Journal of Rock Mechanics and Geotechnical Engineering xxx (2017) 1–21

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

# Safety assessment methodology for a German high-level waste repository in clay formations

M. Jobmann [a,*], A. Bebiolka [b], V. Burlaka [a], P. Herold [a], S. Jahn [b], A. Lommerzheim [a], J. Maßmann [b], A. Meleshyn [c], S. Mrugalla [b], K. Reinhold [b], A. Rübel [c], L. Stark [b], G. Ziefle [b]

[a] DBE TECHNOLOGY GmbH, Eschenstraße 55, Peine D-31224, Germany
[b] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, Hannover D-30655, Germany
[c] Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Theodor-Heuss-Straße 4, Braunschweig D-38122, Germany

ARTICLE INFO

*Article history:*
Received 21 December 2016
Received in revised form
13 March 2017
Accepted 2 May 2017
Available online xxx

*Keywords:*
Clay
Radioactive waste
Safety demonstration method
Barrier integrity
FEP (features, events, and processes) catalogue

ABSTRACT

In the ANSICHT project that was jointly carried out by DBE TECHNOLOGY GmbH, BGR, and GRS gGmbH, two generic geological site models were used to develop a first draft of a methodology to demonstrate the safety of a high-level waste (HLW) repository in argillaceous formations in Germany, taking into account the regulatory requirements. The main results of the project are characterised by the developed repository concepts adapted to the geological conditions. The specific quantifications of the integrity criteria and their exemplary application with calculational proofs were used to demonstrate the integrity of the host rocks. The development of site-specific FEP (features, events, and processes) catalogues provided a complete system description for evaluation of the repository evolution. The developed work flow of the demonstration concept illustrated the complete sequence of the safety proof in a transparent way. It shows that various steps have to be performed, possibly iteratively, to provide a successful safety proof. The results form a useful tool in the pending search for a HLW repository site, especially when providing a basis for comparing safety analyses of different sites in Germany.



## 1. Introduction

With the restart of site selection for a high-level waste (HLW) repository in Germany, different types of host rocks, e.g. clay, are the focus. In Germany's neighbouring countries, such as France, Switzerland and Belgium, different clay formations are investigated as potential host rocks for a HLW repository. In France, the Callovo-Oxfordian clay is investigated (ANDRA, 2005), in Switzerland the so-called Opalinus Clay (Nagra, 2002) and in Belgium the Boom-clay formation (ONDRAF/NIRAS, 2001). Over the past years, the research activities in argillaceous rocks in Germany have been significantly intensified. Extensive participation in underground research laboratories in the Meuse-Haute Marne, France, and Mont-Terri, Switzerland, enabled Germany to build up the knowledge of the thermo-hydro-mechanical (THM) behaviors and the general sealing abilities of clay host rocks.

In the framework of the ANSICHT project, a safety assessment methodology for a HLW repository in clay formations in Germany was developed. This was done by a project team consisting of Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Federal Institute for Geosciences and Natural Resources (BGR) and DBE TECHNOLOGY GmbH. In the ANSICHT project, the idea was to use generic geological models to show typical clay formations and adjacent rock formations in Germany. Exemplarily, for different boundary geological conditions in Germany, two generic geological models, typical for potential clay sites in Northern and Southern Germany, were developed.

The project is important for the German scientific community in the field of the HLW disposal, and it is in line with the new site selection process in Germany, which at the first stage considers different host rocks equally eligible for the final disposal of HLW and spent fuel (SF) (StandAG, 2016).

## 2. Description of the safety and safety demonstration concept

The safety concept defines that barriers ensure the containment of the radionuclides in the waste repository to protect human and

* Corresponding author.
*E-mail address:* jobmann@dbe.de (M. Jobmann).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.05.007
1674-7755 

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007

the environment from ionizing radiation and other harmful effects of heat-generating radioactive waste. In the "Safety Requirements Governing the Final Disposal of Heat-generating Radioactive Waste" (BMU, 2010), the safety concept for heat-generating waste repositories prescribes that the containment of the waste inside the containment providing rock zone (CRZ) has to be proven for a reference period of 1 million years. The CRZ ensures the retardation of radionuclides in combination with the geotechnical barriers. The assessment proofs of the repository are as follows:

(1) The integrity (containment abilities) of the CRZ is maintained over the whole assessment period of one million years and must not be disturbed either by internal or external processes (cf. Section 4.3).
(2) The integrity of the geotechnical barriers is maintained over the designated functional period. For the ANSICHT project, their minimum functional period has been defined as the transient phase of the THM processes in the repository system (cf. Section 4.4).
(3) The subcriticality of the waste to prevent nuclear accidents resulting from an inadvertent, self-sustaining nuclear chain reaction (not analysed in the ANSICHT project).
(4) The insignificance of a potential radiological exposure to the future population. According to the Safety Requirements, a simplified radiological assessment is allowed, in which the radionuclide fluxes outside the CRZ boundary are compared with a regulatory value. No transport in the geosphere outside the CRZ is considered in this case (cf. Section 4.5).

For a radioactive waste repository in clay formations, the containment of the radionuclides inside the CRZ is achieved by:

(1) limiting the advective transport by choosing a host rock with low permeability and restoring the low permeability in excavation damaged zones (EDZs);
(2) limiting the diffusive transport, i.e. choosing a host rock with high sorption capacity and low pore water diffusion.

Additional objectives of the repository design were defined to limit thermal, gas-generating and microbial processes as well as to guarantee canister retrieval for 500 years according to the Safety Requirements.

The concept for a safety case developed for the post-closure phase can be divided into the two-level fundamental modules and system analysis. Fig. 1 gives an overview of these two levels and the interrelations of the individual modules of the safety and safety demonstration concept (Jobmann et al., 2016).

### 2.1. Fundamentals

The concept is based on the Safety Requirements (BMU, 2010) from which the first level module of safety strategy is derived. In addition to the objectives, the safety strategy involves general conceptual specifications and technical measures that are further developed and described in detail in the subjacent modules.

One of the first fundamental modules concerns the quantification of the integrity criteria. The Safety Requirements define the integrity criteria qualitatively. To demonstrate the integrity of the CRZ, it is necessary to quantify these criteria in such a way that a numerical demonstration is possible within the scope of the safety demonstration concept. The quantification of the integrity criteria requires adequate knowledge about the thermal (T), mechanical (M), hydraulic (H), chemical/mineralogical (C), and biological (B) properties of the host rock formation. During this process step, knowledge gaps may be significant that have to be abridged within the scope for further studies. Based on these quantified criteria, numerical simulations of the repository evolution can be carried out for development of future scenarios.

The two modules mentioned above, concerning the safety strategy and the quantification of the integrity criteria, are not specific to a site. All other modules described below are site-specific. The basic module of safety strategy is the geological site description, which comprehensively describes the initial (current) state of the site, especially its structural geology and the (hydro-) geological conditions. In addition to an analysis of the initial state, a long-term geoscientific forecast for future evolution of the site region has to be carried out for the whole reference period. The forecast serves as an important input for the description of the geological processes.

Directly connected with the geological site description is the development of a 3D (three-dimensional) model of the geological situation in the area under investigation. This is carried out on the basis of the module modeling and data compilation. The result is called repository site model that contains all important geological formations and structures to reflect especially the (hydro-) geological conditions in the area under investigation. The model refers to the host rock formation where the repository is located. The repository site model is generated in such a way that – after a further abstraction – it serves as a basis for calculations to prove the integrity of the CRZ, for radiological safety demonstration. Such calculations require numerical model parameters derived from the knowledge about the properties of the geological units. Therefore, the generation of a geoscientific data basis is required. Firstly, all available details related to the geological units are compiled and documented. Then, all units identified in the 3D model can be assigned with adequate parameters. This step gives indications about the quality of the available data and allows the identification of knowledge gaps that have to be filled with the scope of future site explorations.

Based on the repository site model, the emplacement concept and the repository design are developed as the fundamental technical module, which takes into account the extent, thickness, depth, and properties of the host rock formation. They contain a description of the emplacement selected (borehole emplacement or drift emplacement) and the container characteristics based on the waste inventory. They also contain general information for support constructions needed in drifts and shafts. The safety strategy and the integrity criteria give an important guidance to the repository design.

Based on the geological, especially the hydrogeological, settings as well as the emplacement concept and site-specific repository design, a backfilling and sealing concept is developed in the second technical module. This concept describes the measures to backfill and seal the underground excavations in such a way that only minor radionuclide release is to be expected even via the drift and shaft system.

### 2.2. System analysis

The first step of the system analysis is to comprehensively describe the system. This is done with a site-specific FEP (features, events, and processes) catalogue that compiles all processes considered in the description and development of the repository site model, including an estimation of their occurrence probabilities. All data relevant for the safety analysis are included in the FEP catalogue. The catalogue thus contains a complete system description. Based on the FEP catalogue, a scenario development is carried out to derive the descriptions of probable and less probable repository evolutions.

According to the Safety Requirements, the following steps have to be carried out for probable repository evolutions. The integrity proof of the geotechnical barriers is obtained using a methodology

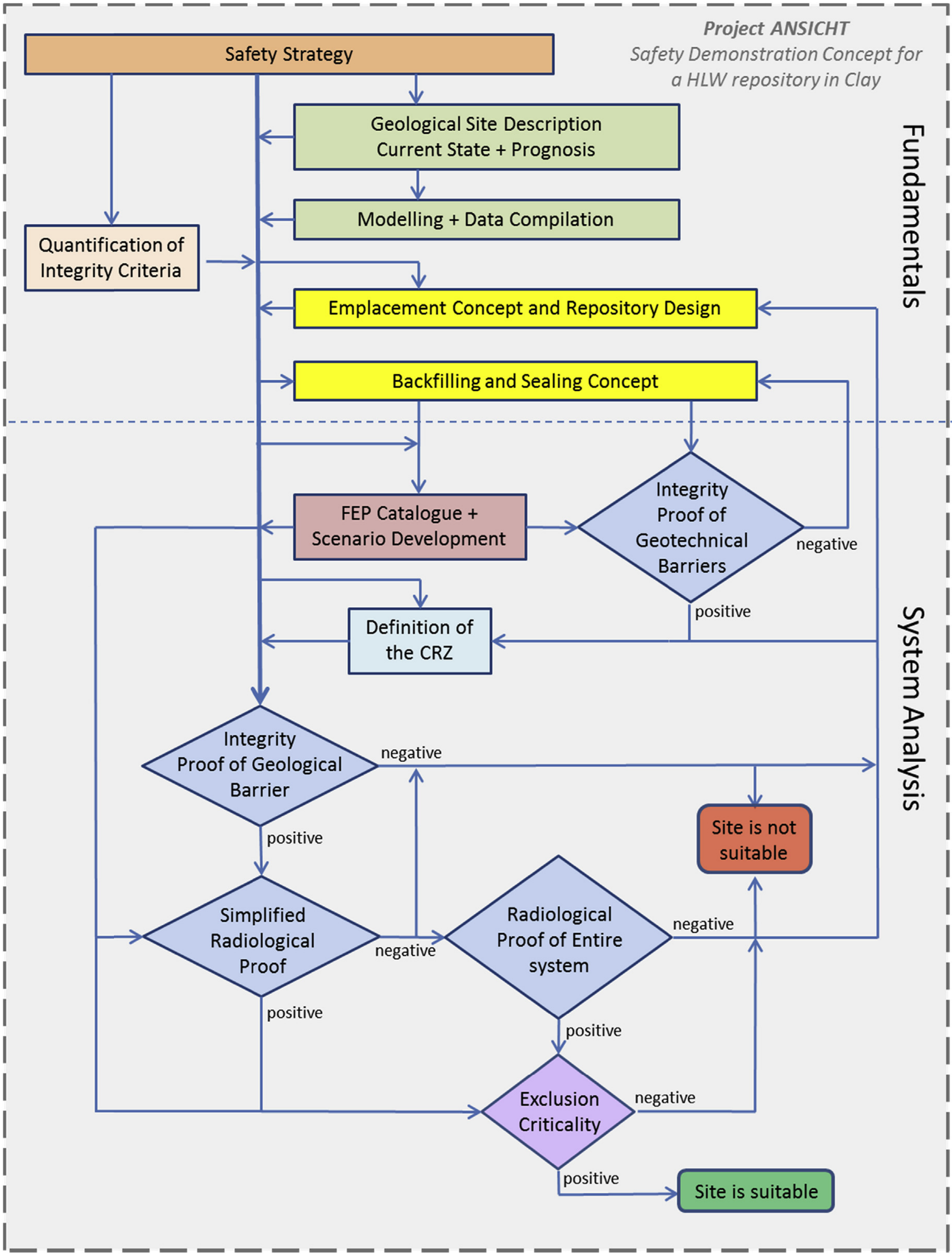


**Fig. 1.** Overview of the modules of the safety and safety demonstration concept.

that has been developed and applied to a previous R&D project (Müller-Hoeppe et al., 2012). The aim is to demonstrate using a common engineering procedure that the barriers function properly and meet the protection goals. If the demonstration fails, the sealing concept or the design of corresponding barrier components needs to be revised. This loop is repeated until the integrities of the sealing construction and of all its components are demonstrated. If the loop shows that changes in the sealing concept or in individual components are necessary, the FEPs related to the sealing system need to be changed.

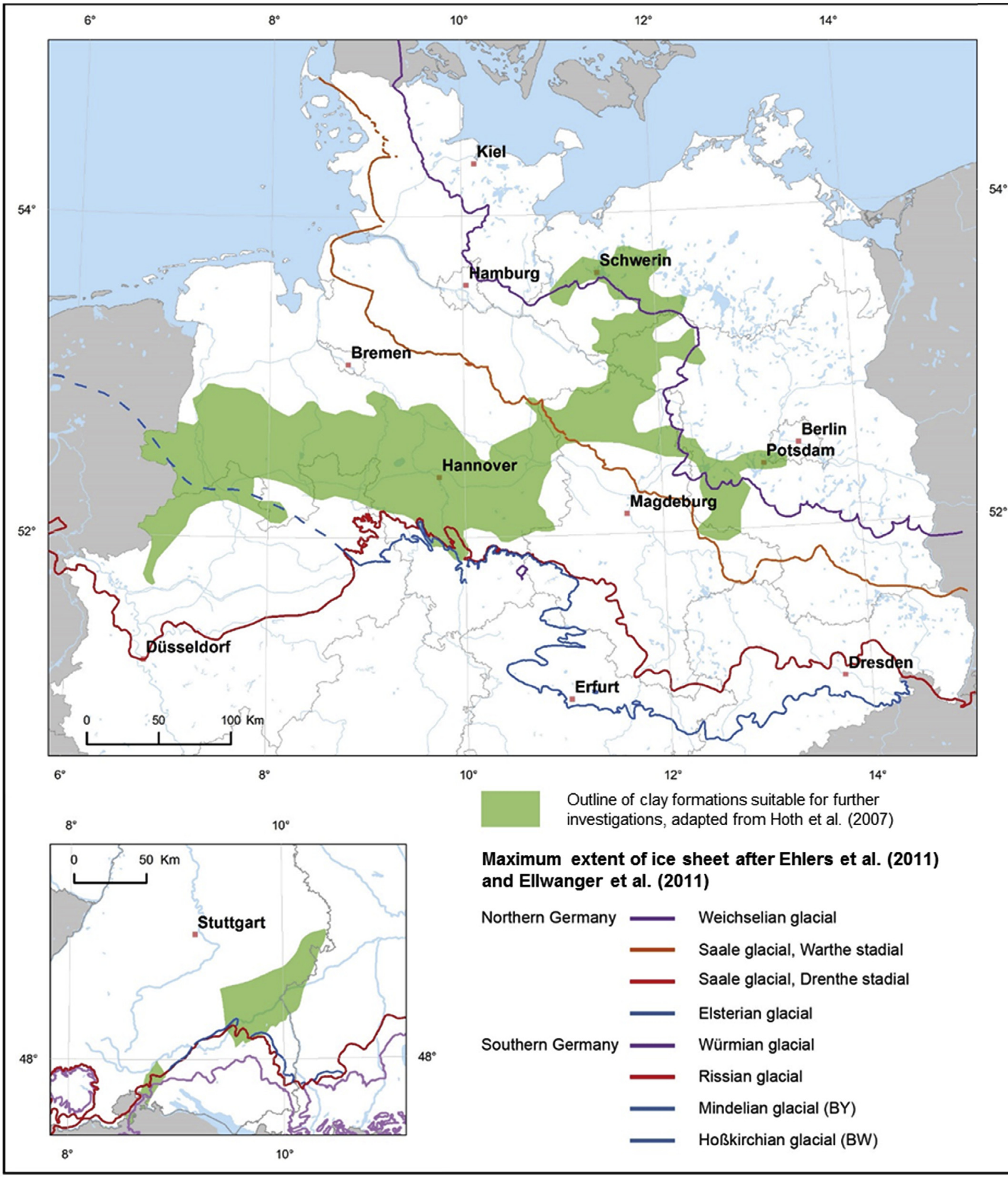


**Fig. 2.** Outline of claystone formations suitable for further investigations (adapted from Hoth et al., 2007) and the maximum extent of ice sheets in Northern and Southern Germany after Ehlers et al. (2011), Ellwanger et al. (2011) and Fiebig et al. (2011), showing the areas expected to be influenced by glacial processes during future glacial periods.

The Safety Requirements stipulate the definition of the CRZ. The CRZ, the extension determined by means of the repository site model, is fundamental for numerical proof of the integrity of geological barrier. The integrity of the CRZ needs to be demonstrated for the reference period of 1 million years.

The integrity proof of the geological barrier is based on numerical calculations on different scales. The calculation results are analysed using the integrity criteria (cf. Section 4.3.1). If the integrity of the CRZ is not proved, it needs to be analysed – if necessary in several loops – what changes are necessary to the

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007

emplacement concept and/or extension of the CRZ in order to maintain integrity. If the integrity of the geological barrier cannot be proved at all, the site is not suitable.

Subsequently, the simplified radiological proof is carried out. It indicates whether the radionuclide release outside the CRZ is negligible in accordance with the radiological criteria as defined in the Safety Requirements. If the criteria are met, the site is suitable. It is possible that the radiological analysis shows that radionuclide release is not negligible although the integrity of the CRZ and the geotechnical barriers has been demonstrated. Then it needs to be analysed what changes to the emplacement and/or the sealing concept and/or the CRZ are necessary to meet the radiological criteria.

If these changes are not reasonable or possible under the existing conditions, it needs to be decided whether the simplified radiological proof should be discarded or the radiological proof of the entire system should be applied. For the latter one, possible dilution effects in overlying aquifers are accepted.

Finally, exclusion of criticality has to be demonstrated. A HLW/SF repository contains fissile material. Criticality can only occur if a sufficiently high amount of water or other moderator is presented together with a sufficiently high amount of fissile material. Critical arrangements have to be excluded for all probable or less probable scenarios. No corresponding studies were carried out within the scope of the ANSICHT project. The site is suitable, if all safety criteria are met. Otherwise, the site is not suitable

## 3. Description of the system modules

### 3.1. Geological situation and future evolution

Preparation of geological models covers the areas with geoscientific designated criteria. These reference areas are defined in Reinhold and Sönnke (2012) for Northern and Southern Germany.

Due to the different geological conditions of Northern and Southern Germany, different implications have to be considered. Nevertheless, selection of merely one host rock formation to represent the argillaceous rock formations in Germany is not possible, therefore, two reference areas are selected. The considered areas comprise parts of the North German Basin and a smaller part of the Molasse Basin in Southern Germany (see Fig. 2). A geological site description is prepared for these two reference areas. That means that the topographical, geological, structural, hydrogeological as well as the sedimentological conditions, the temperature-depth distribution and the thermal maturity were determined and described.

According to the Safety Requirements, the safety demonstration is carried out for a period of one million years. The aim of a long-term geoscientific forecast is to highlight the natural background affecting the evolution of the geosphere to enable improved evaluation of the changes. The evolution of the geosphere is influenced by geological processes, which may be more or less likely or unlikely in some areas, and therefore differ significantly in Northern and Southern Germany. For this reason, two separate long-term forecasts are prepared for the claystone formations within the outline which are suitable for further investigations from Northern and Southern Germany (Hoth et al., 2007; Mrugalla, 2014; Stark, 2014).

The initial states of the long-term forecast are the background conditions which describe the current geomorphological, geological and hydrogeological situations as well as the structures of the host rock and surrounding rock. The forecast starts by explaining previous evolution which gives rise to today's conditions. Based on the principle of uniformitarianism, which states that basic scientific laws will continue to apply in the future and that the associated processes will have the same effects as that in the past, the future evolution of the geosphere can be extrapolated from the conditions and trends observed in the past.

Since the climate change has a significant impact on the evolution of the geosphere, the description of future changes in climate is a key of the long-term forecast. According to the currently occurring climate cycle, it is expected that about ten warm intervals are alternate with glacial periods within the next one million years. Especially the processes associated with glacial periods lead to changes in the near-surface rock layers. Therefore, the characteristic processes which may occur during a glacial period are explained therein. Such processes may be the evolutions of permafrost, periglacial conditions close to the edge of a continental ice sheet or a complete continental glaciation with changes in geomorphology and near-surface rock layers.

The forecast describes the geological evolution which will take place in Germany in the next one million years and will change the current situation. We should first briefly define the changes before sketching out their impact in the past and forecasting their evolution in the future, followed by a discussion of the uncertainties affecting the changes. Changes of the geosphere are basically caused by supra-regional processes like vertical movements of the Earth's crust or crustal deformation and regional processes like erosion, sedimentation or microbiological induced processes. Also tectonic processes may have a major influence on the geosphere and the integrity of the host rock formation. Changes may as well occur in groundwater flow and hydro-geochemical conditions in the host rock and surrounding rocks during the period of one million years. Less probable or improbable evolutions which have general geological significance but are not expected to affect the considered areas are discussed in the forecast as well.

The most intense effect on the near-surface rock layers would be the growth of an ice sheet during a glacial period. Large areas in Northern Germany are covered by an ice sheet during the Elsterian, Saalian and Weichselian glacial periods. In Southern Germany, the North Alpine Foreland Basin was influenced by the Würmian, Rissian, and Hosskirchian between Mindelian glaciations (see Fig. 2). Areas covered by an ice sheet undergo typical changes such as modifications of the subsurface in response to the weight of the ice, faulting associated with glacio-tectonic effects, higher erosion rates (e.g. in the form of glacial ploughing), and the thawing of the permafrost beneath the ice cover. Moreover, glaciogenic channels beneath an ice sheet may occur. During the Elserian glacial period, such channels reached the depths of 200–300 m and in some cases even exceeded the depth of 500 m (Keller, 2009). A glaciation within the range of previous ice stage maxima will again be possible in future glacial periods. Thus, future glaciations will have the potential for forming glaciogenic channels again.

### 3.2. Development of generic geological models

A sound basis for a system analysis is a 3D geological site model. For this, two generic geological models for Northern and Southern Germany (models NORTH and SOUTH) are built up in 3D with defined model units. The model units represent relatively homogenous formations which can regionally be well characterised. The data basis like position, depth, bedding or lithological properties for the units was derived from published data of the exploration industry on oil, gas, salt and other natural resources. In each model, unit representative values for hydraulic and petrophysical parameters are collected. Because the available published data for German clay rocks are insufficient, assumptions derived from comparable geological units are also taken into account. These assumptions are based on the findings from international site investigation programmes, for example in the context of repository projects in Switzerland and in France.

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

The model NORTH represents a typical situation in the North German Basin where potential host rock formations are bedded in a suitable depth under 600 m below ground surface (Reinhold et al., 2013). The reference region and the surrounding generally are structured in a crystalline basement, an overburden cover of sedimentary rock and quaternary sediments. The generic 3D model contains 14 units from the basis Zechstein to the Quaternary (see Fig. 3).

Salt domes or active fault zones are excluded from the model to assume a representative location. The area of the model is 70 $km^2$. The Barremian and Hauterivian formations in the Lower Cretaceous represent the host rock formations. The host rock formations consist of claystone and clayey marl as well as subordinate micritic lime marl. The hydrogeological conditions contain a surficial groundwater reservoir of low salinity in quaternary sediments and several deeper aquifers with high salinity water in the Rhätsandstein, Aalensandstein and Hilssandstein formations (Reinhold et al., 2013).

The geological model SOUTH represents the North Alpine Molasse Basin (Reinhold et al., 2016). The region is structured in a crystalline basement, an overburden cover of mesozoic sedimentary rock, molasses sediments and quaternary sediments. The generic 3D model contains 16 units from the basis Muschelkalk to the Quaternary (see Fig. 3). Active fault zones are excluded from the model. The model covers an area of about 140 $km^2$.

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

### 3.3. Repository concept

The emplacement level of the repository will be completely surrounded by the host rock and excavated at a depth between 600 m and 800 m to avoid any adverse impact from the surface (e.g.

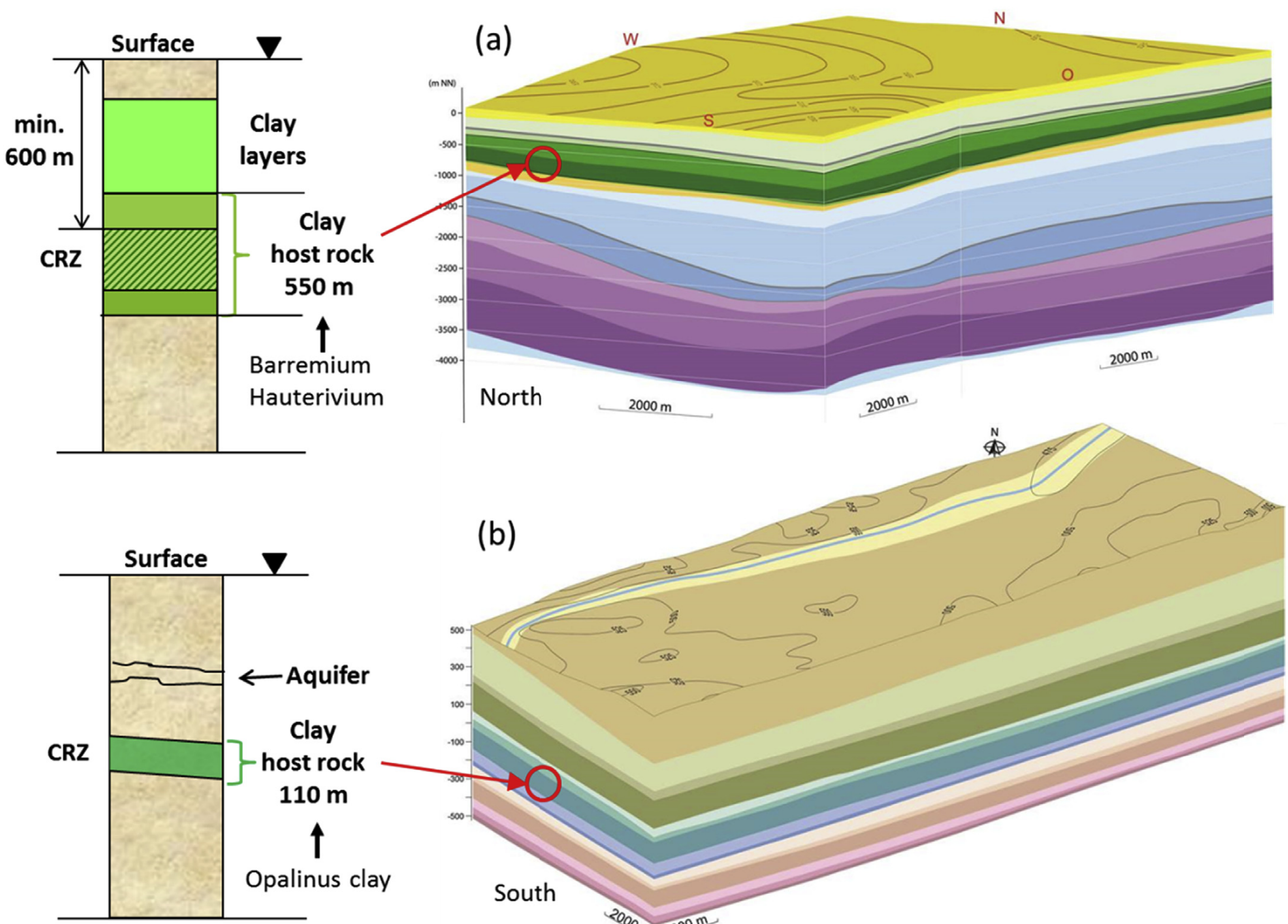


**Fig. 3.** 3D geological sections (right) illustrating the model units of the repository site models for (a) Northern and (b) Southern Germany as well as simplified geological profiles (left) illustrating the availability of clay layers at different model sites.

during ice ages, see Section 3.1). The emplacement strategy must be compatible with the thickness, the characteristics and the extent of the host rock. To reduce disturbance and to reestablish the properties of the host rock, the volume of excavations will be minimised. Operations will be carried out in retreating mode, which means that an emplacement field completely filled with waste packages will be backfilled immediately with swellable material, sealed and abandoned.

The repository will consist of two shafts and one emplacement level with an infrastructure area and the areas of drifts for mining work, waste transport, ventilation, and emplacement (see Fig. 4). The general layout is based on former designs developed by Pöhler et al. (2010) that considered radiological and non-radiological areas, a corresponding air ventilation system, and the transport logistics for parallel work of mining and radioactive waste transport. The emplacement area dimensions are based on design calculations and arranged in a modular way. The disposal strategies include either vertical borehole or horizontal drift emplacement, depending on the available thickness of the host rock. The footprint of the repository mine for the drift emplacement concept is nearly 50% larger than that of the repository mine with vertical borehole emplacement (11.2 km$^2$ vs. 7.6 km$^2$).

These disposal strategies consider the Safety Requirements which stipulate that retrievability has to be ensured during the operational period and for a period of 500 years after repository closure. Retrievability options are currently being investigated in a parallel R&D project called ERNESTA (Herold, 2016).

For the thick Lower Cretaceous clay formations in the model NORTH, the option of borehole emplacement has been analysed (Lommerzheim and Jobmann, 2015). The access drifts to the emplacement boreholes will have a length of 400 m and contain 13 boreholes for heat-generating waste or 20 boreholes for non-heat-generating waste. The depths of the boreholes will be 27 m. To ensure the stability of the borehole during emplacement and to ensure retrievability, each borehole will be equipped with an external and an internal liner. Three canisters will be inserted in the internal liners and the remaining void volume will be filled with sand (see Fig. 5). The space between the inner and the outer liner will be filled with a compacted clay buffer. Each borehole will be sealed with a bentonite plug and an overlying concrete abutment.

Because of the limited thickness (110 m) of the Opalinus Clay in the repository site model for Southern Germany, a drift emplacement concept has been proposed for this region (Jobmann and Lommerzheim, 2015). The emplacement drifts have a length of 400 m and POLLUX® casks will be placed on beddings of highly compacted clay with a spacing of 23 m (see Fig. 6). The remaining void volume will be filled with clay (reprocessed mined rock). The containers for structural elements of SF assemblies will be disposed in emplacement chamber that will be backfilled with concrete.

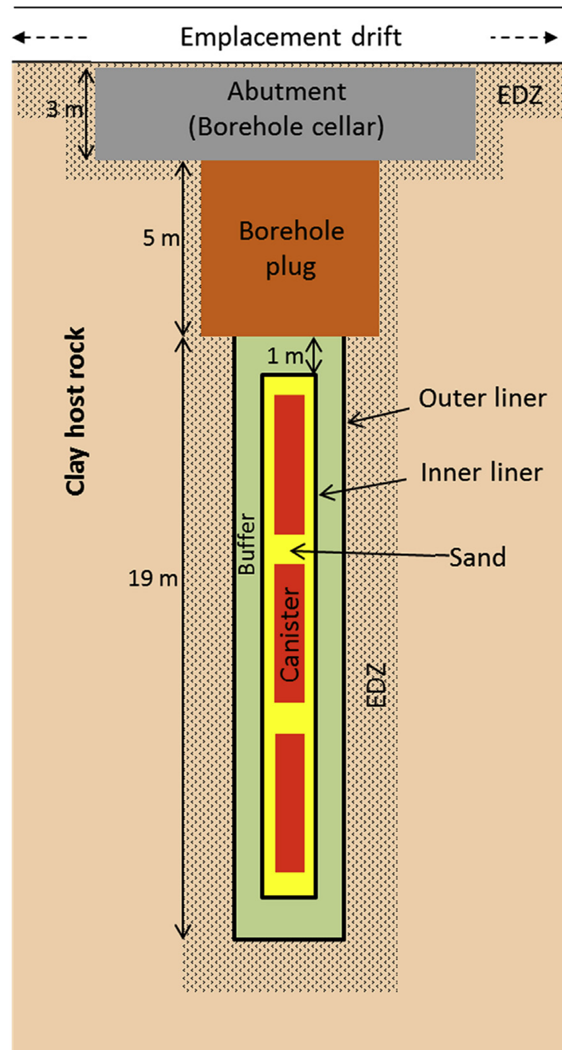


**Fig. 5.** Principle design of an emplacement borehole in the site of model NORTH (Lommerzheim and Jobmann, 2015).

### 3.4. Backfilling and sealing concept

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

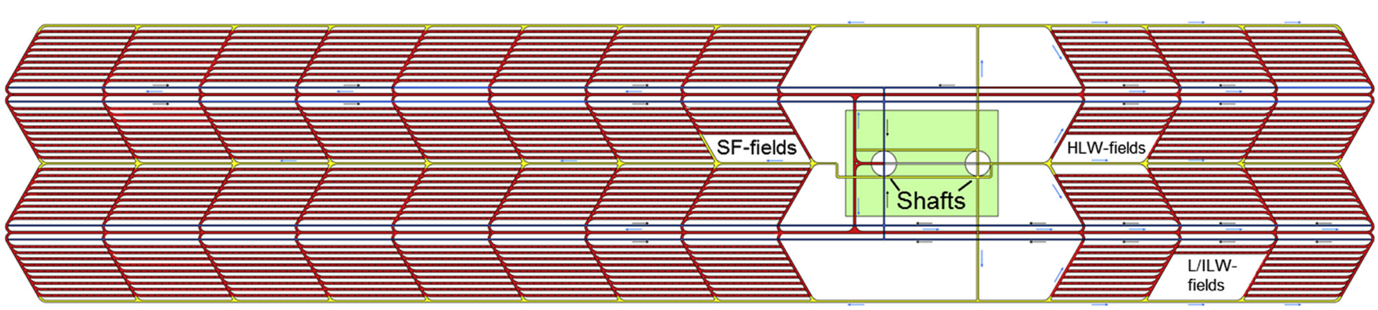


**Fig. 4.** Repository design (borehole disposal, model NORTH) with two shafts, infrastructure area (green) and emplacement areas (red; left: for spent fuel, right: for waste from reprocessing).

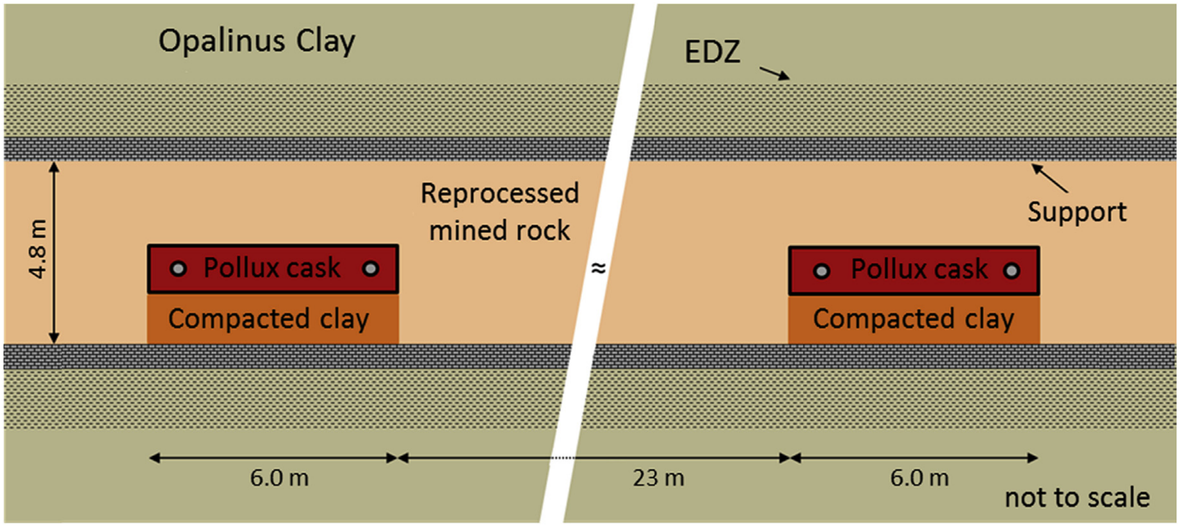


**Fig. 6.** Scheme of drift emplacement in the site of the model SOUTH.

(1) Shaft sealing,
(2) Drift sealing (infrastructural area),
(3) Drift sealing (emplacement fields), and
(4) Emplacement borehole sealing (only model NORTH) and exploration borehole sealing.

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

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

The drift seals in the NORTH and SOUTH models are slightly different. The concept of model SOUTH can be seen as a further development of the concept of model NORTH which was developed first. In the model SOUTH, both types of drift sealings are additionally equipped with an asphalt/bitumen element. Fig. 7 gives an overview of drift seal locations and a sketch of the sealing system. The disposal drifts are reached via the main drifts and access drifts which are backfilled.

The drift support is not dismantled as the operational risks are assumed to be too high. Since the drift support is not dismantled, the backfill cannot take over the sealing function at early times, but only at later times. In addition, the removal of drift support would lead to a damage of the host rock, thus this should be avoided. As long as the drift support is not corroded, it can act as a preferential pathway for potentially contaminated fluids. After the corrosion of the cement, the mechanical support diminishes and the remaining material will be compacted between the converging rock and the already existing swelling pressure of the backfill. The final permeability of this area is still unknown. The gravel backfill in the infrastructural area is intended to act as a temporary gas reservoir.

At both ends of the access drifts at the interface to the main drifts, the so-called migration barriers are built which are smaller than the drift seals at the interface to the infrastructural area. In this barrier, an asphalt element is located in direction to the disposal field. The asphalt element takes over its sealing function immediately after installation. This is necessary because the adjacent bentonite element may need a few decades to develop its full sealing ability and thus to ensure that the sealing function of the barrier is available at early times. In case of instantaneous failure of a canister, the sealing is ensured.

In the larger drift seals at the infrastructural area, the asphalt element is located in direction to the shafts and then outwards. The reason is that due to the immediate sealing capability of the asphalt, the early inflow of fresh water from upper groundwater levels is avoided and the hydro-chemical conditions are kept undisturbed. Analogously to the smaller drift seals, the asphalt element provides time for the bentonite element to develop its full sealing capacity.

Seals for emplacement boreholes are only presented in the model NORTH because of the chosen borehole disposal option. They act as a very first barrier in case of a canister failure. Exploration boreholes are to be sealed in concepts of both models.

## 4. Modules of system analysis

### 4.1. FEP cataloge

Our approach to carry out an analysis of a disposal system aimed at a compilation of its structured description in an FEP cataloge featuring non-overlapping disposal *components*, non-aggregated *processes* interacting with disposal components, and direct interaction records documenting the properties involved into an interaction between a *process* and a *component*.

The compilation of the FEP cataloge was assisted by the following rules: (i) an interaction between two *components* may only occur via *processes*, (ii) an interaction between two *processes* may only occur by mediation of a component, and (iii) a direct interaction between a *process* and a *component* can only occur if at least one component's property changes as a result of it.

We defined a *component* to represent a physical object within the disposal system (e.g. "waste container", "solutions in the repository" or "host rock") and to enclose all the object's properties which may be required by the performance assessment modeling and can be provided by the site exploration. Including a *component* into the FEP cataloge was accordingly accompanied by assignment of the properties characterising the *component* from a predefined property list, which itself is an integral part of our FEP cataloge. This property list was compiled based on expert judgements and contains such intrinsic properties of solid, liquid or gaseous disposal

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007

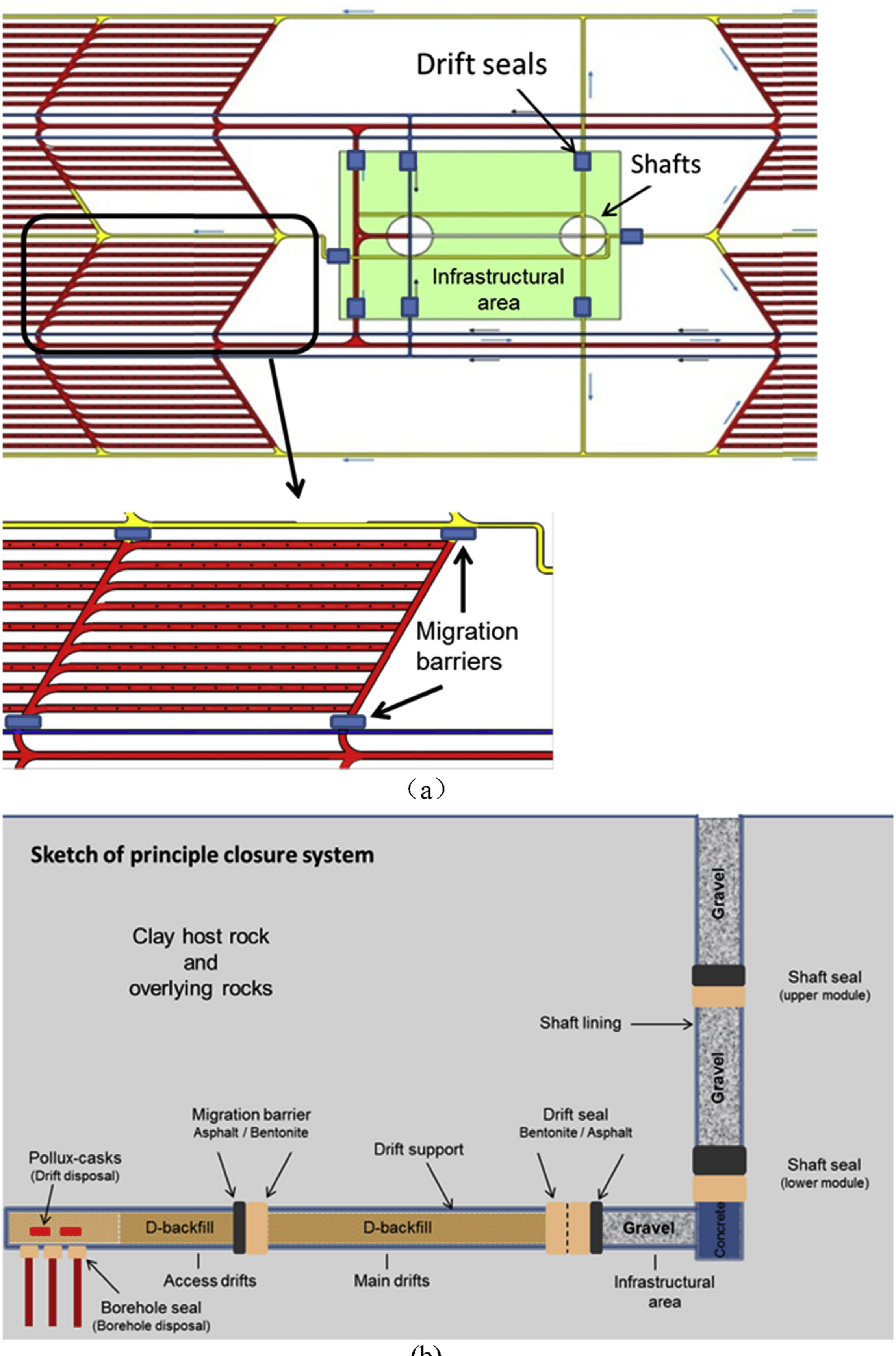


**Fig. 7.** (a) Overview of drift seal locations and (b) sketch of the principle sealing system.

*components* as, e.g. "temperature", "effective stress" or "radioactivity". In Fig. 8, the full list of properties is shown. Our choice of level of detail for *components* is conditioned by the scale, at which the modeling of the long-term evolution of the whole disposal system can reasonably proceed. The *components* of the FEP catalogue should provide a complete description of the repository system (Stark et al., 2016).

We defined a *process* as a transformation acting within the disposal system and changing the states of *components* such as "erosion", "corrosion of metal" or "radiolysis" (see Fig. 8 for the list of *processes* specific to the site model SOUTH). Including a *process* into the FEP catalogue was accompanied by examining whether direct interactions between the *process* and the assigned properties of all disposal *components* exist or not. Thereby, a justification of either existence or non-existence of direct interactions was provided to transparently document the arguments of the examining expert. The assigned properties of a disposal *component* thus form the interface through which a *process* interacts with a *component*. The *components* by their mere existence determine the evolution of the disposal system. Therefore, in our framework only a screening of processes, non-essential for the disposal system evolution – not FEP screening as in previous projects – was needed to be carried out.

Importantly, a direct interaction between a *process* and a *component* means not only that the *process* changes the state of the *component*, but also that the *component* can modify the intensity of the *process*, e.g. the *process* "sorption and desorption" can change the state of the *component* "buffer" by changing its properties of "material composition", "radioactivity", and "surface properties". The property "material composition" in turn determines the intensity with which the sorption or desorption of stable or radioactive substances occurs on the surfaces of minerals constituting the buffer materials.

To be included into the FEP catalogue, a candidate component (or a process) was proven not to contain a part or the whole of a *component* or *process* already included – to be non-overlapping. Otherwise, a change during the system evolution in the state of the component or the intensity of the process contained in the overlapping component would be necessarily mirrored in the latter, evidencing a direct interaction between them in a violation of, respectively, the first or second rule underlying our framework.

It was actually our commitment to comply with the first rule that urged us to shift from the paradigm of using features as defined by NRC (2003) or Posiva (2012), which can refer to different aspects of the same physical object (e.g. "waste inventory" and "heterogeneity of waste inventory" in the FEP list by BSC (2005), or "sealing materials" and "seals" in the VSG FEP list (NEA, 2012)), to the use of *components*. Similarly, our commitment to comply with the second rule urged us to discard the use of processes composed of a chain of events or processes such as "failure of a shaft seal" in VSG FEP list (NEA, 2012) or "seismic induced drift collapse alters in-drift thermo-hydrology" (BSC, 2005). This is a kind of small scenario

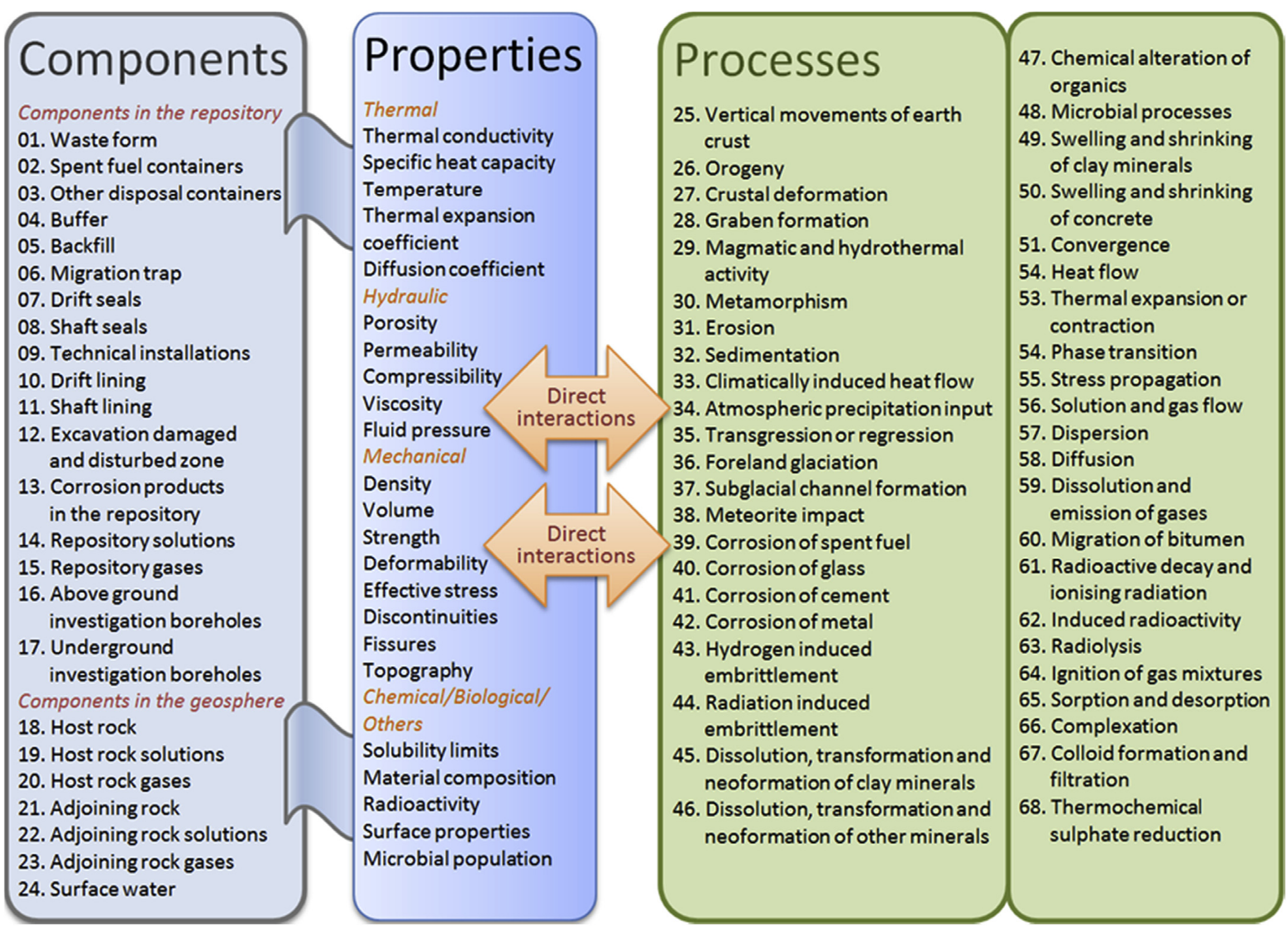


**Fig. 8.** List of components, properties and processes specific to the site model SOUTH of the ANSICHT project (Stark et al., 2016).

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007

and belongs in our opinion to the scenario development and not to the FEP catalogе.

It should be stressed that our use – and in part our definition – of a disposal *component* differs strongly from that by Posiva (2012). Thereafter, a disposal component is used as a wrap for multiple FEPs referring to physical properties and processes characteristic of – or acting on – the physical objects located within a specified disposal subsystem (e.g. canister, buffer, and geosphere). Here, a disposal *component* would be a single FEP in terms of reports, e.g. Posiva (2012) or NEA (2012).

Similarly, our definition of a *process* does not differentiate between events and processes as defined by NRC (2003) or Posiva (2012). We handle earthquakes (an event in terms of the latter reports) as a mere manifestation – which it is indeed – of a broader *process* "stress propagation" responsible for a plethora of mechanical energy transfer modes between solid, liquid and gaseous *components*. This allows a detailed consideration of important mechanical transformations in the disposal system without overfilling the FEP catalogе with too many detailed and interrelated events and processes, which otherwise would make it less clear.

We suggest that our approach can provide for any level of detail of a FEP catalogе: (i) a complete and non-overlapping description of the disposal system through *components*, (ii) a representative and self-consistent set of all *processes* important for the evolution of a disposal system, and (iii) a comprehensive and justified record of direct interactions necessary for scenario formulation and performance assessment modeling.

The scenario formulation in the frames of the ANSICHT project (see Section 5) was carried out using the FEP catalogе model NORTH, which actually represented a developmental stage of our approach (Stark et al., 2014). It still contained overlapping features and aggregated processes with unavoidable consequence that feature–feature and process–process direct interactions had to be allowed. It also did not possess the properties toolkit, which emerged along with the notion of *components* at a later stage of the project.

To cope with the resulting ambiguities and over-description in the thus compiled FEP catalogе of model NORTH, some later obsolete measures had to be devised or adopted from the earlier approaches, e.g. a division of the disposal system into four subsystems or the notion of initial FEP (see Section 5). These methodological drawbacks become even more explicit during the exercise of the scenario formulation and motivated us eventually to overhaul the approach applied for FEP catalogе compilation as described above.

### 4.2. Scenario development

In scenario development, possible future evolutions of the repository system during the reference period will be derived systematically and described comprehensively. The methodology relies on the host rock-specific safety concept – on one hand – and the systematic development of scenarios from a FEP catalogе – on the other hand (Beuth et al., 2012). In summary, the fundamentals for scenario developments are (Fig. 9):

(1) The regulatory framework referring to the definition of probability classes for scenarios and the reference period,

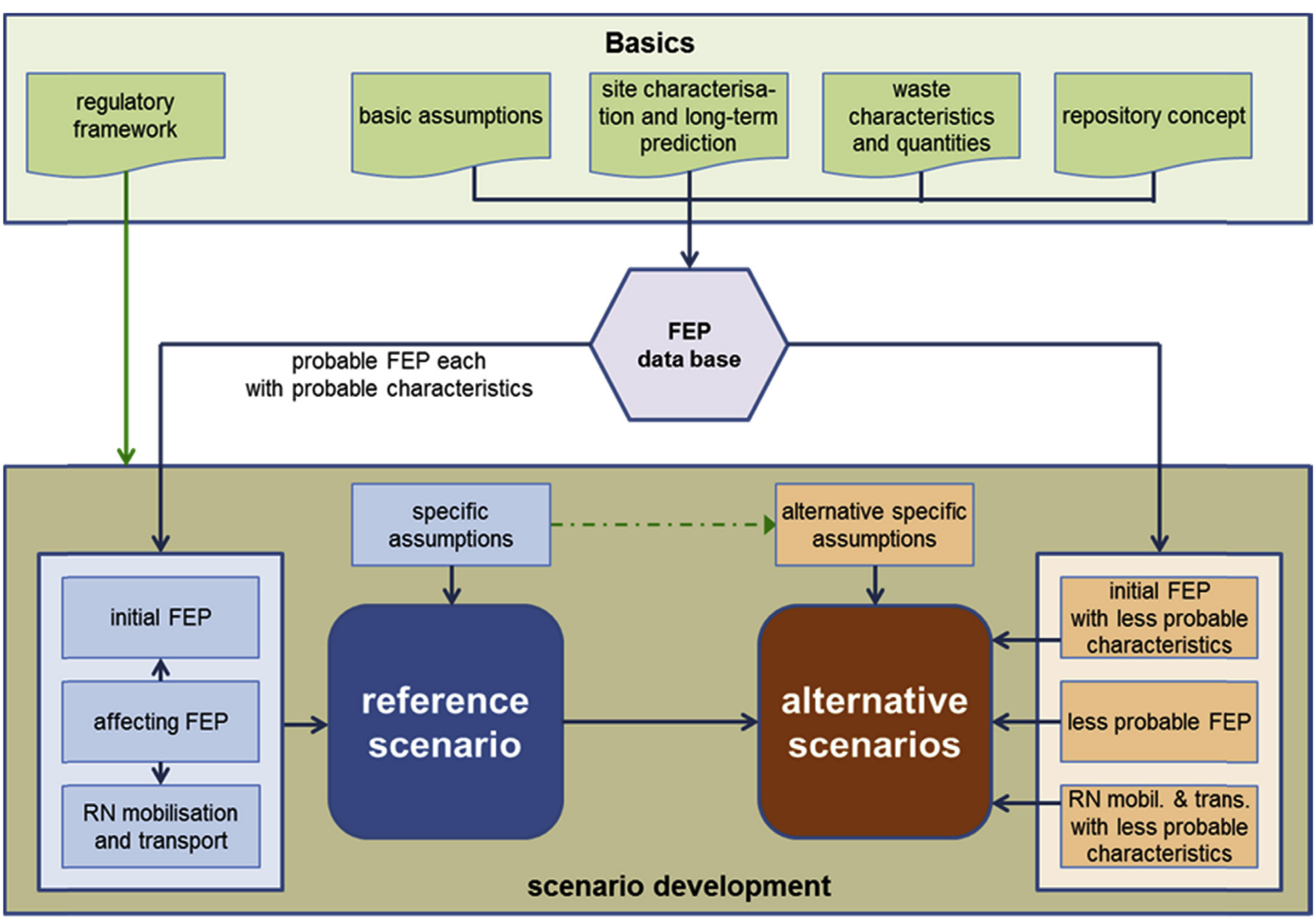


**Fig. 9.** Scenario development methodology (Beuth et al., 2012).

(2) The geological site conditions, long-term geoscientific predictions as well as waste specification and repository concepts, and
(3) The site-specific FEP catalogue that summarises all relevant processes and components in the repository system and the surrounding areas.

The description of the repository system by the FEP cataloge is a connecting link between the fundamentals and the scenario development. All FEPs relevant for scenario description can be directly selected from the FEP cataloge.

According to the Safety Requirements (BMU, 2010), the scenarios shall be grouped in the probability classes "probable", "less probable", and "improbable". In the ANSICHT project, the probability classification of scenarios was justified by the probability of occurrence of the FEPs and their properties. The methodical approach for development of probable and less probable scenarios (Lommerzheim et al., 2016) will be summarised in the following paragraphs. The development of a methodology to handle improbable system evolutions as required by the Safety Requirements is still pending.

To structure the scenario description and to consider the different characteristics of the FEPs in different locations of the repository system, four subsystems have been defined: "Near Field", "Drifts and Shafts", "Host Rock", and "Adjoining Rock".

#### 4.2.1. Reference scenario

A reference scenario describes a set of probable future evolutions of a repository system. The starting points for the development of a reference scenario are:

(1) Consideration of basic assumptions and specific assumptions,
(2) Consideration of probable FEPs that directly affect the function of the initial barriers, and
(3) Consideration of FEPs that describe mobilisation and transport of radionuclides.

Basic assumptions include general settings (e.g. the existing geological data are representative for the area of the host rock considered). Specific assumptions are necessary to structure the process of scenario development and to separate the reference scenario from the alternative scenarios. These assumptions give definitions for circumstances with high uncertainties that may exist in the future (e.g. climatic evolutions). Furthermore, repository-specific boundary conditions that are not yet verified (e.g. the function of the geotechnical barriers) have to be determined.

Initial barriers rely on the clay specific safety concept and include all the geotechnical barriers as well as the host rock. Initial FEP describes processes that directly affect the function of initial barriers. Initial FEP is an important starting point for the description of the reference scenario. They comprise mechanical, hydraulic, thermal, and chemical/microbial processes that are considered with probable characteristics. These characteristics are documented in the FEP cataloge or they can be determined from the interaction with other possible affecting FEPs.

Mobilisation and transport of radionuclides are important processes for the demonstration of compliance with radiological criteria in the consequence analysis. The characteristics of these FEPs will also be developed from the interaction with affecting FEP with probable characteristics. Following this methodology, the probable future evolution at a generic repository system in the clay formations of Northern Germany was successfully developed.

#### 4.2.2. Alternative scenarios

These scenarios mainly describe less probable evolutions of the future repository system. There are four methodical approaches to develop alternative scenarios:

(1) Modification of the specific assumptions (e.g. different climate evolutions or failure of geotechnical barriers),
(2) Less probable characteristics of the initial FEP (e.g. intensive alteration processes),
(3) Less probable characteristics of the FEP "radionuclide mobilisation and radionuclide transport", and
(4) Less probable FEP (e.g. FEP "liquid paths in exploration drillings").

These different approaches may result in very similar evolutions of the repository system. In this case, these evolutions may be summarised in one representative scenario. The applicability and efficiency of these approaches have been exemplarily tested and confirmed.

### 4.3. Integrity proof for the geological barrier

#### 4.3.1. Criteria

The starting point for the integrity proof of the geological barrier is the Safety Requirements. Therein, it is demanded that for probable evolutions, the integrity of the geological barrier must be proven for the reference period of 1 million years by compliance with specific requirements. Further specifications and quantifications have been done by Jobmann et al. (2015) to provide the proof in the context of numerical simulations. Four separate criteria are proposed, which all have to be met within the CRZ over the reference period to prove the integrity of the geological barrier.

THM coupling effects are considered for the proof. Applying the theory of poroelasticity, based on Terzaghi and Fröhlich (1936) and Biot (1941) amongst others, the total stresses in a water saturated rock can be separated into two parts: the pore water pressure acting in the liquid phase and the effective stress acting in the solid phase, which reflect the deformation behaviors.

(i) Fluid pressure criterion

The formation of secondary water pathways (hydraulically open macrocracks) within the CRZ must be excluded, as it can lead to the ingress or escape of potentially contaminated aqueous solutions. Macrocracks can arise only if tensile effective stresses occur. Tensile stress could be caused by thermal, mechanical as well as hydraulic processes and their combination – all are covered by the approach of THM coupling simulations using the effective stress concept. The fluid pressure criterion can be met, if no tensile effective stress occurs in the CRZ, excluding a disturbed zone around the excavations (cf. Section 4.3.2).

(ii) The dilatancy criterion

The formation of secondary permeability exceeding the dilatancy strength of the rock must be excluded. Dilatancy leads to pore volume increase under compressive as well as shear stresses and could result in formation and widening of microcracks and increase the hydraulic connectivity between pores and fissures. It is proposed to use the damage threshold rather than the dilatancy strength, as the damage threshold can easily be derived based on S-wave velocities (microcrack threshold) and this definition yields the lowest value in permissible stress.

The dilatancy criterion can be met if the effective stresses do not exceed the damage threshold in the CRZ, excluding a disturbed zone around the excavations (cf. Section 4.3.2).

(iii) The advection criterion

In BMU (2010), it is demanded that "*any pore water that may be present in the CRZ does not participate in the hydrogeological cycle outside the CRZ*". This is understood to be fulfilled by the following criterion. The advection criterion can be met if a conservative tracer cannot be transported from the emplacement area to the outer boundary of the CRZ within the reference period by advective transport only.

(iv) The temperature criterion

Jobmann and Meleshyn (2015) reviewed the influence of temperature on the barrier effect of the CRZ. Several temperature driven effects at a temperature range up to 150 °C have been considered, such as expansion/contraction, change of THM properties, dehydration, and vaporisation, as well as chemical, biological and mineral impacts. Only two effects are significant: "expansion/contraction" and "limiting the microbial activity". Potential influences from the expansion/contraction behaviors will be covered by the fluid pressure and dilatancy criterion. The limitation of microbial activity by temperatures above 122 °C leads to a sterilisation and thus to a stop of microbial corrosion which is assumed to be more intense than pure chemical corrosion. The temperature criterion can also be met if the temperature in the rock stays below 150 °C.

### 4.3.2. Containment providing rock zone (CRZ)

The criteria have to be analysed with respect to specific local references. The repository, excluding the shafts, is entirely located within the CRZ, which is a part of the host rock. Consequently, the claystone, located close to and in between the excavations, belongs to the CRZ too. The extent of the CRZ is described by a zone that encloses the repository and the surrounding disturbed zone (EDZ and a temporally desaturated zone) with the minimum thickness $s$ (see Fig. 10). The minimum thickness $s$ has to be determined iteratively if necessary by evaluation of the criteria. For the analysis of the advection criterion, the extent of the CRZ needs to be known beforehand. Thus, an a priori determination is required. Following AkEnd (2002), a starting value of $s = 35$ m is recommended for the minimum thickness.

### 4.3.3. Exemplary numerical simulations

The integrity proof for the geological barrier is a challenging task for numerical modeling. Different processes and their couplings have to be simulated over a time period of 1 million years. Considering the broad range of length scales, for instance temperature-driven multiphase flow processes in the near field and subsidence at the top ground surface, it is meaningful to use several numerical models which describe together the entire system behaviors. Nevertheless, thermo-hydro-mechano-chemical (THMC) processes have to be calculated in an integrated manner to understand strong coupling in between the processes, as depicted in Fig. 11. For each model, it has to be decided which processes and coupling mechanisms are important and have to be taken into account.

The model approach concentrates on the behavior of the claystone barrier outside the EDZ during the post-closure period. Processes due to excavation as well as installation of support and sealing elements are not considered. Numerical evaluations have been done by the open source software package OpenGeoSys (Kolditz et al., 2012). The model setups are based on the reference scenario (cf. Section 4.2) and the description of the system components (see Section 3). Concerning the geometry and material properties (Jahn and Sönnke, 2013; Jahn et al., 2016), some simplifications have been assumed for numerical reasons (Nowak and Maßmann, 2013; Maßmann, 2016). Both models consider THM coupling with Darcy flow and linear elasticity, neglecting chemistry and gas production. The Richards approach (Richards, 1931) combined with the molecular diffusion model by Philip and De Vries (1957) is used in the local model. It allows simulation of temperature-influenced de- and re-saturation of the claystone in the near-field of the emplacements drifts. The heat producing waste is modeled as an averaged volume source (global model) and an averaged line source (local model). An operational phase of 80 years for excavation and filling and 20 years for closing the repository is assumed.

Concerning the evaluation of the numerical results, we are now investigating a generic geological site. Consequently, the result and its interpretation have to be understood as exemplary only. For investigations on a real site, an adequate material model would be needed to describe the behavior of the claystone. The poroelastic formulation is not capable of considering damage or post-failure behavior. However, the main THM coupling effects due to heating basically can be covered.

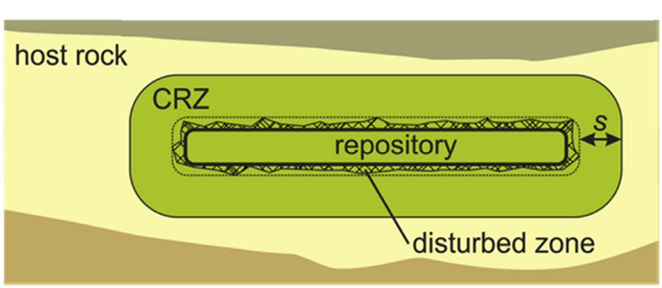


**Fig. 10.** Illustration of the containment providing rock zone (CRZ).

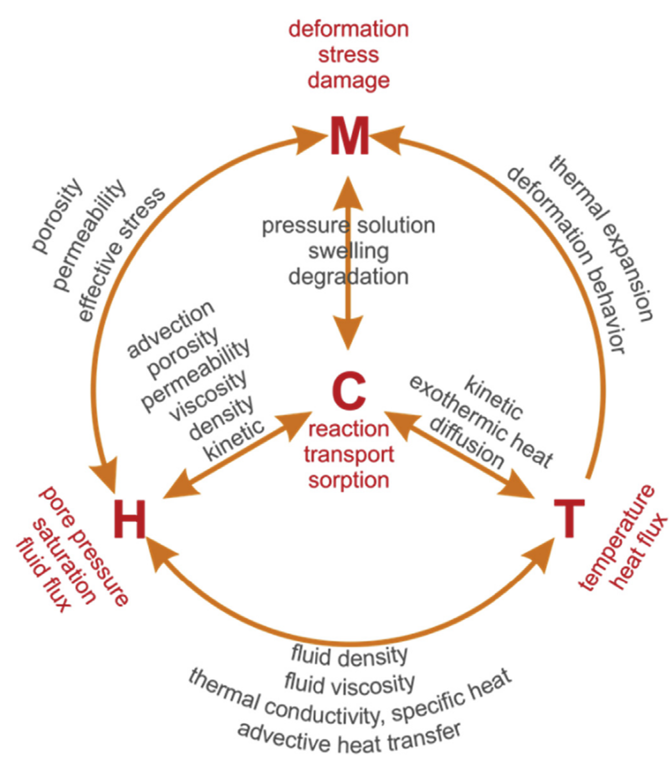


**Fig. 11.** Exemplary illustration of process coupling.

Exemplary results are shown in Figs. 12 and 13. Several evaluations can be deduced from these simulations, which represent the THM impact of the repository on the underground system. While the two-dimensional (2D) model provides insights in the near-field processes, as the development of the desaturated zone; the 3D model allows a better estimation in the far-field due to the temperature increase of aquifers or uplifts at the top ground surface.

The system development can be subdivided into different phases (see Fig. 14). The first phase is dominated by the excavation and ventilation of the repository mine. It leads to a decrease of pore water pressure and desaturation next to the excavations. Due to the hydro-mechanical (HM) coupling by the concept of effective stresses, the compressive stresses increase and the subsequent compaction causes subsidence. When the repository is closed, the pore water pressure will increase again and the desaturated area decreases. In the second phase, the heat of the waste results in diffusive heat transport into the rock and an increasing temperature, depending on the distance to the heat source. Since the thermal expansion of the liquid is greater than that of the solid, the temperature rise leads to an increase in the liquid pressure during the heating phase. The zones of increased pressure are located in some distance to the repository (see Fig. 13), because in the near field of the repository, the desaturated zone, or at least a zone of decreased pressure, is still presented from the first phase. Due to the HM coupling, the pressure rise results in decrease of compressive effective stresses. The thermal expansion induces uplift at the surface in a range of up to 20 cm. The third and longest phases are dominated by cooling. Diametrical to the heating phase, pressure drops due to density change and the effective stress increases. In the last phase, the cooling is completed and the initial, undisturbed state is reached in the system.

The criteria are evaluated with specific local reference: the advection and temperature criterion have to be met in the entire CRZ; the fluid pressure and dilatancy criteria also have to be satisfied in a zone, in which the repository and the surrounding disturbed zone are enclosed with a minimum thickness of 35 m (cf. Fig. 10). The fluid pressure, dilatancy and temperature criteria can be analysed by simple post-processing. For the fluid pressure criteria, all principal effective stresses must be in compression. For the dilatancy criteria, the Mohr-Coulomb criterion is used. The

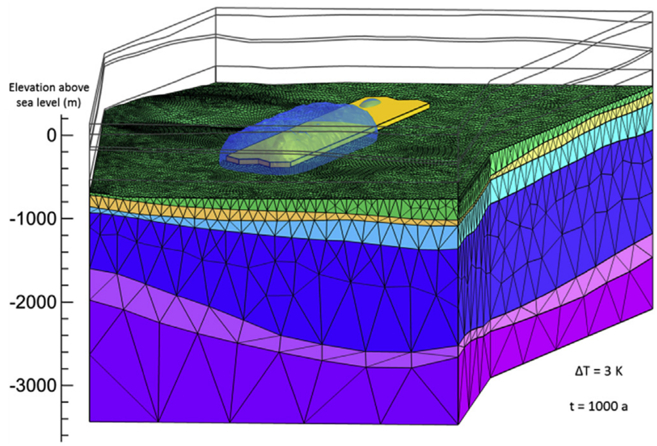


**Fig. 12.** Global model (NORTH): Geological units beneath the host rock, emplacement area (orange) and zone of 3 K temperature increase (blue bubble), 1000 years after emplacement.

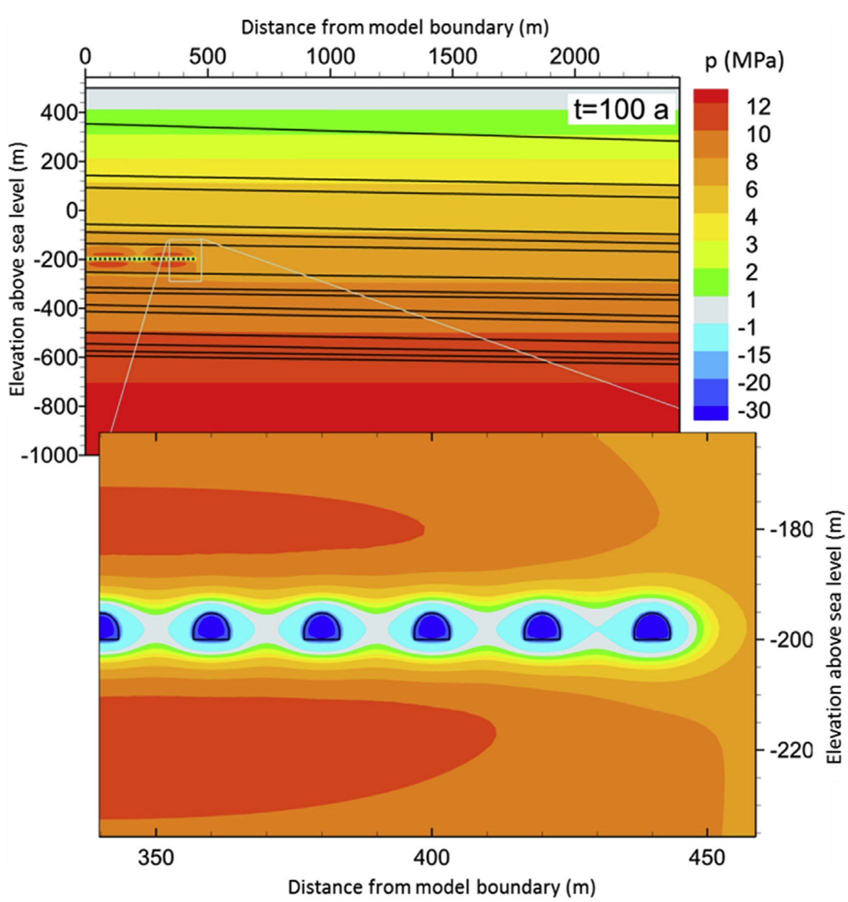


**Fig. 13.** Local model (SOUTH): Pore pressure $p$ after 100 years. Negative values (blue) indicate the water desaturated zone.

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007

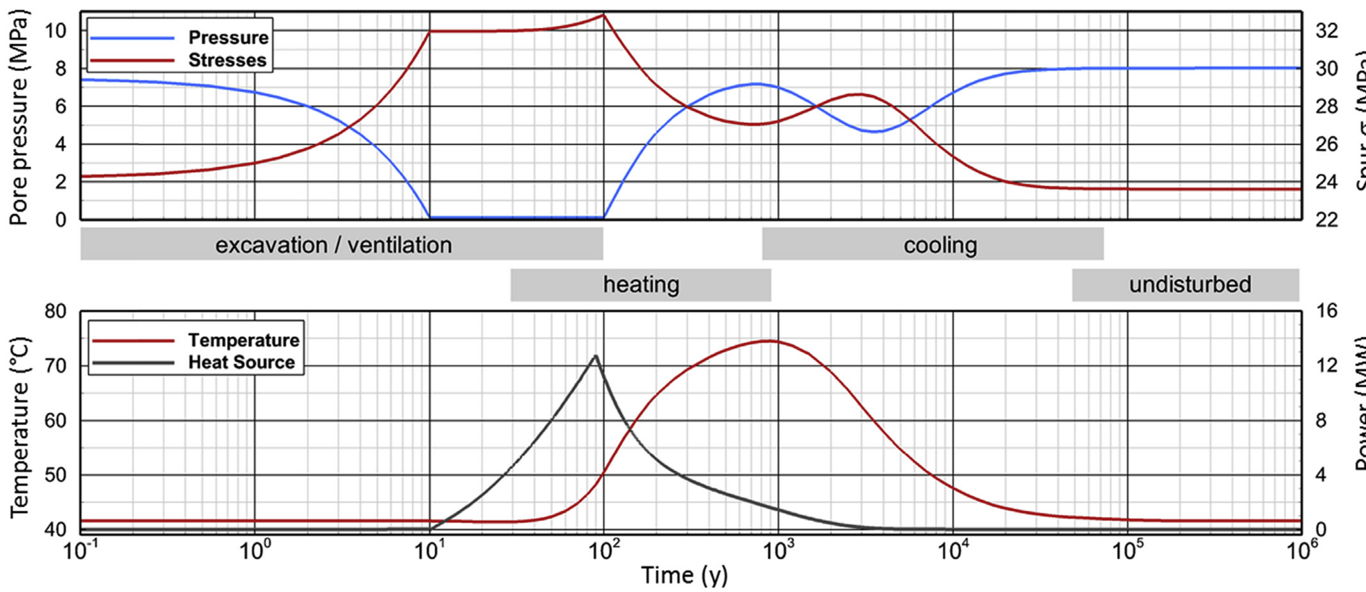


**Fig. 14.** Global model (NORTH): Simulated temporal evolution of pore pressure, mechanical effective stresses and temperature at a point 35 m above the emplacement area.

temperature can be evaluated directly from the numerical results. The advection criterion is analysed by evaluating the flow velocities over 1 million years, along representative flow paths through the CRZ. In terms of the minimum velocity, a conservative tracer would be needed to migrate from the emplacement area to the boundary of the CRZ, and we should know whether the advection criterion is met. For the investigated cases, all criteria are met.

### *4.4. Integrity proof for the geotechnical barriers*

The geotechnical barriers serve as modules for sealing the underground openings. The individual geotechnical barriers must be designed to have a sufficiently low permeability to minimise fluid migration into the repository or out of it. The interplay of all geotechnical barriers has to cover the whole reference period of 1 million years. The basic structure of the proof for the geotechnical barriers is illustrated in Fig. 15. It consists of four key elements:

(1) The conceptual design of the individual barriers,
(2) The specification of the hydraulic resistance of the individual barriers,
(3) The proof of the structural integrity of each barrier, and
(4) The proof that the interplay of all geotechnical barriers is able to meet the advection criterion (cf. Section 4.3).

The proof is carried out in two steps. As a first step, a compliance assessment has to be performed for each individual barrier by specifying the hydraulic resistance and by proving the structural integrity of the barrier. As a second step, the hydraulic resistances of all the individual barriers (emplacement borehole seals, drift seals and part of the shaft seals) located within the limits of the CRZ will be combined to check whether the whole hydraulic resistance is high enough to meet the advection criterion.

The safe enclosure of the radioactive waste shall be mainly achieved by the host rock and the swelling backfill in the underground drifts. With regard to the safety concept described above (cf. Section 2), the structural integrity of the individual barriers is to be proven for the transient phase of the THM system, which ends as soon as the THM system has nearly reached its undisturbed conditions prior to repository construction (cf. Fig. 14).

For the post-transient phase, it is assumed that due to the use of mainly native material like the excavated material or swelling clay material (e.g. bentonite), the impact of the geological processes on the geotechnical barriers will be similar to that on the host rock. Thus, the integrities of host rock and geotechnical barriers can be assumed to be comparable. During the post-transient phase, driving forces for transport processes induced by the repository will come to a halt.

The period of the transient phase has to be specified under site-specific conditions. Based on indicative calculations for the repository site models, the transient phase will last for about 50,000 years. It can be assumed that within this time period, the backfill in the drifts has reached its final compaction state and is able to take over its designated sealing function. This is still to be confirmed by corresponding experiments and process analyses.

In this context, there is one remaining issue to be solved regarding the drift support which has to be left in the repository. The drift support will mainly consist of cement-based material, which means that corrosion processes will occur at the cement part and in the course of time when the mechanical support ability will come to an end. The remaining part of the support including the corrosion products will be compacted due to the convergence of the claystone and the swelling clay in the backfill. The remaining permeability in this area is still unknown.

#### *4.4.1. Assessment of the individual barriers*

For plug design and compliance assessment, a consistent concept shall be applied. With respect to the internationally accepted state-of-the-art technology (JRC, 2008), the compliance assessment shall be performed by applying the method of partial safety factor (Herold et al., 2016). The semi-probabilistic, reliability-oriented safety assessment concept using partial factors is implemented in the Eurocodes (DIN EN, 1990). In civil engineering, it can thus be considered as state-of-the-art for demonstrating the load bearing capacity (resistance) of a structure. During a former R&D project (Müller-Hoeppe and Ebert, 2009), this method was applied to a generic shaft seal for the first time. Within the scope of the preliminary safety analysis for the Gorleben site (VSG), this method was exemplarily applied to a seal and an abutment as a part of the overall shaft sealing concept (Müller-Hoeppe et al., 2012).

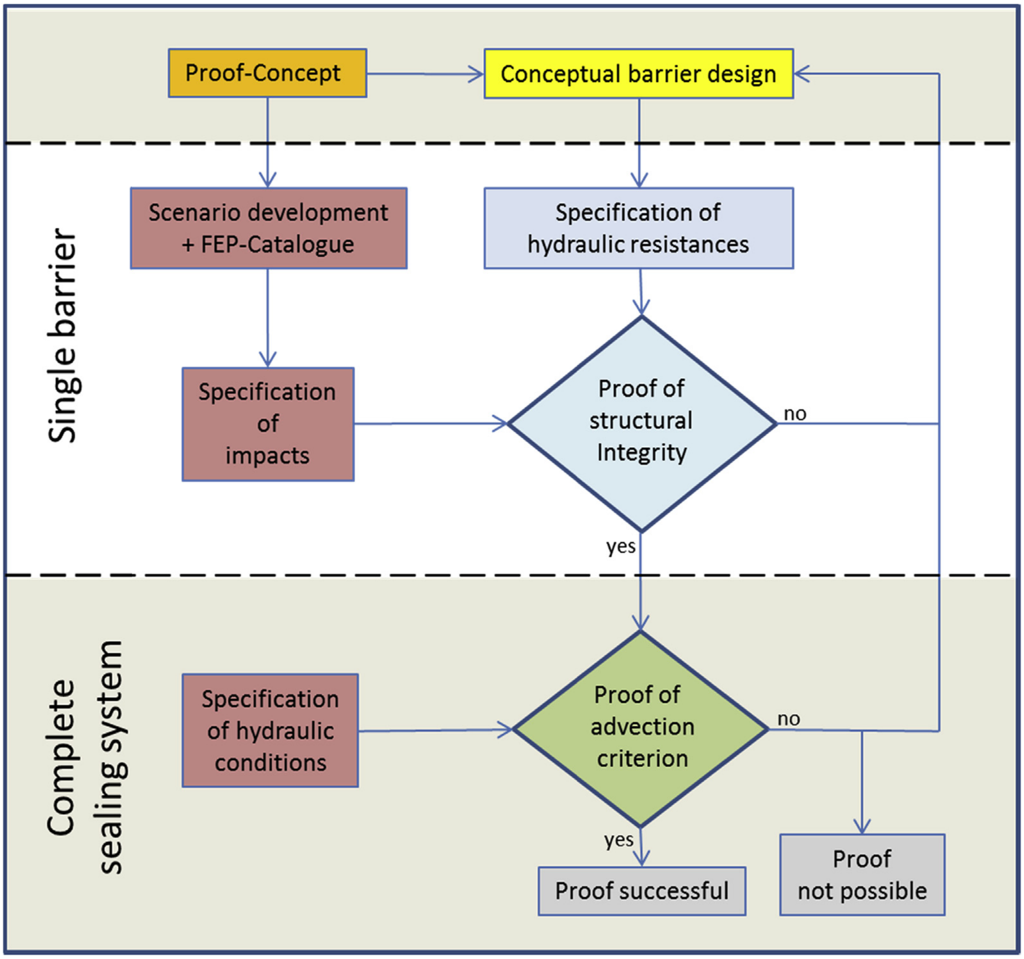


**Fig. 15.** Structure of the integrity proof process.

The proper demonstration is carried out by means of a limit state evaluation of the opposing actions (impacts) and resistances. The actions on the structure are compared with the resistances of the structure by means of limiting criteria which are allocated to the combinations of actions. The kind of actions on the structure is determined with the help of the FEP catalogue. The analyses by means of assessment cases have to be carried out for all relevant combinations of actions as well as for their limit states. The so-called *rated values* are determined by the characteristic values of the actions and the resistance abilities of the barrier in combination with partial safety factors. This approach is illustrated in Fig. 16.

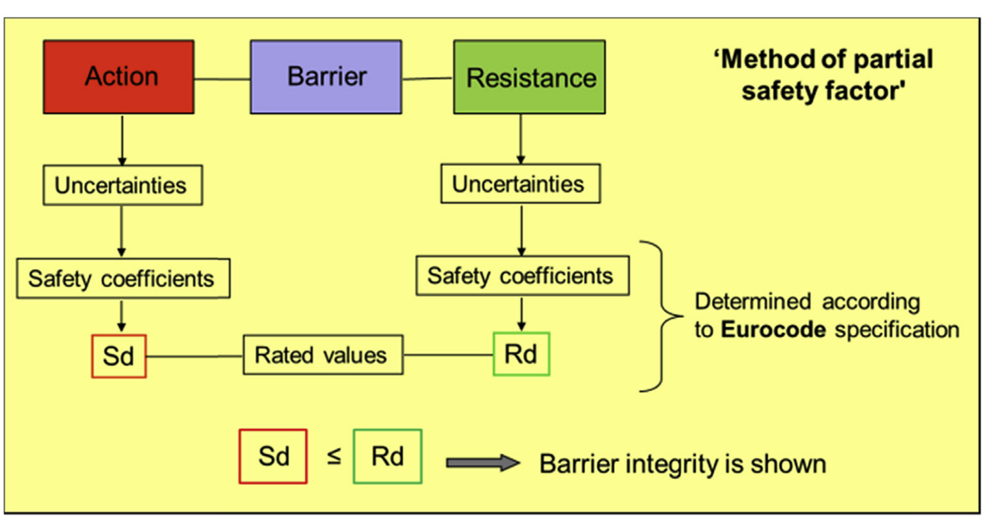


**Fig. 16.** General principle of the method of partial safety factor.

Actions or impacts ($S_d$) are multiplied by partial safety factors and thus increased in their effect. The resistance capabilities ($R_d$) are divided by partial safety factors and thus decreased in their effect. This approach and the use of partial safety factors cover uncertainties of the characteristic values of the actions as well as those of the conditions of the barrier.

#### 4.4.2. Assessment of the hydraulic resistance of the sealing system

After proper specification of the hydraulic resistance and the successful proof of the structural integrity of the individual plugs, it finally has to be shown that the combination of all geotechnical barriers, including the backfill, is able to provide an overall hydraulic resistance that meets the advection criterion in the long term. The criterion says that during the reference period of 1 million years, the advective driven transport of radionuclides has to be so slow that no radionuclides will reach the boundary of the CRZ – in this case the boundary of the lower shaft sealing module – via the underground openings. To reach the boundary of the CRZ, fluids that might be contaminated will have to go through a series of geotechnical barriers on the way to the boundary of the CRZ (Fig. 17).

These barriers are:

(1) The borehole seals (if applicable),
(2) The backfill in the access drifts,
(3) The migration barriers,
(4) The backfill in the main drifts,
(5) The drift seals,
(6) The backfill in the infrastructural area, and
(7) The lower module of the shaft sealing system.

Each of these modules (including the EDZ) has its own hydraulic resistance which impedes the migration of solutions through the underground openings. It has to be considered that the clay-based material will need some time to saturate and to develop its full sealing capabilities. The overall hydraulic resistance is the sum of all the individual ones as illustrated in Fig. 17.

To meet the advection criterion, a specific velocity limit must not be exceeded by the migrating water during its way through the geological barrier and the CRZ, respectively (Maßmann and Ziefle, 2017). Regarding the geotechnical barriers, the proof is to be carried out in a similar way (Herold et al., 2016). For calculating the limit velocity $v_{limit}$, a conservative tracer would be needed to migrate from an emplacement field through the geotechnical barrier system up to the boundary of the CRZ. The limit velocity $v_{limit}$ can be calculated as $v_{limit} = sn_{eff}/t$, where $v_{limit}$ is the Darcy velocity, $s$ is the distance from the emplacement field to the CRZ boundary, $t$ is the reference time, and $n_{eff}$ is the mean effective porosity of the filling material. To demonstrate that the advection criterion is met, the quotient of the mean Darcy velocity $v$ and the limit velocity $v_{limit}$ is calculated. If the quotient is less than 1, the advection criterion is met.

### 4.5. Radiological proof

According to the Safety Requirements, radiological consequences have to be assessed for probable and less probable future evolutions of the repository system. For the project ANSICHT, the simplified long-term radiological statement without modeling the dispersion of substances in the overburden and adjoining rock explicitly should be decided, e.g. permissible if "the radioactive substances released from the CRZ lead to a maximum of 0.1 person-millisievert per year for probable developments and a maximum of 1 person-millisievert for less probable developments" (BMU, 2010). The reference group considered in the assessment contains 10 persons that obtain their entire annual water requirement of 500 $m^3$ for nutritional purpose from a well that contains all the radionuclides escaped from the CRZ during 1 year.

The release of radionuclides from the CRZ may occur through diffusive transport due to the concentration gradients, or through advective transport along with the water flow due to potential differences. The integrity of the CRZ has to be proven, including the fact that "*the dispersion of pollutants by advective transport processes is at best comparable with dispersion by diffusive transport processes*". If the long-term requirement on the integrity of the CRZ is met, the advective transport should therefore only play a minor role, so that for the radiological assessment it primarily has to be shown that:

(1) The release of dissolved radionuclides from the CRZ through diffusive transport is lower than the value given in the Safety Requirements, and
(2) The release of volatile radionuclides from the CRZ through advective and diffusive transport in the gas phase is lower than the value given in the Safety Requirements.

The transport from the emplacement area to the CRZ boundary can occur in two distinct pathways, which are the transport

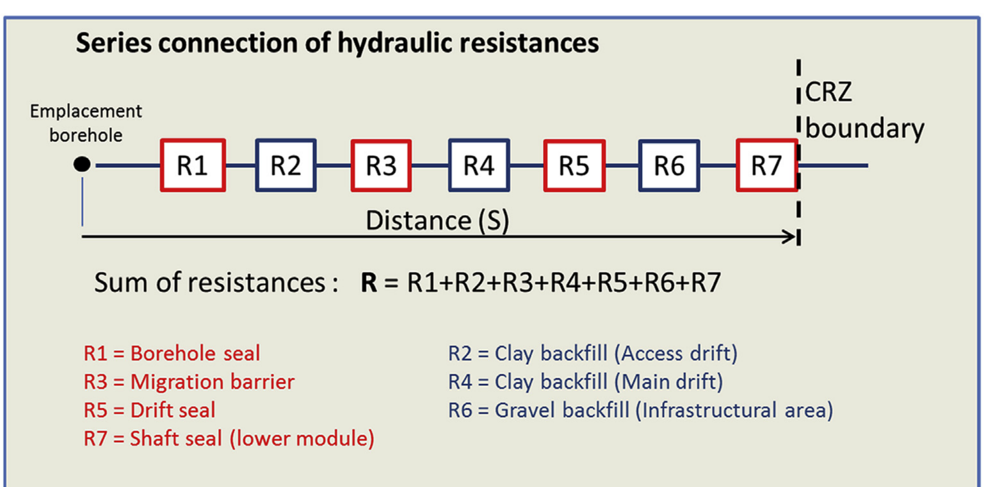


**Fig. 17.** Hydraulic resistances in the underground openings.

through the undisturbed host rock and the one along the drifts and shafts of the repository mine (including the EDZ and liner area). In principle, the radiological assessment requires a coupled modeling of dissolved and volatile transport along both pathways. In addition, there are still open questions about the mechanism of gas transport in the clay host rock and highly compacted bentonite. According to the latest research, two-phase flow seems unlikely, since the gas entry pressure of clay rocks is very high. A potential gas transport may occur through the so-called pathway dilation, which creates new pore space in the rock. The gas pressure needed to start this process depends on the mechanical properties of the rock and its stress state. However, the process of pathway dilation is not fully understood yet and no consecutive material laws exist that would allow predictive modeling of such process in clay rock (Shaw, 2013). For this reason, a repository concept may be preferable that considers gas storage areas or allows for a sufficient gas transport in drifts and shafts to evacuate all gases generated. In this case, there is no gas transport in the host rock, and the transport in the host rock and the drift system can be modeled independently.

A check of the quality and relevance of the existing data for the two generic repository site models considered in ANSICHT came to the conclusion that the current data basis collected in this project is too uncertain to carry out first orienting safety assessments. The highest priority to improve the data basis for the radiological assessment is to determine site-specific diffusion coefficients and sorption data for the host rocks considered. Nevertheless, to demonstrate the procedure for the long-term safety assessment, radionuclide dispersion was modeled anyway as part of the ANSICHT project using the geometrical and material data collected in the ANSICHT project (Jahn and Sönnke, 2013), to test the existing transport codes and to get an idea of the influence of different system parameters.

Modeling the release of dissolved radionuclide dispersion through the host rock for the reference scenario was carried out (Rübel, 2016a) with the GRS CLAYPOS module of the RepoTREND package (Reiche, 2016), considering diffusive transport from the waste package to the CRZ boundary. The simulation results presented in Fig. 18 account for a transport length from the waste to the CRZ boundary of 50 m and are comparable to those of previous projects (Rübel et al., 2007). Other transport distances of 35 m, 75 m and 100 m were regarded in variant simulations. The results for the radionuclide release from the CRZ are very sensitive to some of the modeling parameters, especially the sorption coefficient of the radionuclides on the clay host rock. Radionuclides with sorption coefficients above a certain threshold value are transported so slowly that they are retained within the CRZ over the whole reference period of 1 million years. This is for example true for all actinides.

Consequently, the most relevant radionuclides for a potential radiation exposure are those that show no or only a weak sorption on the clay host rock and that have half-lives long enough not to decay during transport. Radionuclides that match both prerequisites are Cl-36, Se-79 and I-129 and to some extent also C-14, which has a rather short half-life, so it usually decays during transport to a large extent. The results in Fig. 18 show that I-129 is the most relevant radionuclide with respect to the radiation exposure indicator (Rübel, 2016a). In this figure, the time after the end of the reference period is shown for comparison, shaded in grey. No sorption was assumed for I-129 in the reference case. Only a weak sorption of $5 \times 10^{-4}$ $m^3$/kg leads to the transport of I-129, which is delayed in such a way that the flux at the CRZ boundary occurs after the end of the reference period (dotted red curve in Fig. 18 compared with the dashed red curve). The high sensitivity of the released radionuclide flux on the sorption coefficients of the radionuclides on the clay host rock underlines the statement that preliminary safety assessments suffer from high uncertainties with regard to the data available.

Modeling of the release of volatile radionuclides through the drift system was carried out with TOUGH2 (Rübel, 2016b) exemplarily for a subsection of the repository layout from the emplacement fields up to the drift seal to the infrastructure area. Due to the limitation of the TOUGH2 code, the material properties were regarded constant in time. Only C-14 was regarded as radionuclide in these simulations. Fig. 19 shows the temporal development of the gas pressure, the gas flux, and the mass fraction of C-14 in the gas phase at the drift seal. The gas flux is mainly caused by the gas production from metal corrosion. In all cases, the release of C-14 at the drift seal starts after about 1000 years and decreases again after several 10,000 years due to its decay.

The mixing of C-14 in the gas phase and its subsequent transport through the drifts yield a significant retention of the C-14 compared with its release from the waste forms. The maximum flux of C-14 at the drift seal is determined to be about 120 Becquerel/year. However, these simulations can only be regarded as exemplary because other simulations carried out show that the gas pressure and the resulting transport highly depend on the boundary conditions assumed (Rübel, 2016b).

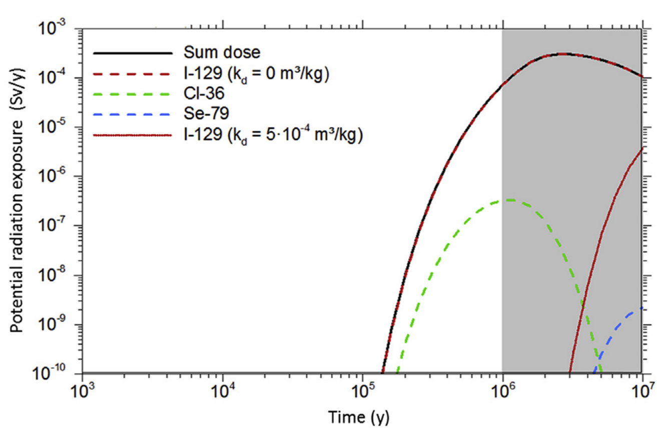


**Fig. 18.** Indicator for the release of the radionuclides at the CRZ boundary (distance *s* to the repository = 50 m, see Fig. 10).

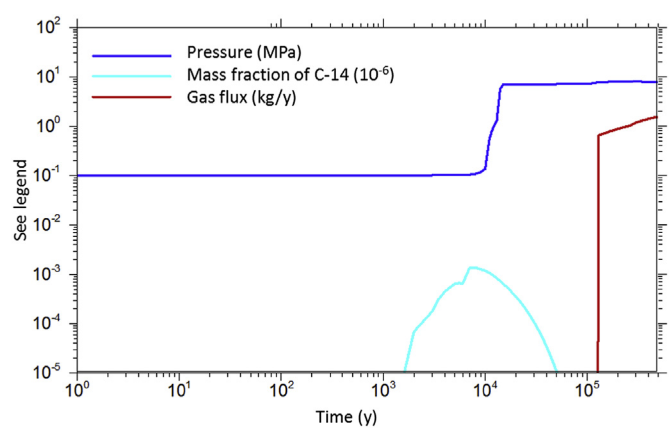


**Fig. 19.** Pressure, gas flow and C-14 content in the gas phase at the outer boundary of a drift seal. See legend for description and units of the *y*-axis.

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007

## 5. Summary and conclusions

Over the past years, the research activities in argillaceous rocks have been significantly intensified. Extensive participation in underground research laboratories in the Meuse-Haute Marne, France, and Mont Terri, Switzerland, built up the knowledge in Germany on the THM behavior and the general sealing abilities of clay host rocks. As a logical consequence, this knowledge led to the development of a safety assessment and safety demonstration concept for a HLW repository in clay host rocks in Germany. This concept has currently being developed in the ANSICHT project.

Based on investigations of the Federal Institute for Geosciences and Natural Resources (BGR), clay formations are available in Germany, potentially suitable to act as a host rock for HLW. Due to the different geological conditions of Northern and Southern Germany, it is not possible to select just one host rock formation which represents an argillaceous rock formation on the whole. Therefore, two reference areas have been selected that comprise parts of the Lower Saxony Basin in Northern Germany and a smaller part of the Molasse Basin in Southern Germany. For both regions, a long-term geoscientific forecast covering a period of 1 million years without influences of a repository is carried out to highlight the natural evolution of the geosphere. As a result, we hold that impairments of the repository due to earthquakes or tectonic processes as well as volcanic activities can be excluded and that glacial channel formation will not reach the depth level of the repository.

Generic geological models have been developed, i.e. the so-called "repository site models" describing typical geological situation at the different regions considered as the basis for the safety demonstration concept. These models are fundamental with regard to the development of a repository concept, especially for a backfilling and sealing concept since both have to be adapted to the geological situation. Both repository site models have been completed by an intensive research and compilation of available data and information about different formations depicted in the geological models. This data basis is a significant outcome of the project and has been used to define representative values for all necessary model parameters to use them in the calculations of the exemplary integrity proof.

As a significant outcome of the project, repository concepts have been developed for both selected reference areas including specific disposal concepts adapted to different host rock extensions as well as corresponding sealing concepts that are able to seal the underground access ways to the emplacement areas.

Specific knowledge is necessary about the rock behavior as well as about all physico-chemical processes (i) that will occur in and around the planned repository during its future evolution, (ii) the processes due to the geological evolution, and (iii) those induced by the underground repository and the waste. An identification of such processes and repository components has been performed and compiled in specific FEP catalogs. These new developed FEP catalogs contain all necessary information for the development of scenarios and thus allow a comprehensive system description. Based on this information, the future evolution of the repository can be described. As a specific outcome, these FEP can be used to identify and describe the processes that have an impact and thus a load on individual geotechnical barriers. This provides fundamental information for the successful development of a suitable system of geotechnical barriers to seal the underground accesses. During the project FEP catalogs for both, the Lower Saxony Basin and the Molasse Basin have been developed. Deduced from the FEP catalog, scenarios have been developed exemplarily for the model NORTH. This comprises a reference scenario covering all probable processes and components as well as examples of alternative scenarios. The comprehensiveness of the alternative scenarios covering all less probable system evolutions is still to be demonstrated.

In the current Safety Requirements, it is stipulated that the radioactive waste has to be evidently enclosed in the CRZ. This implies the proof that the isolating function of the CRZ will not be jeopardized neither by geological nor by repository induced processes over a period of 1 million years. To provide the evidence, criteria are given in a qualitative manner, the so-called integrity criteria, which have to be met by the safety proof. During the ANSICHT project, a specific quantification of these criteria has been achieved that allows the performance of calculational proofs. Exemplary calculations regarding the integrity of the geological barrier have been performed to illustrate the successful application of these quantified criteria.

As a final outcome, the developed work flow of the demonstration concept has been presented to illustrate the complete sequence of the safety proof in a transparent way. It shows what steps should be performed, possibly iteratively, to provide a successful safety proof.

This method has the advantage that it links geological boundary conditions with the development of a repository concept, especially the development of an emplacement and sealing concept and of a corresponding demonstration of the barrier integrity, and with an analysis of the expected and alternative repository evolutions. The results achieved during the ANSICHT project provide a fundamental prerequisite for the design of repository components in a suitable clay formation in Germany. The results may contribute to an optimisation of information requirements for site evaluation and requirements for repository safety. They can as well support a target-oriented development of a site exploration programme in clay formations. Organisations responsible for final disposal are provided with a tool that can be used during the site selection procedure for a HLW repository, especially when it comes to point of making safety analyses of different sites and host rocks comparable.

## Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

## Acknowledgements

The authors would like to thank the Federal Ministry for Economic Affairs and Energy (BMWi = Bundesministerium für Wirtschaft und Energie) represented by the Project Management Agency Karlsruhe (Karlsruhe Institute of Technology, KIT) for funding the research work performed in this project.

## References

AkEnd. Auswahlverfahren für endlagerstandorte empfehlungen des AkEnd – arbeitskreis auswahlverfahren endlagerstandorte. Köln: W & S Druck GmbH; 2002 (in German).
ANDRA. Dossier 2005: Argile tome: architecture and management of a geological repository. Technical report. 2005.
Beuth T, Bracke G, Buhmann D, Dresbach C, Keller S, Krone J, Lommerzheim A, Mönig J, Mrugalla S, Rübel A, Wolf J. Szenarienentwicklung: Methodik und anwendung, bericht zum arbeitspaket 8, vorläufige sicherheitsanalyse für den standort gorleben. Technical report GRS-284. Köln: Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH; 2012 (in German).
Biot MA. General theory of three-dimensional consolidation. Journal of Applied Physics 1941;12(2):155–64.

BMU. Safety requirements governing the final disposal of heat-generating radioactive waste. as at 30 September 2010. Bonn. 2010. http://www.bmub.bund.de/fileadmin/bmu-import/files/english/pdf/application/pdf/sicherheitsanforderungen_endlagerung_en_bf.pdf.
BSC. The Development of the total system performance assessment – license application – features, events, and processes. Technical report TDR-WIS-MD-000003 REV 02. Las Vegas, USA: Bechtel SAIC Company; 2005.
DIN EN. Grundlagen der tragwerksplanung. Eurocode 0: DIN EN 1990: Grundlagen der tragwerksplanung (Deutsche Fassung: EN 1990:2002 + A1:2005 + A1: 2005/AC:2010). Berlin: Beth Verlag; 1990 (in German).
Ehlers J, Grube A, Stephan HJ, Wansa S. Chapter 13-Pleistocene glaciations of North Germany – new results. Developments in Quaternary Sciences 2011;15: 149–62.
Ellwanger D, Wielandt-Schuster U, Franz M, Simon T. The quaternary of the southwest German Alpine foreland (Bodensee-Oberschwaben, Baden-Württemberg, Southwest Germany). E&G/Quaternary Science Journal 2011;60(2–3):306–28.
Fiebig M, Ellwanger D, Doppler G. Chapter 14-Pleistocene glaciations of Southern Germany. Developments in Quaternary Sciences 2011;15:163–73.
Herold P. Entwicklung technischer konzepte zur rückholung von endlagerbehältern mit wärmeentwickelnden radioaktiven abfällen und ausgedienten brennelementen aus endlagern in salz- und tongesteinsformationen. Annual report, FuE-Vorhaben ERNESTA. Peine: DBE TECHNOLOGY GmbH; 2016 (in German).
Herold P, Jobmann M, Kuate Simo E. Integritätsnachweis geotechnische Barrieren. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein haw-endlager im tonstein. In: Jobmann M, editor. Systemanalyse für die endlagerstandortmodelle – methode und exemplarische berechnungen zum sicherheitsnachweis. DBE TECHNOLOGY GmbH, BGR, GRS; 2016 (in German).
Hoth P, Wirth H, Reinhold K, Bräuer V, Krull P, Feldrappe H. Endlagerung radioaktiver Abfälle in tiefen geologischen formationen Deutschlands, untersuchung und bewertung von tongesteinsformationen. Berlin/Hannover: BGR; 2007 (in German).
Jahn S, Sönnke J. Endlagerstandortmodell Nord – Teil II: Zusammenstellung von Gesteinseigenschaften für den Langzeitsicherheitsnachweis. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Hannover: BGR; 2013 (in German).
Jahn S, Mrugalla S, Stark L. Endlagerstandortmodell SÜD – Teil II: Zusammenstellung von gesteinseigenschaften für den langzeitsicherheitsnachweis. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Hannover: BGR; 2016 (in German).
Jobmann M, Lommerzheim A. Endlagerkonzept sowie verfüll- und verschlusskonzept für das endlagerstandortmodell SÜD. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report TEC-26-2015-TB. Peine: DBE TECHNOLOGY GmbH; 2015 (in German)
Jobmann M, Meleshyn A. Evaluation of temperature-induced effects on safety-relevant properties of clay host rocks with regard to HLW/SF disposal. Mineralogical Magazine 2015;79(6):1389–95.
Jobmann M, Maßmann J, Meleshyn A, Polster M. Quantifizierung von kriterien für Integritätsnachweise im tonstein. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report TEC-08-2013-AP. DBE TECHNOLOGY GmbH; 2015 (in German).
Jobmann M, Bebiolka A, Jahn S, Lommerzheim A, Maßmann J, Ziefle G, Meleshyn A, Mrugalla S, Reinhold K, Rübel A, Stark L. Sicherheits- und Nachweismethodik für ein Endlager in einer Tongesteinsformation in Deutschland, Synthesebericht. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. DBE TECHNOLOGY GmbH, BGR, GRS; 2016 (in German).
JRC. The Eurocodes: implementation and use. Booklet B1. Joint Research Centre (JRC) and Enterprise and Industry Directorate General (DG ENTR), European Commission; 2008.
Keller S. Eiszeitliche rinnensysteme und ihre bedeutung für die langzeitsicherheit möglicher endlagerstandorte mit hochradioaktiven abfällen in norddeutschland. Hannover: BGR; 2009 (in German).
Kolditz O, Bauer S, Bilke L, Böttcher N, Delfs JO, Fischer T, Görke UJ, Kalbacher T, Kosakowski G, McDermott CI, Park CH, Radu F, Rink K, Shao H, Shao HB, Sun F, Sun YY, Singh AK, Taron J, Walther M, Wang W, Watanabe N, Wu Y, Xie M, Xu W, Zehner B. OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. Environmental Earth Sciences 2012;67(2):589–99.
Lommerzheim A, Jobmann M. Endlagerkonzept sowie verfüll- und verschlusskonzept für das endlagerstandortmodell NORD. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report TEC-14-2015-TB. Peine: DBE TECHNOLOGY GmbH; 2015 (in German).
Lommerzheim A, Jobmann M, Mrugalla S, Rübel A. Strategies for final disposal of HLW in German clay formations. In: Proceedings of 47th annual meeting on nuclear technology; 2016.
Maßmann J. Endlagerstandortmodell SÜD. Teil III: Auswahl von gesteins- und fluideigenschaften für numerische berechnungen im rahmen des langzeitsicherheitsnachweises. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Hannover: BGR; 2016 (in German).
Maßmann J, Ziefle G. Integritätsnachweis geologische barriere. Projekt ANSICHT: Methodik und Anwendungsbezug eines Sicherheits- und Nachweiskonzeptes für ein HAW-Endlager im Tonstein. In: Jobmann M, editor. Systemanalyse für die Endlagerstandortmodelle – Methode und Exemplarische Berechnungen zum Sicherheitsnachweis. DBE TECHNOLOGY GmbH, BGR, GRS; 2017 (in German).
Mrugalla S. Geowissenschaftliche langzeitprognose für norddeutschland – ohne endlagereinfluss. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Hannover: BGR; 2014 (in German).
Müller-Hoeppe N, Ebert S. Übertragung des sicherheitsnachweiskonzeptes für ein endlager im salz auf andere wirtsgesteine. Abschlussbericht. Peine: DBE TECHNOLOGY GmbH; 2009 (in German).
Müller-Hoeppe N, Buhmann D, Czaikowski O, Engelhardt HJ, Herbert HJ, Lerch C, Linkamp M, Wieczored K, Xie M. Integrität geotechnischer barrieren – Teil 1 vorbemessung. Technical report GRS-287. DBE TECHNOLOGY GMbH, GRS; 2012 (in German).
Nagra. Projekt Opalinus clay: the long-term safety of a repository for spent fuel, vitrified high-level waste and long-lived intermediate-level waste sited in the Opalinus clay of the Züricher Weinland. NTB 02–05. Wettingen: Nagra; 2002.
NEA. Updating the NEA international FEP list. Technical Note 1: Identification and review of recent project-specific FEP lists. Technical report NEA/RWM/(2013)7. Paris, France: OECD/NEA; 2012.
Nowak T, Maßmann J. Endlagerstandortmodell NORD. Teil III: Auswahl von gesteins- und fluideigenschaften für numerische modellberechnungen im rahmen des langzeitsicherheitsnachweis. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report B3.1/B50112–B50143/2012-0009. Hannover: BGR; 2013 (in German).
NRC. Yucca mountain review plan. Final report. Technical report NUREG-1804, Revison 2. Washington, DC, USA: U.S. Nuclear Regulatory Commission; 2003.
ONDRAF/NIRAS. Safety assessment and feasibility. Interim Report 2. NIROND 2001-06 E. 2001.
Philip JR, De Vries DA. Moisture movement in porous materials under temperature gradients. Transactions, American Geophysical Union 1957;38(2):222–32.
Pöhler M, Amelung P, Bollingerfehr W, Engelhardt HJ, Filbert W, Tholen M. Referenzkonzept für ein Endlager für radioaktive Abfälle in Tongestein. Projekt ERATO. Final report. Peine: DBE TECHNOLOGY GmbH; 2010 (in German).
Posiva. Safety case for the disposal of spent nuclear fuel at Olkiluoto, features, events and processes. Posiva report 2012–07. Eurajoki, Finland. 2012.
Reiche T. RepoTREND – Das programmpaket zur integrierten langzeitsicherheitsanalyse von endlagersystemen. Technical report GRS-413. Braunschweig: Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH; 2016, ISBN 978-3-944161-95-2 (in German).
Reinhold K, Sönnke J. Geologische referenzprofile in süd- und norddeutschland als grundlage für endlagerstandortmodelle in tongestein. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report. Hannover: BGR; 2012 (in German).
Reinhold K, Jahn S, Kühnlenz T, Ptock L, Sönnke J. Endlagerstandortmodell NORD – Teil I: Beschreibung des geologischen endlagerstandortmodells. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report. Hannover: BGR; 2013 (in German).
Reinhold K, Stark L, Kühnlenz T, Ptock L. Endlagerstandortmodell SÜD – Teil I: Beschreibung des geologischen endlagerstandortmodells. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Technical report. Hannover: BGR; 2016 (in German).
Richards LA. Capillary conduction of liquids through porous mediums. Journal of Applied Physics 1931;1:318–33.
Rübel A. Nachweiskonzept für den radiologischen Nachweis. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. In: Jobmann M, editor. Systemanalyse für die Endlagerstandortmodelle – Methode und exemplarische Berechnungen zum Sicherheitsnachweis. DBE TECHNOLOGY GmbH, BGR, GRS; 2016a (in German).
Rübel A. Modellierungen zum gastransport im grubengebäude. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. In: Jobmann M, editor. Spezifische Prozessanalysen. DBE TECHNOLOGY GmbH, BGR, GRS; 2016b (in German).
Rübel A, Becker DA, Fein E. Radionuclide transport modeling- Performance assessment of repositories in clays. Technical report GRS-228. Braunschweig: Gesellschaft für Anlagen und Reaktorsicherheit (GRS) gGmbH; 2007.
Gas generation and migration. Forge Report D0.09. In: Shaw RP, editor. International symposium and workshop, 5th to 7th February 2013, Luxembourg, Proceedings; 2013.
StandAG. Gesetz zur suche und auswahl eines standortes für ein endlager für wärme entwickelnde radioaktive abfälle (Standortauswahlgesetz – StandAG). vom 23. Juli 2013 (BGBl. I 2013, Nr. 41, S. 2553), zuletzt geändert durch Artikel

2 des Gesetzes vom 26. Juli 2016 (BGBl. I 2016, Nr. 37, S. 1843). 2016 (in German).

Stark L. Geowissenschaftliche langzeitprognose für süddeutschland – ohne endlagereinfluss. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. Hannover: BGR; 2014 (in German).

Stark L, Jahn S, Jobmann M, Lommerzheim A, Meleshyn A, Mrugalla S, Reinhold K, Rübel A, Keller S, Gerardi J. FEP katalog für das endlagerstandortmodell NORD – konzept und aufbau. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. DBE TECHNOLOGY GmbH, GRS, BGR; 2014 (in German).

Stark L, Jahn S, Jobmann M, Lommerzheim A, Meleshyn A, Mrugalla S, Reinhold K, Rübel A. FEP katalog für das endlagerstandortmodell SÜD – konzept und aufbau. Projekt ANSICHT: Methodik und anwendungsbezug eines sicherheits- und nachweiskonzeptes für ein HAW-Endlager im tonstein. DBE TECHNOLOGY GmbH, GRS, BGR; 2016 (in German).

Terzaghi K, Fröhlich O. Theorie der setzung von tonschichten: Eine einführung in die analytische tonmechanik. Wien: Franz Deuticke; 1936 (in German).

**Michael Jobmann** is currently the deputy Head of Research & Development Department in DBE TECHNOLOGY GmbH. After finishing his study at Technical University of Clausthal with a degree as Diplom-Geophysiker in 1986, he participated in geothermal energy exploration as well as the Con-tinental Deep Drilling Project (KTB) in Germany. As project scientist, he gained extensive experience during work at the Grimsel Test Site (GTS) in Switzerland, especially with regard to the flow and transport of contaminated fluids in fracture networks in crystalline rock. From 1994 to 2001, he managed different research projects at the company DBE in Germany where he dealt predominantly with the development of fibre optic monitoring systems. Since 2001, he has been a member of DBE TECHNOLOGY GmbH as project manager and deputy head of the Research & Development Department. His current work focuses on the monitoring of high-level waste repositories and the development of a safety and safety demonstration concept for an HLW repository in clay and crystalline rock in Germany.

Please cite this article in press as: Jobmann M, et al., Safety assessment methodology for a German high-level waste repository in clay formations, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.05.007