A systematic approach to scenario development for long-term safety assessments for a high-level waste (HLW) repository concept in German crystalline rock

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Abstract

The safety assessment of a repository is based on a comprehensive description of the repository system and a prognosis of potential future system evolutions. In Germany, corresponding methodologies have been developed for sedimentary rock formations. Taking into account the safety strategy and specific FEP catalogues, expected and alternative scenarios have been derived systematically and transparently. In the current project, a suitable methodology has been developed for a modified KBS3 concept in crystalline rock. Although the general approach of the former methodology could be transferred to the crystalline concept, some rock-type and safety concept-specific adaptions were necessary. For scenario development, the FEP catalogue provides processes impairing the barrier function, and processes that are linked to radionuclide mobilisation and transport.

For performance assessment in fractured crystalline rock, the properties of the near field of the barriers have to be considered. Hence, the barriers and their surrounding components as well as the affecting processes have been compiled in initial groups. The intensity of these processes can be derived from the interaction with other FEP. For waste canisters, referring to manufacturing defects and their detection rates in industrial production, the occurrence of a small number of defect canisters has been assumed for the expected system evolution.

The description of expected evolutions complies with a bottom-up approach. The basic system framework includes the geological site descriptive model, a geoscientific long-term prognosis and the repository concept as well as specific assumptions for climate and barrier performance. The FEP catalogue provides all components with expected properties and the processes with most likely intensity. To start scenario development, initial groups will be integrated into the system framework as modules.

The proposed systematic approach to scenario development increases transparency of the expected repository system evolution and thus supports communication with stakeholders.

Introduction

Due to a political decision, the site selection process for a high-level waste repository in Germany has been restarted and has to consider different kinds of host rock. To implement the site selection process, the "Site Selection Act" has been decreed (BMU 2017). The Site Selection Act defines exclusion criteria, minimum requirements as well as geoscientific and socioeconomic weighting criteria for site screening. Supplementary preliminary safety assessments will be performed. The site selection procedure is subdivided into 3 steps, which continuously increases the data set for regional screening with the aim to focus from large areas to the selected site at the end.

To implement the site selection procedure, comprehensive knowledge about the properties of the different host rock types, generic host rock-specific safety strategies, disposal concepts and prototype repository designs, as well as safety demonstration methodologies are prerequisites. Therefore, basic research on different host rocks and the development of corresponding safety and safety demonstration methodologies were in the focus of R&D work. Adequate studies for sedimentary rock formations (salt and clay) have been carried out (Mönig et al. 2013, Jobmann et al. 2017, Lommerzheim et al. 2019). The R&D project CHRISTA constitutes the current study analysing the safety and safety demonstration strategy for a HLW repository in German crystalline rock. The main objective of this study is to analyse the transferability and/or the necessity of adaptions of the safety demonstration approach developed for German sedimentary rock to crystalline rock. German regulations (BMU 2020) define requirements for the safety demonstration of repositories.

The present paper focusses on the safety strategy, repository system description (incl. FEP catalogue), and scenario development, which are basic tools for long-term safety assessments.

Current status of scenario development

The current status of the German strategy for long-term safety demonstration has been developed in the course of several R&D projects for sedimentary rocks (Mönig et al. 2013, Jobmann et al. 2017, 2021, Lommerzheim et al. 2019) and is in line with German regulations (BMU 2010, 2020) and international Safety Case Methodology (IAEA 2012, NEA 2012, NEA 2019). The objective was to develop a systematic and logical procedure that connects all relevant aspects of a safety case. FEP catalogue and scenario development are basic issues for the safety case (Kuhlmann et al. 2024). The German approach takes into account the safety strategy, and systematically and transparently derives expected and alternative scenarios for potential future evolutions from the corresponding FEP catalogue (Lommerzheim et al. 2019). Because undisturbed salt and claystone have a very low hydraulic conductivity, BMU (2020) states that these host rocks can provide a “Containment Providing Rock Zone (CRZ)” which is the key barrier for the corresponding safety strategies. Therefore, if long-term integrity of the geological barrier can be demonstrated, safety demonstration focusses on the performance of the geotechnical barriers that seal the underground excavations. In the methodology for scenario development, key barriers are defined as “initial barriers”, processes impairing the barrier function as ”initial FEP“, and supplementary processes that are linked to radionuclide mobilisation and transport as additional starting points for scenario development.

Due to the limited data from crystalline rock in Germany, the CHRISTA project is a generic study. To close the gaps, reference data from other countries and other fields of research (e.g. geothermal energy) have also to be considered for preliminary safety assessments. Different safety strategies and adequate performance criteria for the barriers in crystalline

rock have been discussed, and a modified KBS3 concept has been selected for the CHRISTA project.
The present paper focusses on the basic steps for safety demonstration that consist of the system description (FEP catalogue) and the scenario development.

Legal requirements

As stipulated in German regulations (BMU 2020), the "safety demonstration" has to include the following verifications:

- integrity verifications for the geological barrier;
- integrity verifications for the geotechnical barriers;
- long-term radiological statement;
- verification of subcriticality.

The corresponding proofs for the safety assessment require a comprehensive description of the repository system (incl. FEP catalogue) and its expected and alternative future evolution.

Adaption of methodology for crystalline rock

Referring to the current status of the German methodology for scenario development, the combination of safety strategy and description of the repository system (e.g. by a FEP catalogue) is the basis for scenario development.

Safety strategy for the modified KBS3 concept

The key elements of a safety concept for a HLW repository are isolation from the biosphere and containment of radionuclides close to the disposal area. In this project, the Scandinavian modified KBS3 concept was adapted to the German waste inventory. Isolation will be provided by the depth of the disposal level, and containment will be provided by the properties of the technical and geotechnical barriers and their integrity in the long term. The crystalline rock contributes to the protection of the canisters and the surrounding buffer from harmful external impacts. Furthermore, the host rock reduces the risk of human intrusions. The objectives and safety functions for the key barriers for the post-closure phase of the modified KBS3 concept are as follows (Jobmann et al. 2021):

- The containment function of the disposal canister has to be met for a demonstration period of 1 M years and should neither be impaired by internal nor by external events or processes.
    - ➢ To comply with this safety function, the canisters have to be gas- and liquid-tight, as well as corrosion resistant in the hydrochemical environment of the disposal areas.
- In accordance with the legal requirements, retrievability of the disposal containers must be possible during the operating period, and recovery must be possible for a period of 500 years after repository closure; this will be met by stability and tightness of canisters (adequate design);
- The disposal container will be surrounded by a clay buffer, which has a protective function with regard to mechanical, hydraulic, chemical, and biological impacts:
    - ➢ The buffer reduces the impact of mechanical strains from the geosphere on the canister.
    - ➢ The low hydraulic conductivity minimises the fluid flow in the close surroundings of the canister and reduces corrosion processes.

- The buffer stabilises the hydrochemical environment through a high ion exchange capacity.
- The high density of the buffer material minimises the habitat for microbes.
- The buffer contributes to the retention of radionuclides by its sorption capacity.

- In case of a mobilisation of hazardous substances from the waste, the release of the substances will be retarded and impeded by the following chemical and physical safety functions:
  - Restriction of advective transport by the buffer, further geotechnical barriers, and the backfill in the other mine excavations
  - Restriction of diffusive mass transport: the pore volume of the clay buffer material has low diffusion coefficients for harmful substances.
  - Retention of harmful substances: the clay has a high sorption capacity, and the hydrochemical conditions will be balanced to favourable solubility limits.
- The temperature burden of the clay barriers will be limited to 100°C max. by the following safety functions of the waste packages and the repository design:
  - Limit of surface temperature of the waste packages: adequate loading of the disposal canisters
  - Limit of the temperature in disposal fields: geometry of disposal fields (distances between containers and disposal boreholes) will be defined by thermo-mechanical calculations.
- Limitation of microbial processes in the mine openings by:
  - Sterilisation of the near field of waste containers: surface temperature of waste container up to 100°C
  - Minimisation of habitats: clayish material in buffer / backfill has a low porosity;
  - Minimisation of nutrients: very little organic matters in buffer / backfill;
- Gas generation and gas pressure build-up rate will be restricted by:
  - Limitation of construction materials with a high gas generation potential (e.g. steel, organic matters);
- Criticality will be excluded by safety functions of the disposal packages for spent fuel by:
  - Limitation of radionuclide inventory;
  - Moderation of neutron flux by canister design
- Consequences of inadvertent human intrusion into the repository and the probability of occurrence of human intrusion will be reduced as far as possible by safety functions of repository design, like caution indications and complications of access.

Additionally, design requirements and technical measures have been defined that altogether will ensure compliance with the objectives of the safety concept.
It is a fundamental approach to derive the starting points for scenario development from the key barriers (marked with*) and supporting barriers of the safety strategy (called “initial barriers”):
Disposal containers*, buffer*, borehole seals, fracture zone seals, backfill, shaft/ramp seals, and host rock.

Repository system description

To test the methodology for safety assessment of a HLW repository in crystalline rock, a generic repository system has to be defined. The repository system description includes the geological site descriptive model, the repository concept and the FEP catalogue, which complement each other (Jobmann et al. 2021).

The generic geological model refers to the geological data on THMC properties that were compiled by the Federal Institute for Geosciences and Natural Resources (BGR). Supplementary geological data were taken from well-known international sites, e.g. from Äspö and Onkalo. The fracture network is a key issue to evaluate the hydraulic and mechanical properties of crystalline rock. For modelling, two approaches were used: the discrete fracture network (DFN) approach and equivalent continuum models for upscaling.

As the long-term safety assessment has to cover a period of 1 M years, a geological long-term forecast for Southern Germany has been considered, which was provided by Stark (2014). Important aspects of these prognoses include the consequences of climate change (glaciation), the tectonic development, seismic activity., the stress field in the geosphere, and the hydrogeology.

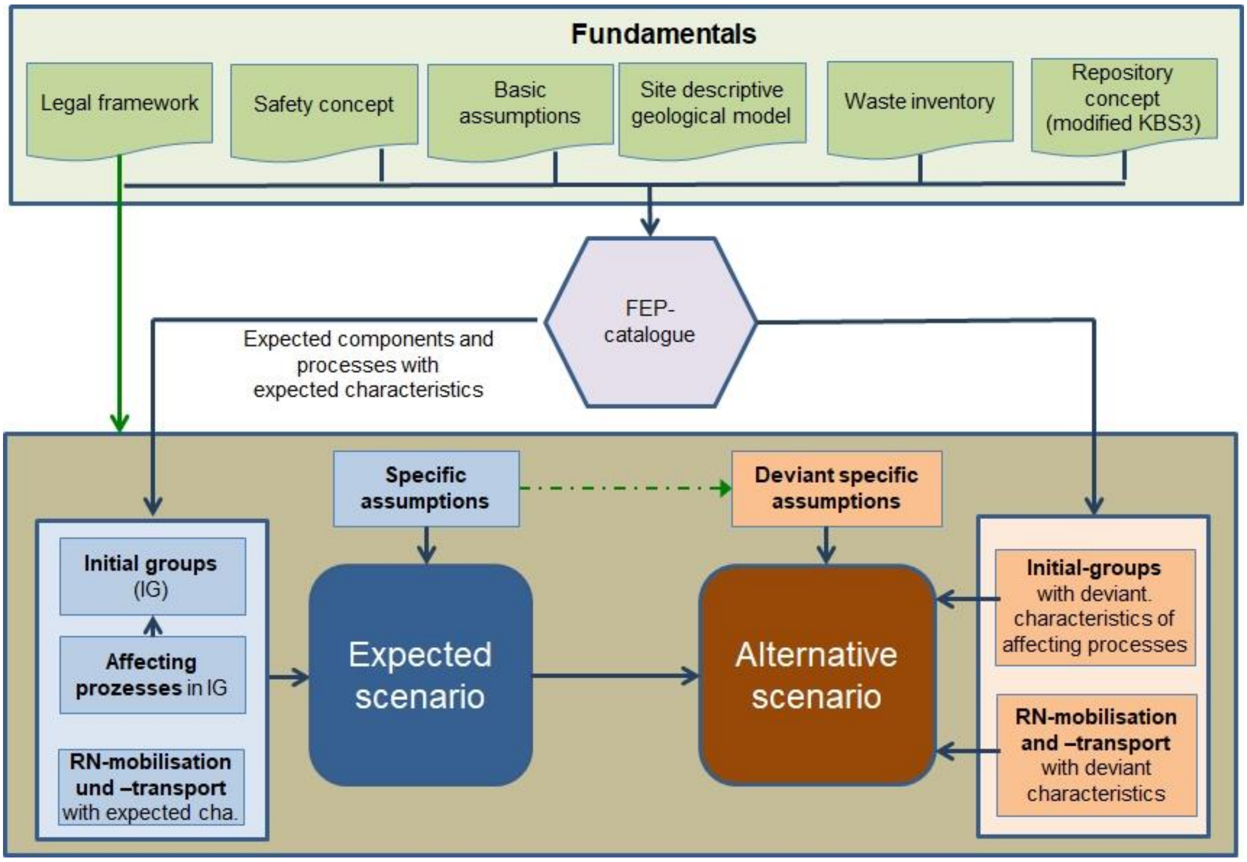
For the disposal of heat-generating radioactive waste, a maximum temperature of 100°C at the canister surface has been defined to avoid a thermal alteration of clay minerals in the buffer. The geometry of the copper canisters of the KBS3 concept has been adapted to the dimensions of German fuel elements. The German radioactive waste inventory requires 10,200 canisters with spent fuel, 1,865 canisters with HLW from reprocessing, 2,345 canisters with ILW from reprocessing / conditioning, and 290 canisters with spent fuel from research reactors. The emplacement level of the repository has been assumed to be at 600 m below surface. Access to the underground facilities will be provided via a shaft (for air intake, as well as transport of staff and mining equipment/materials) and a ramp (for waste package transport and exhaust air). Underground facilities consist of infrastructure rooms, connecting drifts, and disposal areas that are arranged in between larger faults / large water-bearing fractures / dykes with higher hydraulic conductivity. The disposal strategy is based on the Scandinavian concept of short vertical boreholes (KBS3). The loading and the distance between the boreholes consider the 100°C criterion. Different waste types will be disposed in separate disposal areas to avoid undue interaction during the post closure period.

It is international standard to compile the initial state of a repository site and the understanding of factors influencing the future development of the site in a FEP catalogue (Kuhlmann et al. 2024). In the context of a safety assessment, the FEP catalogue is the connecting link between the repository site description and the system analysis. The interrelation between the site-specific conditions and the impact of the disposal of heat generating radioactive waste has to be described. The completeness of the CHRISTA-FEP catalogue was checked against the NEA-IFEP catalogue (NEA 2019). Furthermore, experience from mining as well as top-down and bottom-up approaches for causal chains were helpful to check “completeness”. In addition, the FEP catalogue includes all information necessary for scenario development and performance assessment (Lommerzheim et al. 2019), e.g. probabilities of occurrence of FEP, identification of "initial barriers", and "initial FEP", as well as descriptions of the interactions between FEP. The FEP catalogue increases the transparency and traceability of the information required for the safety assessment and identifies open questions.

Host rock-specific adaption of methodology

The main objective of the CHRISTA project was to analyse whether the methodology for scenario development that has been proposed for sedimentary rock is also applicable to safety demonstrations for crystalline rock. Therefore, a plausibility check was carried out to analyse whether the previous procedure for scenario development is reasonable for a HLW repository in crystalline rock. In this context, the different geological environments and the corresponding safety strategy had to be taken into account. As a result, it was possible to transfer some of the principles of the former methodology to the methodology for crystalline rock, but other aspects required rock-type and safety concept-specific adaptions (figure 1).

Figure 1: Structure of methodology for scenario development.



So, the close link between the safety concept, the comprehensive description of the repository system in the FEP catalogue, and the methodology for scenario development is also valid for the crystalline concept. The structure of the FEP catalogue proposed in Lommerzheim et al. (2019) also complies with the requirements for safety assessment in crystalline rock.

In the case of repository systems in sedimentary rock, the undisturbed host rock has a low hydraulic conductivity, which assures the long-term containment of radionuclides (CRZ). Impairments of the host rock by mine openings have to be sealed by drift, shaft, ramp, or borehole seals in the short-term and by backfill in the long-term. Due to the increased hydraulic conductivity of fractured crystalline rock, the long-term containment of radionuclides has to be assured by adequate waste canisters. The buffer and supplementary barriers in the far field (drift and shaft seals, backfill) should minimise external impacts on the canisters.

In fractured crystalline rock, groundwater flow paths are difficult to predict, as they can potentially occur anywhere. At worst, they bypass the geotechnical barriers. Therefore, the properties of the technical and geological components in the near field of the key barriers are important for the evaluation of barrier performance and of radionuclide transport-related processes. This demands a modified definition of the “initial barriers” by extending them to “initial groups”, including all surrounding components. Looking at the safety concept and the (generic) repository system, four “initial groups” (IG) have been defined for the CHRISTA project. For the first IG, the corresponding components are specified as example:

- HLW disposal borehole: IG includes radioactive waste, canisters for HLW, canisters for spent fuel, buffer, borehole abutment, Excavation Damaged Zone, liquids in mine openings, gases in mine openings, corrosion products from metal corrosion, host rock, fractures and faults in host rock, liquids in host rock, gases in host rock
- LILW disposal borehole
- Fracture seals
- Shaft and ramp seals

During repository system evolution, the “initial groups” will be impacted by a spectrum of thermal, mechanical, hydraulic, chemical, and radiological processes in the near field and from the far field (“initial FEP”). Examples for important thermal FEP are *thermally induced expansion and contraction*, for mechanical FEP *earthquake*, *stress change*, for hydraulic FEP *piping* and *fluid flow,* for chemical FEP *metal corrosion,* and *alteration of bentonite,* and for radiological FEP *radionuclide mobilisation* and *radionuclide transport*. The intensity of these processes can be derived from the interaction with other FEP (causal chains). The corresponding information is included in the FEP catalogue. For the appraisal of the intensity of the processes, the FEP interactions have to be considered for 2 or 3 levels. This step will be documented in a separate report, whose structure is adapted to the “initial groups” and the results are important starting points of scenario description.

Scenario development

The expected scenario comprises a comprehensive description of the repository system, which will be developed by a bottom-up approach. The basic system framework consists of the geological site descriptive model, the geoscientific long-term prognosis and the repository concept as well as specific assumptions for repository system evolution. The specific assumptions address some aspects with high uncertainties that can never be clarified (e.g. climatic development) or can only be clarified at a later stage (e.g. geotechnical / technical barriers will comply with their safety function). The components and processes extracted from the FEP catalogue will have expected characteristics and/or intensities. The “initial groups” characterise the detailed near field of the barriers and the relevant processes in these areas and will be integrated in adequate numbers in this system framework as modules. The near field processes are closely linked to geological and climatic processes in the far field and, on the other hand, repository-induced processes may affect far field processes. Radiological processes are only relevant, if container failures occur in the expected scenario. This point can only be evaluated in a reliable way at a later stage, when the container design has been finally completed, and production procedures as well as corresponding quality assurance measures have been defined. At the moment, it is useful to consider the experience from industrial production, which shows that when large numbers of components have to be produced (more than 15,000 disposal canisters in Germany), manufacturing defects can neither be completely excluded nor completely detected. Therefore, a small number of canisters with undetected defects has currently been assumed for the expected system evolution. In the context of radionuclide mobilisation and transport, fluid flow and groundwater hydrochemistry are key issues.

The development of alternative scenarios will be a top-down approach, referring to less probable properties of components (e.g. failures of barriers) and intensities of processes.

Conclusions

An adequate methodology for scenario development for a modified KBS3-concept in crystalline rock has been developed. This methodology is based on the safety strategy and the initial state of the repository system, as reflected in the geological site descriptive model, the repository concept, and a FEP catalogue, including possible future changes in component properties and processes. Scenario development is based on processes that may affect the function of barriers as well as on processes that are linked to radionuclide mobilisation and transport. The expected scenario takes into account all components with expected properties and all processes and events with likely intensity. As the performance of the barriers is closely linked to the properties of the surrounding components, e.g. the fractured host rock, the near field of the barriers has been combined into “initial groups” to derive the intensity of important processes. The results are – in combination with the system framework – starting points for scenario development. This approach highlights the interdependence of host rock-specific properties and the barrier functions as well as their influence on many key processes of repository system evolution. The proposed systematic and descriptive approach to scenario development will increase transparency and traceability of the expected repository evolution and may thus support the communication between implementer and authorities and/or other stakeholders.

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