions or source terms/perturbations up till now.

5.5. Enresa, Spain

In both design specifications and long-term assessments of bentonite, it is assumed that homogenization will occur and that the hydro-mechanical properties of the barrier will be equivalent to the properties of mean installed density, which is defined using a deterministic approach. The bentonite buffer is treated as a homogenized material at the end of the saturation period.

5.6. Andra, France

In the safety assessment of Andra, heterogeneity is addressed using a deterministic approach, as there are mean values for the reference case (NES) and conservative and pessimistic values respectively for the altered scenarios and the "What-if" scenarios. No probabilistic assessments accounting for spatial or temporal distributions in the safety assessment exist as yet.

However, temporal and spatial evolutions of certain parameters are taken into account by using environmental conditions whose effects were predetermined via performance assessment evaluation (see also section 6.6.2).

5.7. GRS, Germany

Although the German repository concept has not yet advanced to the stage where consideration is given to the topic of heterogeneity, some approaches to addressing heterogeneity in the German safety cases were developed. Based on a deterministic approach, parameters are varied within a range of a factor of 2 to 10 from the reference value. Only one parameter out of those considered is varied at a time. For probabilistic assessments accounting for spatial and temporal distributions, parameters are varied within a range of a factor of 2 to 10 from the reference value. Independent variations of all parameters according to their probability density distributions (uniform or log-uniform) are performed. A single random value is sampled for each varied parameter per simulation and a large number of simulations is carried out.

6. Bentonite modelling

6.1. Nagra, Switzerland

In the Swiss disposal concept, bentonite-based buffer systems are adopted in sealing components (tunnel seals, shafts) of the repository and in the SF/HLW near-field. Comprehensive phenomenological modelling activities were carried out in previous long-term safety assessments considering the entire repository system and the individual buffer components, respectively. Emphasis was on the assessment of the impact of repository-induced effects (heat, gas, chemical effects) on the long-term safety functions of the buffer system.

Most of the modelling studies were conducted with thermo-hydraulic (TH) models (Nagra, 2016b) using the multi-phase flow simulator TOUGH2 (Pruess et al., 2012). Fully coupled THM models were used to assess the evolution of the bentonite near-field in the early unsaturated phase after HLW emplacement (Nagra, 2016c). The fully coupled THM simulations were conducted with the code LAGAMINE (LAGAMINE, 2007) and the constitutive framework ACMEG-TS for unsaturated soils under non-isothermal conditions (Francois & Laloui, 2009). In the context of Nagra's RD&D program, further THM codes have been used in several benchmark exercises (FEBEX, FE Experiment). In this context, code comparisons have been conducted with CODE_BRIGHT and CODE-ASTER.

6.2. SKB, Sweden

The type of model used to simulate bentonite evolution in the performance assessment is dependent on the studied process (Åkesson et al., 2010). THM and HM define the level of coupling. The main characteristics of the models used were based on finite element models, while the main numerical models used are Abaqus and CODE_BRIGHT, as well as a new development of COMSOL Multiphysics®.

Additionally, SKB does not differ between performance and safety assessment when it comes to the mechanical modelling of the clay barrier. The assessment of the mechanical evolution is done in support of the overall safety assessment.

6.3. Posiva, Finland

6.3.1. Model type used to simulate bentonite evolution in performance assessment

The geometry of the buffer, backfill and deposition tunnel/hole, near-field host rock conditions and fracture locations, as well as material parameters under different conditions, are needed to describe the system on the macroscopic scale. Simplifications or approximations of these details are to be considered (e.g. smooth tunnel rock surfaces, gaps between bentonite blocks, etc.). Information on couplings between microscopic–macroscopic level phenomena is needed for double structure models. Earlier assessments were carried out with TH and THM couplings, but in the future THMgas-C coupling will be pursued. Past calculations include application of one structural level model. For the future performance assessment simulations, double pore structure concept is to be applied. THMgas-C phenomena and couplings will be considered on both structural levels and the mechanical model is based mainly on the Barcelona expansive model (BExM) framework. The finite-element method for spatial discretization and various time discretization schemes has been utilized with CODE_BRIGHT, COMSOL Multiphysics®, Abaqus and PLAXIS software to perform model simulations. Current performance assessment work is focused on using COMSOL Multiphysics® and CODE_BRIGHT.

6.3.2. Model type used to simulate bentonite evolution in safety assessment

This section considers “bentonite evolution in safety assessment” as bentonite evolution in the context of analysis of releases (AOR) in Posiva’s safety assessment. AOR is the next step from performance assessment (PA) and formulation of scenarios (FOS).

The scale in the AOR focuses on the near-field that includes a single deposition hole with a canister and surrounding buffer. The near-field continues further to a deposition tunnel section that extends from above the deposition hole to an intersecting bedrock fracture. Modelling is done with a geometry that is cylindrical in the deposition hole and Cartesian in the tunnel. The clay components are considered to be homogeneous, with the exception of scenarios where low bentonite content regions are considered in the buffer at different bedrock fracture locations, i.e. some bentonite erosion is assumed (see report Posiva 2014-02 (Poteri et al., 2014)) for more details. Couplings are not included explicitly in the “main” AOR modelling that focuses on solute transport in the disposal system. Solute transport modelling is based on diffusive and possibly advective conditions in the barriers and bedrock. Linear sorption (equilibrium assumption) and solubility limits are taken into account in the modelling. Changes in chemistry (groundwater composition) are included by using definitions of “bounding waters” and their timing in the disposal system evolution (determined in PA+FOS work). The ranges and deterministic values are then determined for AOR parameters and changes are taken into account in the simulation. Gas transport is modelled separately as a complementary case (source term small). The AOR model is built from homogeneous compartments in the near-field regarding solute transport. Mainly diffusive conditions but also advective conditions are possible. Linear sorption and solubility limits are possible in the barriers, and radioactive decay with decay chains is taken into account. The buffer consists of 194 compartments and tunnel sections from 55 compartments. The model is developed in the GoldSim Software which allows probabilistic simulations with multiple parameter values for the sorption, groundwater flow rates, etc.

6.4. SÚRAO, Czech Republic

For simulating bentonite evolution in performance assessment, only the THM defines the level of coupling. One of the modeling approaches is a hypoplastic double structure model (Mašín, 2017) and the main numerical models used are Flow 123D and COMSOL Multiphysics®. Models to simulate bentonite evolution in safety assessments are under development.

6.5. Enresa, Spain

Enresa uses CODE_BRIGHT, a fully coupled THMgas model to simulate bentonite evolution in the performance assessment. Double structure features are incorporated to account for the time evolution of the macro-/micro-porosity structure of the bentonite.

6.6. Andra, France

6.6.1. Simulation of bentonite evolution in performance assessment

The type of model used to simulate bentonite evolution in performance assessment is highly dependent on the type of phenomena which have to be quantified:

- **Evaluation of chemical effects at interfaces.** For modelling chemical transport, a 2D axisymmetric model of core, concrete plugs and surrounding host rock is used. This model assumes saturated homogeneous media and explicit chemical interactions, in particular mineralogy changes. The main numerical models used for modelling chemical transport are finite difference models, such as CRUNCHFLOW or PHREEQC.

- **Evaluation of mechanical effects.** Modelling the HMgas needs a fine geometrical description and is based on a 3D model of core, concrete plugs and surrounding host rock. Due to high non-linearities in the coupling representation, this type of model can only be performed at component (seal) level. There are specific HMgas models for bentonite (UPC model). The main numerical models used to model HMgas rely on finite elements, i.e. LAGAMINE, CODE_BRIGHT, CODE_ASTER.
- **Evaluation of hydraulic-gas effects.** A 3D model of the total repository with non-conforming mesh and homogenization methods is used to model the THgas transient period that can last several tens of thousands of years. A two-phase flow porous medium is used, i.e. homogenization of the fractured EDZ. The main numerical code used, TOUGH-MP, is based on finite volume.

6.6.2. Simulation of bentonite evolution in safety assessment

The model used to simulate bentonite evolution in safety assessment is a total repository model with explicit representation of core, confinement plug and EDZ. The model is based on single porosity two-phase flow assumptions and only saturated hydraulic conditions are assumed; “perturbations” are taken into account via environmental variables, such as variation of permeability in time and space in relation with performance assessment results, e.g. chemical evolution or desaturation. The main numerical model used is PORFLOW, which is based on a finite volume scheme.

6.7. GRS, Germany

6.7.1. Simulation of bentonite evolution in performance assessment

On the process level, bentonite evolution is modelled by THM-coupled models as provided by the finite element code CODE_BRIGHT, with realistic geometry and models of varying complexity as required by the problem. Double structure models have not yet been employed, but are planned to be used in the future. A second code (Viper) specialized on bentonite re-saturation via the vapor phase has been developed and will be refined. On a more abstract level, the models for safety assessment (see section 6.7.2) are used.

6.7.2. Simulation of bentonite evolution in safety assessment

A code developed in-house - RepoTREND - is used to simulate bentonite evolution in safety assessment. The boundary conditions are defined as 30-35 cm thickness of the bentonite buffer, 1D radial diffusive transport and initially saturated bentonite. H and C are simulated without coupling and bentonite is represented as a homogeneous medium. The main numerical model is based on a finite volume scheme.

7. Natural properties of the reference bentonite

Some natural properties of bentonite may impact the degree of homogenization, i.e. the remaining heterogeneity such as density differences. Tab. 2 shows which natural properties seem to be relevant for remaining heterogeneities of bentonite in the specific repository concepts. Additional comments from the waste management organizations for each property can be found in Appendix B.

Tab. 2: Relevant natural properties for bentonite regarding heterogeneity. (Legend: × = relevant)

Natural Properties	Nagra	SKB	Posiva	SÚRAO	Enresa	Andra	GRS
Mineralogy			×	×	×	×	×
Organic carbon							×
CEC (cation exchange capacity)			×	×			
Original exchangeable cations	×	×	×	×	×	×	×
Water content	×	×	×	×	×	×	×
Gas content	×	(×)	×		×	×	
Pore-water composition		×	×		×	×	
Grain size distribution	×	(×)	×	(×)	×	×	
Grain density	×		×		×	×	
Bulk density	×	×		×	×	×	×
Swelling pressure	×	×	×	×	×	×	
Hydraulic conductivity	×	×	×	×	×	×	
Pore-water pressure	×	×				×	
pH		(×)	×			×	
Thermal conductivity		×	×				
Pore clogging	×				×		

8. Performance measures

8.1. Nagra, Switzerland

8.1.1. Performance measures specified for bentonite-based EBS components

A more comprehensive description of the requirements for the bentonite used in a HLW repository in Opalinus Clay can be found in Nagra (2014b). The different requirements are presented below as a shortlist.

- **Low hydraulic conductivity**

This requirement supports the buffer safety function "attenuate releases". The hydraulic parameters of the saturated buffer should prevent advective flow through the buffer and therefore result in an effective transport barrier. Possible cracks in the buffer should close due to self-sealing.

- **Chemical retention of radionuclides**

This requirement supports the buffer safety function "attenuate releases" by retarding transport of radionuclides from the buffer.

- **Sufficient density**

This requirement supports the buffer safety function "attenuate releases" by ensuring that the density of the buffer will be high enough that the resulting microporous structure provides an effective barrier for colloid transport.

- **Sufficient swelling pressure**

This requirement supports the rock safety function "attenuate releases". Emplacement tunnels in the Opalinus Clay may be supported with rock bolts and liner. In either case, the lifetime of the support is designed to provide stable conditions during construction and operation (up to several years). After waste and buffer emplacement, there may be interactions of the support system with other system components (host rock, buffer, canister, waste form). These interactions should not be detrimental to the safety of the system. The support will eventually fail due to corrosion and deformation and allow additional time-dependent deformations of the near-field host rock and compaction of the buffer. The maximum convergence-induced compaction of the buffer, which is controlled by the stress field and the mechanical properties of host rock and swelling pressure of the buffer material, should be limited to avoid significant extension of the excavation damaged zone (EDZ) of the host rock. Limited convergence will also enhance the self-sealing capacity of the Opalinus Clay in the EDZ. The consequences of such an extension may include significant increases in permeability of the EDZ that are difficult to evaluate quantitatively. In addition, a too high swelling pressure could also initiate fracturing of the rock. Furthermore, an adequate swelling pressure will prevent canister sinking. The canister should be placed in a way that its distance to the tunnel wall is constant and so that it is encased by a thick layer of buffer material to avoid hydraulic short-cuts to the EDZ of the tunnels. Having sufficient swelling pressure also supports the buffer safety function "protect the canister" (Leupin & Johnson, 2014). The rheology of the buffer material (viscous material behavior) should keep deviant stresses and stress inhomogeneity as low as possible to protect the canisters (e.g. avoid point loading of canister). Potential larger deformations of the host rock resulting from tectonic events (e.g. earthquakes) should be attenuated.

- **Sufficient gas transport capacity**

This requirement supports the buffer safety function "attenuate releases". The buffer should transport corrosion gases without significant reduction of its function as a hydraulic barrier.

- **Minimize microbial corrosion**

This requirement supports the buffer safety function "protect the canister". Studies of the reduction of sulphate to sulphide in bentonite indicate that the rate decreases as saturated density increases. Based on an extensive literature review and results of ongoing studies, a value for saturated density may be defined in order to minimize the viability of microorganisms in the bentonite (Stroes-Gascoyne, 2011).

- **Resist transformation**

This requirement supports the buffer safety functions "attenuate releases" and "protect the canister". Mineralogical interactions occurring over time due to elevated temperatures and chemical interactions with other components of the disposal system should not lead to significant alteration and /or loss of the buffer functions.

- **Suitable thermal conductivity**

This requirement supports the buffer safety functions "attenuate releases" and "protect the canister". The buffer should conduct heat sufficiently well that the waste form, canister and buffer do not experience conditions detrimental to the performance of their safety functions.

8.1.2. Performance measures specified for a given period of repository evolution

After 100 years, the buffer should be close to full saturation, i.e. a residual gas saturation of 1 – 2% is expected in the buffer at the end of the re-saturation phase. By about 1,000 years, the near-field rock temperature should decrease to about 60° C. Pore-water pressure should reach its maximum in the near-field of about 5 MPa above the initial formation pressure as a result of the coupled effects of gas generation (dominated by corrosion of tunnel support materials) and thermal expansion.

Temperatures in the near-field should decrease from about 60° C to about 50° C from 1,000 to 10,000 years. Corrosion of steel materials used for tunnel support should cease after a few thousand years, although gas generation from the thick-walled disposal canisters should continue. The gas production rate is thus reduced and pore-water pressure falls by several MPa in the near- and far-field rock due to the combined thermal and gas production effects. Based on current understanding, compaction of the bentonite around the canister is not expected to occur as the adjacent rock reconsolidates. A high-pH plume is expected to affect a few centimeters of the host rock and bentonite (Nagra, 2014a). Corrosion of the canister produces mobile iron species that migrate through the bentonite and form iron-rich clay minerals or Fe(II) precipitates around the canisters.

Beyond 10,000 years, the temperatures will decrease gradually from 50° C back to ambient rock values. Though some of the canisters are now expected to be locally breached, corrosion and gas production will continue for tens of thousands of years. As a result, hydrogen will continuously be transported through the backfill into the EDZ and host rock and mobile Fe (II) will diffuse into the bentonite. The pore-water pressure in the rock surrounding the emplacement rooms will increase again slightly as canister corrosion continues, until corrosion is complete after about 50,000 – 100,000 years.

8.2. SKB, Sweden

Tab. 3: Measures specified for bentonite-based EBS components of the SKB concept.

Safety-relevant attributes	Application	Preferred values
Low hydraulic conductivity	Design criteria and assessment target	10^{-12} m/s
Chemical retention of radionuclides	No (bonus from the selection of bentonite)	
Montmorillonite content	No (only for quality control)	
Content of organic carbon	Design criteria	<1 weight %
Sulphide content	Design criteria	<0.5 weight %
Total sulphur content	Design criteria	<1 weight %
Sufficient density	Design criteria and assessment target	Related to material-specific swelling pressure
Sufficient swelling pressure	Design criteria and assessment target	Design criteria >3 MPa Performance target >2 MPa
Sufficient gas transport capacity	Design criteria and assessment target	"Sufficient"
Minimize microbial corrosion	Design criteria and assessment target	Material-specific minimum dry density
Resist transformation *(thermal requirements)*	Design criteria for the total repository system	<100 °C
Suitable thermal conductivity	Indirect through thermal requirement	
Limit advective transport in the near-field	Through hydraulic conductivity	
Attenuate rock shear movements/shear strength	Design criteria	Unconfined compressive strength at failure < 4 MPa at a deformation rate of 0.8 %/min
Resist transformations *(requirement on temperature)*	Same as thermal requirement	
Prevent canister sinking	Design criteria and (through swelling pressure)	0.2 MPa
Limit pressure on canister and rock	Design criteria and assessment target (through swelling pressure)	10 MPa
Other requirements… Retain sufficient mass over life cycle	Assessment target	Combination of material properties and groundwater chemistry
Filter colloids	Assessment target	Dry density > 1000 kg/m^3
Keep the buffer in place (backfill)	Design criteria	Swelling pressure of >1 MPa in a wet state. Certain compression properties in a dry state

All defined performance measures are listed in Tab. 3. SKB does not have performance measures for different time scales. They are divided into design criteria (for initial state) and assessment targets (or safety function indicators) for the entire assessment period.

8.3. Posiva, Finland

The requirements for the buffer and the backfill are listed below (Tab. 4) for different safety-relevant attributes based on the latest buffer and backfill design (work in progress). The plug is separated from the backfill where appropriate. The given requirements may appear on different levels in Posiva's five-level requirement management system (VAHA) or have been defined by specific relations, thus there are no clear bounding values for every listed attribute. Performance measures apply to long-term performance, not initial state. The concept of performance targets is used, which are not absolute requirements.

Tab. 4: Measures specified for bentonite-based EBS components of Posiva's concept.

Safety-relevant attributes	Application	Preferred values
Low hydraulic conductivity	Buffer, backfill, closure	Buffer: ≤ 10^{-12} m/s Backfill: ≤ 10^{-10} m/s Closure: ≤ 10^{-8} m/s for central tunnels, elsewhere higher values may be allowed
Chemical retention of radionuclides	Buffer	The buffer material should have known radionuclide retention properties
Montmorillonite content	Buffer, backfill, plug	Buffer: 75–90 wt-% Backfill: > 65 wt-% Plug: 75–90 w-% in the sealing layer
Content of organic carbon	Buffer, backfill	Buffer: < 1 wt-% Backfill: < 1 wt-%
Sulphide content	Buffer, backfill,	< 0.5 w-%
Total sulphur content	Buffer, backfill,	< 1 w-%
Sufficient density	Buffer, backfill, closure	Buffer: 1400 kg/m^3 (av.) Backfill and closure: the material-specific density will be defined by separate laboratory tests. Plug: >1400 kg/m^3 (av.)
Sufficient swelling pressure	Backfill	The average dry density in a tunnel section between two adjacent deposition holes should yield a swelling pressure > 1MPa
Sufficient gas transport capacity	Buffer	Should allow gas transport
Minimize microbial corrosion	Buffer	Minimize microbial activity through material selection, dry density and sulphur availability
Resist transformation *(thermal requirements)*	Buffer	Performance target: to limit mineral transformation, the buffer temperature should be < 100 °C
Suitable thermal conductivity	Buffer	Design requirement: After installation, the buffer should be in contact with the deposition hole walls to ensure sufficient thermal conductivity Design specifications: the gap between buffer block and deposition hole will be filled with bentonite

		The water content of the buffer material at installation shall be at least 15 wt-%
Limit advective transport in the near-field	Buffer, backfill, closure	Buffer: $\leq 10^{-12}$ m/s Backfill: $\leq 10^{-10}$ m/s Closure: $\leq 10^{-8}$ m/s for central tunnels, elsewhere higher values may be allowed
Attenuate rock shear movements/shear strength	Buffer	Unconfined compressive strength $\leq$ 4 MPa at deformation rate of 0.8 %/min
Resist transformations *(requirement on temperature)*	Buffer	< 100 °C
Prevent canister sinking	Buffer	The buffer displacement should be limited to maintain the target thicknesses
Limit pressure on canister and rock	Buffer	Swelling pressure $\leq$ 10 MPa
Other requirements…		

8.4. SÚRAO, Czech Republic

SÚRAO did not define any quantitative performance measures either for the bentonite-based engineered barrier system components or for a given period of repository evolution. The primary requirement of bentonite is the retardation of radionuclides. Therefore, a sufficient swelling pressure is needed to ensure self-healing of fractures caused by possible movement of the rock, as well as low hydraulic conductivity and diffusivity to restrict the radionuclide migration rate. Further, high sorption capacity, filtering property and chemical stability – in particular from the viewpoint of colloid formation – provide transport retardation. In addition it is required that the supporting functions of bentonite ensure confinement of radionuclides in the disposal canisters. These include sufficient swelling pressure to ensure favorable properties, but not so high as to pose an excess load for the disposal canister and surrounding rock. Low hydraulic conductivity and diffusivity are required to restrict water contact with disposal canisters and sufficient thermal conductivity to remove heat from disposal canisters. It is required that bentonite generates mechanical protection and stabilization of disposal canisters in the emplacement borehole. Moreover, bentonite should provide sufficient permeability for gases, which are produced during the corrosion process (Vokál et al., 2010).

8.5. Enresa, Spain

Safety function indicators, which are intended to quantitatively evaluate whether a repository component fulfills its assigned safety functions, were not explicitly stated in Enresa (2000), with the exception of the temperature limit in the bentonite (< 100 ºC). No measures are specified for a given period of repository evolution in the Enresa concept.

A qualitative description of these safety indicators is as follows:

- **Low hydraulic conductivity**

  An important safety function of the buffer is to limit transport of dissolved corroding agents to the canister and potential radionuclide releases from the canister. The hydraulic conductivity of the buffer should be low enough to make advective transport negligible so that transport is then diffusion-controlled. The buffer homogeneity is ensured partly by the fact that the buffer is made of a clay material that swells when water-saturated.

- **Sorption of radionuclides**

  The sorption of radionuclides in the buffer may provide a significant limitation on the transport of radionuclides from the canister.

- **Buffer density**

  Another safety function of the buffer is to mechanically isolate the canister from limited shear displacements in the disposal drift walls. The buffer density has to be limited to cope with rock shear movements.

  The buffer should, on the other hand, be dense enough to prevent transport of colloids through it.

- **Swelling pressure**

  The swelling pressure should be sufficient to avoid canister sinking in the disposal drift that could result in a direct contact of the canister with the rock, hence short-circuiting the buffer. In addition, the buffer homogeneity is ensured partly by the fact that the buffer is made of a clay material that swells when water-saturated. A sufficient swelling pressure is therefore also needed.

  Swelling pressures that could contribute to total pressures that the canister cannot withstand must be avoided.

- **Resist transformation**

  Temperatures (>100 ºC) that could result in chemical alteration of the bentonite, by transferring radiogenic heat from the waste package to the host rock, must be avoided.

- **Gas pressure**

  The build-up of excessive gas pressure in the near-field must be limited in order to avoid undue impairment of the safety functions.

8.6. Andra, France

Tab. 5: Measures specified for bentonite-based EBS components of Andra's concept.

Safety-relevant attributes	Application	Preferred values
Low hydraulic conductivity	x	< 10^{-9} m/s at repository level, < 10^{-11} m/s in the access
Chemical retention of radionuclides		
Montmorillonite content		
Content of organic carbon		
Sulphide content		
Total sulphur content		
Sufficient density		
Sufficient swelling pressure	x	> 3-4 MPa
Sufficient gas transport capacity		
Minimize microbial corrosion		
Resist transformation *(thermal requirements)*		
Suitable thermal conductivity		
Limit advective transport in the near-field		
Attenuate rock shear movements/shear strength		
Resist transformations *(requirement on temperature)*		
Prevent canister sinking		
Limit pressure on canister and rock		
Other requirements…	Length	Depends on type of seal

The performance measures are mostly linked to the safety function "Limit water flow in the repository drifts":

- However, the function of the buffer material permeability is direct and the values have been assessed during several performance exercises;
- For the swelling pressure, the function is indirect and linked to the recompression of the EDZ, which in turn implies a low permeability after re-saturation. The value is extrapolated from in-situ experiments (CDZ) with some uncertainty margins added, linked, for example, to heterogeneity of emplaced density (feedback of FSS demonstrator) and possible chemical evolution (numerical study);
- Concerning the length of the core, the value is linked partly to the expected "hydraulic resistance" of the seal, and partly to technical constraints (i.e. the need to maintain part of the concrete liner even where the core is emplaced, see Fig. 8 in section 2.6.1).

These specifications may evolve but are, for the moment, the "high level" specifications for the bentonite core of the seals. Once a specific bentonite has been chosen, these "high level" specifications will be reduced to more pragmatic ones, for example a minimum value for the emplaced dry density and the water content in relation to the "density/permeability" and "density/swelling pressure" curve of this material.

Andra has no specifications for radionuclide retention in the bentonite core, but some specifications concerning the gas transport capacity may emerge in the future.

8.7. GRS, Germany

8.7.1. Performance measures specified for bentonite-based EBS components

- **Low hydraulic conductivity**

This requirement taken alone is considered a primary performance measure for all bentonite-based EBS components to retard either solution inflow from the adjoining rock area during the early phase after repository closure or the outflow of potentially contaminated solutions from the repository thereafter.

- **Chemical retention of radionuclides**

This requirement taken alone is considered a primary performance measure only for buffer and backfill, as well as for emplacement borehole seals (in the borehole emplacement concept).

- **Sufficient density**

This requirement taken alone is not considered a primary performance measure in any bentonite-based EBS components. Instead, it is considered only as a secondary performance measure which should provide for the fulfillment of the primary performance measure of low hydraulic conductivity. Additionally, for the buffer it is considered a secondary performance measure which should provide for the fulfillment of the primary performance measure of minimizing microbial corrosion.

- **Sufficient swelling pressure**

This requirement taken alone is considered a primary performance measure only for the buffer and backfill after their saturation and before the drift support loses its stability. Thereafter, the buffer (in the drift disposal concept) and backfill should take over the mechanical support of the converging clay rock. In the borehole emplacement concept, the buffer should take over the mechanical support of the converging clay rock after the outer liner loses its stability. In the other bentonite-based EBS components, sufficient swelling pressure is considered only a secondary performance measure which should provide for the fulfillment of the primary performance measure of low hydraulic conductivity.

- **Sufficient gas transport capacity**

This requirement taken alone is considered a primary performance measure for the buffer and for emplacement borehole seals (in the borehole emplacement concept) to avoid development of increased gas pressures because of thermal expansion, metal corrosion and radiolysis, which would otherwise cause fissuring of the clay-based barrier.

- **Minimize microbial corrosion**

This requirement taken alone is considered a primary performance measure for the buffer. For this purpose, the density of the buffer in the saturated state should not fall below 2 g/cm³.

- **Resist transformation**

This requirement taken alone is considered a primary performance measure for the buffer. For this purpose, the density of the buffer in the saturated state should not fall below 2 g/cm³.

8.7.2. Performance measures specified for a given period of repository evolution

The buffer should retain its sorption capacity at least until the drift seals (between access drifts and emplacement fields and main drifts) develop their full functionality. The buffer should also possess sufficiently high permeability and sorption capacity for gases in the early phase after repository closure. Further, the buffer should have a low hydraulic conductivity for solutions after full saturation and reaching the maximum swelling pressure. In addition, the buffer should remain thermally stable for at least several hundred years after repository closure. Additionally, for the borehole emplacement concept, the buffer should provide mechanical stability of boreholes and an abutment function for emplacement borehole seals for 50,000 years after repository closure. Bentonite elements of drift seals, shaft seals, emplacement borehole seals and exploration borehole seals should retain their stability during the projected functionality period of 50,000 years. The swelling pressure of bentonite elements of shaft seals, emplacement borehole seals and backfill should not exceed the minimum principal stress of the host rock. The backfill should develop its functionality at the latest 50,000 years after repository closure and remain stable thereafter. The backfill should have a low hydraulic conductivity for solutions after full saturation and compaction.

9. Relevant periods in repository evolution concerning heterogeneity

9.1. Nagra, Switzerland

9.1.1. Pre-emplacement phase

Proper production of the bentonite blocks and pellets, as well as dry storage of the material, is required during the pre-excavation phase to minimize heterogeneities caused, for example, by relative humidity differences between ambient air and bentonite material.

9.1.2. Emplacement phase

The bentonite buffer must have a sufficiently high density to generate a sufficient swelling pressure, thus contributing to EDZ self-sealing under fully saturated conditions, providing sufficient sorption capacity for radionuclide retention on canister breaching and a low enough swelling pressure such that gas generated by canister corrosion can migrate through the buffer. A homogeneous distribution of the bentonite pellets is needed to generate a sustained high density.

9.1.3. Re-saturation phase with high thermal and hydraulic gradient (0 to 100 years after emplacement)

The bentonite backfill will saturate within about 50 to 100 years, although pore-water pressure within the backfill will be low. Re-saturation heterogeneity in the form of irreversible damage could occur if the re-saturation process is not radially-symmetric as expected. For HLW canisters, the initial heat output is limited to 1,500 W, which will result in a temperature at the canister interface with the backfill of about 130 °C within about ten years (Senger & Ewing, 2008). The temperature of the rock at the tunnel boundary will reach its maximum (about 70 °C) after about 50 years. Gas generation due to corrosion of the steel used in tunnel support and the canisters will begin, although most of the gas produced in the first hundred years should dissolve and therefore not cause any irreversible heterogeneity in the buffer. The re-saturation phase largely coincides with the observation phase of the pilot repository, which is thoroughly monitored to identify any deviation from the expected evolution. Only the pilot repository will be monitored.

9.1.4. After complete saturation of the near-field

Some of the canisters are expected to be locally breached after 10,000 years, therefore corrosion and gas production will continue for tens of thousands of years. Thus, the pore-water pressure in the bentonite will increase again slightly as the canister corrosion continues, until corrosion is complete after about 60,000 years. Pore-water could contact the waste matrix and radionuclides could diffuse through the saturated buffer and into the host rock. Depending on the chemical forms and half-lives of the radionuclides, the transport distances into the rock will vary.

9.2. SKB, Sweden

Heterogeneity is of high relevance in the initial state / EBS emplacement phase as well as in the THM(C) transient period. The installed components will determine the final heterogeneity and therefore the initial state needs to be verified. Additionally, the HM coupling is apparently very strong and the H transient will have an impact on the final heterogeneity. The assessment period is only relevant under certain circumstances, for example during mass loss from erosion.

9.3. Posiva, Finland

Evolution of the repository can be described or conceptualized by the following phases:

- Initial state. For the buffer and backfill, the state of the system after the installation of these barriers.
- Early evolution phase (up to ~10 000 years). The evolution of the system due to prevailing and evolving conditions after the initial state. Addresses water uptake, swelling and the thermal pulse from the decay heat of the fuel. Could be referred to as the “THMC transient period”.
- Long-term evolution phase (after ~10 000 years). The period of the long-term safety assessment, which begins after the system has evolved as predicted and reached the state where the performance targets are met. The long-term evolution phase can be divided into three distinct phases: temperate period up to the first glaciation, glacial conditions and subsequent repetition of glacial cycles.

Bentonite density differences are considered to be at a maximum in the initial state or at the beginning of the early evolution phase. The density differences are expected to homogenize to a sufficient degree over the early evolution phase for the EBS to reach the performance target criteria. External perturbations may introduce additional density differences during the long-term evolution phase, but these are expected to be “self-healed” by the swelling of bentonite.

9.4. SÚRAO, Czech Republic

The evolution of the SÚRAO repository is split into three periods. The installation period consists of the installation of the buffer and backfill, the THM(C) transient period lasts up to approximately 10,000 years and the long-term evolution period is defined as the period after 10,000 years. The bentonite density differences occurring during the installation period are expected to homogenize during the THM(C) transient period to meet the safety functions. Nevertheless, in the SÚRAO concept heterogeneity is relevant for the THM(C) transient period and the assessment period of the repository evolution. For the initial state and during the engineered barrier system emplacement, heterogeneity is not so important.

9.5. Enresa, Spain

ENRESA (2000) considered three main time periods of repository evolution, the first two being transient periods with high temperature and hydraulic gradients:

- the bentonite buffer saturation period (about 100 years)
- the thermal period of <10,000 years, when canister failure takes place
- the “steady-state” period (after 10,000 years), when the temperature is almost uniform in the repository and is approaching the ambient rock temperature

Heterogeneity is relevant in the initial state and the EBS emplacement and in the THM(C) transient period.

9.6. Andra, France

9.6.1. Operating period

Desaturation of the gallery walls depending on ventilation flux and the duration of the opening period will lead to re-saturation heterogeneity after repository closure.

Emplacement of the seal core will involve a certain heterogeneity in the emplacement density, especially in a vertical direction due to gravity and filling of off-profiles. Only on-site tested pellets and powder mixtures will be used for the core to be certain that it fulfills the requirements (i.e. dry density and water content).

9.6.2. THM(C) transient period

During the THM transient period, the re-saturation will be mainly radial in all the galleries. Water arriving at the seal core will be a mixture of host rock and concrete water. The chemical evolution of the seal core will locally affect the swelling pressure and the permeability.

In parallel, gas production due mainly to radiolysis and corrosion will cause an increase in the gas pressure and impact on the re-saturation time of the seals. Although, in the current Cigéo concept the gas is assumed to pass mainly through the EDZ around the core seal, some gas will pass through the bentonite core and may generate some heterogeneity by creating local flow paths.

9.6.3. Long term (after re-saturation of all repository components)

On the long term, a certain homogenization should occur in the core seal, due to rearrangement of mechanical constraints in the core and its vicinity, leading to a reduction of local heterogeneity in the permeability and swelling pressure. However, even if some heterogeneity continues to be present in the core, the expected performance of the seal should be achieved due to the specifications applied taking into account this heterogeneity in the dimensioning of the core characteristics (mainly dry density).

Specified swelling pressure and permeability will be maintained due to host rock convergence allowing only small longitudinal movement of the mechanical plug even though there is concrete degradation (mechanical and chemical).

9.7. GRS, Germany

The saturation of the buffer and backfill is estimated to take several hundred to two thousand years after repository closure. The saturation of the bentonite elements of drift seals is estimated to take up to 5 000 years. It is estimated that, at the latest after 50 000 years, the influence of the repository on the host rock will become negligible and the natural conditions in the host rock will be re-established. However, the German repository concept has not yet advanced to a stage where consideration is given to the topic of heterogeneity.

10. Expectations of the Beacon project

10.1. Nagra, Switzerland

Nagra expects answers to the following questions about safety assessment:

- What phenomena and processes are expected in backfilled repository sections that could be detrimental to safety and that are caused by a heterogeneous backfill?
- What degree of backfill/buffer homogeneity is needed to ensure long-term safety?
- If heterogeneities are detrimental to long-term safety, how can these be limited or avoided?

10.2. SKB, Sweden

As an outcome of the Beacon project, SKB expect a general consensus that the modelling tools available are appropriate for purpose.

10.3. Posiva, Finland

The most valuable output from Beacon would be material models that are accurate enough to be used as a tool for design and engineering purposes, i.e. to assess behavior and performance of the bentonite-based EBS both on the short- and long-term under variable design and environmental conditions. Benchmarking and comparison of different bentonite material models would help engineers to choose the best predictive tools for their applications under variable circumstances.

The second – and maybe more realistic – goal for Beacon would be to facilitate the further development of bentonite material models. Different modelling approaches practiced by different groups may reveal promising new directions for future research and provide clues as to where further effort could be invested or indicate dead-ends to be avoided.

10.4. SÚRAO, Czech Republic

SÚRAO expects from the Beacon project a mathematical model of EBS density evolution with time, as well as verification of mathematical models used in the Czech Republic.

10.5. Enresa, Spain

Modelling results using CODE_BRIGHT concerning the hydration process and the final state of the bentonite barrier in the EB experiment (Mont Terri URL) were in reasonable agreement with the actual findings after dismantling. The real data obtained in this experiment (and other recent dismantling operations such as FEBEX) provide a sound basis for better formulation of the numerical models; reducing their uncertainties and providing more clear criteria to be conservatively applied in the design and performance assessment of bentonite engineered barriers.

10.6. Andra, France

Andra expects from the Beacon project a consolidation of the currently available elements showing that, if preparation of the sealing material (e.g., pellets, powder) and emplacement method are performed appropriately, the remaining residual heterogeneity is not problematic for safety cases and seal cores can be represented in the safety assessment by a well-chosen homogeneous material evolving under two-phase flow assumptions with possible parameter changes with time due to interactions of other phenomena.

10.7. GRS, Germany

Since the German repository concept in clay rock is not so far developed at present, detailed performance assessment or safety analysis calculations have not been performed up to now. Consequently, the results of Beacon, in terms of (hydro-) mechanical evolution and homogenization of bentonite materials, can provide direct input for the further concept planning. Moreover, model development and validation will be a great help for future PA modelling.

11. Conclusions

The assessment of the long-term safety of a geological repository must rely on a robust model of the spatial and temporal distribution of the safety-relevant properties of bentonite. Thus, developing predictive capabilities for the mechanical behavior of bentonite buffers, seals and backfills are a common need for all radioactive waste management programs that use bentonite in one or more engineered barrier system (EBS) components. The “Beacon” (Bentonite Mechanical Evolution) project will address key technical issues that must be tackled to support the implementation of planned geological disposal projects for high-level radioactive wastes across the EU. The overall objective of the project is to evaluate the performance of an inhomogeneous bentonite barrier.

To safely contain the waste and to comply with overriding safety principles, the key requirements for a buffer material in the case of high-level waste disposal independent of the host rock are: (1) a low hydraulic permeability/conductivity; (2) a self-sealing ability; and (3) durability of properties in the very long-term. The bentonite buffer is required to maintain a large diversity of safety functions, which can only be fulfilled once the bentonite saturates and swells, tightly closing the construction gaps between the bentonite components and the drift wall or the canister wall on the one hand and between the bentonite components themselves on the other.

Occurrence of heterogeneity in the repositories could impact the safety functions of bentonite components. Therefore, it needs to be determined to what extent this could affect the safety case of the repositories. Heterogeneity can occur in the initial material, through the emplacement or the re-saturation phase as well as on the long term after re-saturation of all repository components. The heterogeneities in the initial state, i.e. after installation of the EBS, are mainly due to density differences. Inhomogeneous saturation and swelling of bentonite could cause irreversible damage, while gas generation through corrosion of the steel used in tunnel support and of the canisters increases gas pressure and may keep pathways open. The role of uncertainties related to these bentonite heterogeneities is addressed in most repository concepts using a deterministic approach, defined with a preferred density value. There are several natural properties of bentonite that may impact the degree of homogenization. Most waste management organizations consider water content, original exchangeable cations, bulk density, swelling pressure and hydraulic conductivity as relevant natural properties for the bentonite regarding heterogeneity, while organic carbon or thermal conductivity seem to be incidental to the homogenization process.

All participating waste management organizations agree that the most valuable output from Beacon would be material models that are accurate enough to be used as a tool for design and engineering purposes, i.e. to assess the behavior and performance of the bentonite-based EBS both on the short- and long-term under variable design and environmental conditions. It is expected that, if preparation of the sealing material (e.g. pellets) and emplacement method are performed properly, heterogeneity will not be problematic for safety cases and that the buffer material can be represented in the safety assessment by a well-chosen homogeneous material.

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A Appendix A – Questionnaire

Dear participants of the Beacon project,

This questionnaire was prepared to capture in how far non-homogeneous material property distributions have been taken into account in the different safety cases. The information collected from the questionnaire will help understanding to frame the state-of-the-art regarding the conceptualization of heterogeneous material property distribution and its impact on the long-term safety of radioactive waste repositories.

If you have any questions, please do not hesitate to contact us:

Cornelia Wigger – Nagra, Switzerland
Olivier Leupin
cornelia.wigger@nagra.ch
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We would like to ask you to return the completed questionnaire to: cornelia.wigger@nagra.ch
Deadline is: **31st October 2017**.
We would like to thank you in advance for your participation.

Yours sincerely,
Cornelia Wigger

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Contact Information of Responder
Waste Management Organization
Name
Email
Deputy contact

Role of bentonite in the repository concept

What components are bentonite-based in your repository? *(e.g., seals, buffer , ...)*

What are the specific safety functions of the bentonite in these components? *(e.g., hydraulic barrier, stabilization , ...)*

What type of emplacement do you foresee in your repository? *(e.g., blocks, granular, sand, bentonite)*

Key references on bentonite related research

What are the key references on bentonite related research of your organization (incl. mechanical properties/processes)? *(approx. 5 references)*

Heterogeneity occurrence in the repository

What kind of heterogeneity is expected in your repository concept?

Role of uncertainties related to the heterogeneity of bentonite

How do you address heterogeneity?

a) Deterministic approach (upper lower limit, mean values)
b) Probabilistic assessments accounting for spatial/temporal distributions

Which type of heterogeneities do you consider in your assessments?

a) Material properties (spatial variability)
b) Initial conditions (spatial variability)
c) Boundary conditions (variability in space and time)
d) Source terms/perturbations (variability in space and time)

Bentonite modelling

What type of model do you use to simulate bentonite evolution in performance assessment?

a) Level of details needed (representation scale, geometry…)
b) Level of coupling (THMgas-C)
c) Main characteristics of the models used (double structure…)
d) Main numerical model used

What type of model do you use to simulate bentonite evolution in safety assessment?

a) Level of details needed (representation scale, geometry…)
b) Level of coupling (THMgas-C)
c) Main characteristics of the models used (double structure…)
d) Main numerical model used

Natural properties of your reference bentonite:

Which natural properties are required for the bentonite regarding heterogeneity?

	relevant	**irrelevant**	***Comments***
Mineralogy			
Organic Carbon			
CEC (cation exchange capacity)			
Original exchangeable cations			
Water content			
Gas content			
Pore water composition			
Grain size distribution			
Grain density			
Bulk density			
Swelling pressure			
Hydraulic conductivity			
Pore water pressure			
pH			
Thermal conductivity			
Pore clogging			

Performance measures

Do you have performance measures specified for:

a) bentonite based EBS components? *(specify in the table below)*

safety-relevant attributes	Application	Preferred values	accepted variation
Low hydraulic conductivity			
Chemical retention of radionuclides			
Montmorillonite content			
Content of organic carbon			
Sulphide content			
Total Sulphur content			
Sufficient density			
Sufficient swelling pressure			
Sufficient gas transport capacity			
Minimize microbial corrosion			
Resist transformation *(thermal requirements)*			
Suitable thermal conductivity			
Limit advective transport in the near field			
Damp rock shear movements/shear strength			
Resist transformations *(requirement on temperature)*			
Prevent canister sinking			
Limit pressure on canister and rock			
Other requirements…			

b) a given period of repository evolution

Relevant periods in repository evolution

Give a short description of the repository evolution focusing on the relevant periods.

In what periods of the repository evolution is heterogeneity relevant?

a) Initial state / EBS emplacement
b) THM(C) transient period
c) Assessment period
d) Other…

Expectations of the Beacon project

What outcome do you expect from the beacon project regarding the repository design/safety case?

B Appendix B – Individual comments about relevant natural properties of bentonite regarding heterogeneity

Nagra, Switzerland

Tab. 6: Required natural properties for the bentonite regarding heterogeneity.

Properties	**Nagra, Switzerland**		
	relevant	irrelevant	Comments
Mineralogy		x	
Organic carbon		x	Organic carbon occurrence is only relevant for low- and intermediate-level waste.
CEC (cation exchange capacity)		x	
Original exchangeable cations	x		Original exchangeable cations are relevant due to their different impacts on the swelling behavior.
Water content	x		
Gas content	x		The simulations reveal that the contribution of the tunnel installations to the total gas generation rates is not negligible, resulting in peak pressures at 2,000 years when the tunnel installations are completely corroded. However, it should be noted that the material for tunnel installations can be reduced if needed (see discussion in Chapter 5). After 2,000 years, a distinct pressure drop is observed, followed by a more gentle increase until complete corrosion of the canisters. The pressure increase during late times accounts for the slow, but long-lasting, corrosion of the steel containers and ends after around 60,000 years.
Pore-water composition		x	
Grain size distribution	x		A specific mixing cycle was designed to obtain a grain size distribution close to a 'Fuller distribution'.
Grain density	x		
Bulk density	x		
Swelling pressure	x		
Hydraulic conductivity	x		
Pore-water pressure	x		Reactivation of existing or creation of new water-conducting pathways would affect the safety functions: (i) retention of radionuclides in the near-field and geosphere, and (ii) attenuated release of radionuclides to the environment.
pH		x	
Thermal conductivity		x	
Pore clogging	x		Pore clogging is relevant, in particular at the cement-bentonite interface.

SKB, Sweden

Tab. 7: Required natural properties for the bentonite regarding heterogeneity.

Properties	SKB, Sweden		
	relevant	irrelevant	Comments
Mineralogy		x	Not important for a given material
Organic carbon		x	
CEC (cation exchange capacity)		x	Not important for a given material
Original exchangeable cations	x		
Water content	x		
Gas content	(x)		Is a function of water content
Pore-water composition	x		
Grain size distribution	(x)		unclear
Grain density		x	Not important for a given material
Bulk density	x		
Swelling pressure	x		
Hydraulic conductivity	x		
Pore-water pressure	x		
pH	(x)		Possibly, under some circumstances
Thermal conductivity	x		
Pore clogging		x	

Posiva, Finland

Tab. 8: Required natural properties for the bentonite regarding heterogeneity. The following points are considered as potential factors affecting homogenization of bentonite, i.e. persisting density differences. The rationale or hypothesis is given in the “comments” field.

Properties	**Posiva, Finland**		
	relevant	irrelevant	Comments
Mineralogy	x		Properties of bentonite are defined by mineralogical composition and structure/composition of montmorillonite
Organic carbon		x	Excluded due to other requirements (microbial activity)
CEC (cation exchange capacity)	x		Related to montmorillonite layer charge property and, thus, to swelling properties
Original exchangeable cations	x		Effect on early evolution, initial mechanical properties
Water content	x		Effect on stress state (swelling pressure) and porosity
Gas content	x		Gas development and transport (especially water vapor transport), effect on stress state
Pore-water composition	x		Effect on swelling pressure, possibly mechanical properties and water transport
Grain size distribution	x		Effect on pore size (distribution) and mechanical properties
Grain density	x		“Effective montmorillonite dry density” (EMDD) is usually considered instead. Effect on swelling pressure
Bulk density		x	Dry density, EMDD and grain density are considered more relevant
Swelling pressure	x		Homogenization of density differences is mainly driven by this property
Hydraulic conductivity	x		Effect on system evolution
Pore-water pressure		x	Understood here as positive pressure (not suction), therefore considered not relevant in homogenization of bentonite that occurs probably mainly in unsaturated conditions
pH	x		Effect on mineral solubility and montmorillonite edge charge
Thermal conductivity	x		Effect on water transport (vapor) and water content distribution
Pore clogging		x	Relevant only if processes such as cementation are considered here

SÚRAO, Czech Republic

Tab. 9: Required natural properties for the bentonite regarding heterogeneity.

Properties	SÚRAO, Czech Republic		
	relevant	irrelevant	Comments
Mineralogy	x		
Organic carbon		x	
CEC (cation exchange capacity)	x		Related to mineralogy
Original exchangeable cations	x		
Water content	x		
Gas content		x	
Pore-water composition		x	
Grain size distribution	(x)		
Grain density		x	
Bulk density	x		
Swelling pressure	x		Related to mineralogy
Hydraulic conductivity	x		
Pore-water pressure		x	
pH		x	
Thermal conductivity		x	
Pore clogging		x	

Enresa, Spain

Tab. 10: Required natural properties for the bentonite regarding heterogeneity.

Properties	Enresa, Spain	
	relevant	irrelevant
Mineralogy	x	
Organic carbon		x
CEC (cation exchange capacity)		x
Original exchangeable cations		x
Water content	x	
Gas content	x	
Pore-water composition	x	
Grain size distribution	x	
Grain density	x	
Bulk density	x	
Swelling pressure	x	
Hydraulic conductivity	x	
Pore-water pressure		x
pH		x
Thermal conductivity		x
Pore clogging	x	

Andra, France

Tab. 11: Required natural properties for the bentonite regarding heterogeneity.

Properties	Andra, France	
	relevant	irrelevant
Mineralogy	x	
Organic carbon		
CEC (cation exchange capacity)		
Original exchangeable cations	x	
Water content	x	
Gas content	x	
Pore-water composition	x	
Grain size distribution	x	
Grain density	x	
Bulk density	x	
Swelling pressure	x	
Hydraulic conductivity	x	
Pore-water pressure	x	
pH	x	
Thermal conductivity		x
Pore clogging		

GRS, Germany

Tab. 12: Required natural properties for the bentonite regarding heterogeneity.

Properties	GRS, Germany		
	relevant	irrelevant	Comments
Mineralogy	×		Mineralogy variation may lead to a variation of bulk density, porosity, permeability, and chemical composition on micro- and mesoscale because of aggregation and presence of accessory minerals. It influences THMC properties and can be directly measured.
Organic carbon	×		Organic carbon variation may lead to a variation of bulk density, porosity, permeability and chemical composition on micro- and mesoscale because of uneven distribution over the bentonite bulk and clogging. It influences THMC properties and can be directly measured.
CEC (cation exchange capacity)		×	CEC has no direct influence on THM properties. The influence of C properties strongly depends on the identity of solute and is as such not an independent bentonite property. Specific surface area might be a better choice for consideration of heterogeneity.
Original exchangeable cations	×		Original exchangeable cations influence the stacking of individual clay mineral sheets and may influence the variation of bulk density, porosity, permeability, and chemical composition on micro- and mesoscale.
Water content	×		Only the in-situ water content of bentonite after emplacement, which depends on its localization with respect to the heat-producing waste, is of relevance. The water content of bentonite before emplacement is irrelevant.
Gas content		×	Content of adsorbed gas in clays is negligible when compared with other adsorbents available in the system and hence is irrelevant.
Pore-water composition		×	Pore-water composition can lead to a variation of directly measurable THMC properties only in conjunction with a variation of mineralogy. No relevance of this property taken alone is recognized.
Grain size distribution		×	No relevance of this property taken alone is recognized.
Grain density		×	No relevance of this property taken alone is recognized.
Bulk density	×		Bulk density can be considered a direct measure of heterogeneity.
Swelling pressure		×	A variation of swelling pressure is a consequence of variations in mineralogy, bulk density, water content, and pore-water

			composition. No relevance of this property taken alone is recognized.
Hydraulic conductivity		×	A variation of hydraulic conductivity is a consequence of variations in mineralogy, bulk density, and pore water composition. No relevance of this property taken alone is recognized.
Pore-water pressure		×	A variation of pore-water pressure can be a consequence of variations in mineralogy and bulk density. No relevance of this property taken alone is recognized.
pH		×	A variation of pH is a consequence of variations in mineralogy, water content, and pore-water composition. No relevance of this property taken alone is recognized.
Thermal conductivity		×	A variation of thermal conductivity is a consequence of variations in mineralogy and bulk density. No relevance of this property taken alone is recognized.
Pore clogging		×	Pore clogging can be a consequence of variations in mineralogy, organic carbon, and bulk density. No relevance of this property taken alone is recognized.