



Safety concept, FEP catalogue and scenario development as fundamentals of a long-term safety demonstration for high-level waste repositories in German clay formations

A. LOMMERZHEIM^{1*}, M. JOBMANN¹, A. MELESHYN², S. MRUGALLA³,
A. RÜBEL² & L. STARK³

¹*BGE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany*

²*Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH,
Theodor-Heuss-Straße 4, D-38122 Braunschweig, Germany*

³*Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2,
D-30655 Hannover, Germany*

 A.L., 0000-0002-5524-9378

*Correspondence: Andree.Lommerzheim@bge.de

Abstract: A safety concept and a safety demonstration concept for the disposal of high-level radioactive waste in German clay formations have been developed. The main safety objective is to retain the radionuclides inside a ‘Containment Providing Rock Zone’. Thus, the radionuclide transport should be restrained by adequate safety functions of the geological and geotechnical barriers. The compliance with legal dose constraints has to be demonstrated for probable evolutions and less probable evolutions.

As a basis for system analysis, generic geological reference models, disposal concepts and repository designs have been developed for northern and southern Germany. All data relevant for future system evolution were compiled in two FEP (features, events and processes) catalogues. They provide information on FEP characteristics, their probabilities of occurrence, their interactions and identify ‘initial FEP’ that impair the safety functions of relevant barriers. A probable reference scenario has been deduced systematically from the probable ‘initial FEP’, and from probable processes relevant for radionuclide mobilization and transport. Four different starting points to develop alternative scenarios (i.e. less probable evolutions) were identified.

The scenario development methodology is applicable to different kinds of host rock and therefore may be a basis for the preliminary safety analyses necessary in the future site selection process in Germany.

Due to a political decision, the site-selection process for a high-level waste (HLW) repository in Germany has been restarted and has to consider different kinds of host rock. For implementation of the site-selection process, the ‘Repository Site Selection Act’ has been decreed (Stand AG 2017). The site-selection procedure defined in this Act is a stepwise approach with three steps. During phase 1, potentially suitable regions will be identified by applying criteria for exclusion, minimum requirements and weighting criteria defined by Stand AG on existing data at the geological offices of the federal states. For evaluations of the regions, ‘representative, preliminary safety evaluations’ will be performed. During phase 2, surface investigations in potentially suitable regions will be carried out to identify suitable sites for underground exploration. During this phase, ‘advanced, preliminary safety evaluations’ have to be made. During phase 3, underground exploration will take place. During this phase, ‘comprehensive, preliminary safety evaluations’ have to be made,

including detailed investigations, evaluations and comparisons of sites based on test criteria. For an adequate implementation of 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 is the focus of current research and development (R&D) work.

In the R&D project ANSICHT, a safety concept and a safety demonstration methodology for HLW repositories in German clay formations have been developed on a generic level. One aim of this project was to check whether the methodology recently developed for a HLW repository in rock salt as part of the ‘Preliminary Safety Analysis of the Gorleben Site (VSG)’ can also be used in argillaceous rock. Another objective was to refine and optimize the methodology, taking into account problems that

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have been identified during its application. Then, the applicability of the modified methodology had to be tested with data from two generic German clay sites. The project team consisted of Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, the Federal Institute for Geosciences and Natural Resources (BGR) and DBE TECHNOLOGY GmbH (which became BGE TECHNOLOGY GmbH in March 2018).

The ANSICHT project is a generic study. For the development of the models, various data from Germany and other countries had to be combined, because in Germany there is little mining carried out in clay formations and, thus, corresponding geological, hydrogeological and hydrochemical data are limited. A safety concept, new integrity criteria for the host rock and a suitable repository closure concept for German clay formations have to be developed. To support a comprehensive overview of a repository system in German clay formations, detailed FEP (features, events and processes) catalogues have to be established and the methodology for scenario development has to be tested. Safety concept, FEP catalogues and scenario development are basic tools for long-term safety assessments.

Fundamentals

Safety concept

A safety concept for a deep geological repository describes which circumstances and measures contribute to accomplishing and maintaining the required level of safety. A safety strategy must include a safety concept for the operational and the post-closure period. The following discussion only focuses on the safety concept for the post-closure period.

Requirements for a suitable safety concept have been defined in the regulatory framework: for example, in the Atomic Energy Act, the Radiation Protection Ordinance, Mining Act and, especially, in the Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste (BMU 2010). The primary protection goals mentioned here are 'to protect man and the environment from harmful ionizing radiation' and 'to avoid unreasonable burdens and obligations for future generations'. Three of the safety principles defined by the Safety Requirements are of particular relevance:

- the radioactive and other pollutants in the waste must be concentrated and contained in the containment-providing rock zone (CRZ), and thus kept away from the biosphere as long as possible;
- final disposal must ensure that in the long term, any release of radioactive substances from the final repository only negligibly increases the risks associated with natural radiation exposure;

- the final repository shall be constructed and operated in such a way that no intervention or maintenance work is required during the post-operational phase to ensure the reliable long-term containment of the radioactive waste in the CRZ.

So the key elements for the safety concept are:

- the isolation and
- the containment of the radioactive waste in a deep geological repository.

A basic element of the German safety concept is the containment of the radionuclides in a defined rock zone surrounding the mine openings, called the containment-providing rock zone (CRZ). Thus, isolation will be provided by the depth of the repository, and containment by the properties of the CRZ and its integrity (i.e. retention of the CRZ's containment capabilities) in the long term. For those areas of the CRZ that are penetrated due to the construction of the repository, a suitable technical barrier system must be provided. From the safety principles, design requirements can be derived. These are the basis for specific objectives and resulting strategic measures (embracing design specifications).

The specification of the safety concept depends on the type of host rock and other site-specific characteristics.

The guiding principle of the clay-specific safety concept is the containment of radionuclides by retarding or impeding radionuclide transport (Rübel & Meleshyn 2014).

To comply with this principle, the following objectives and safety functions for the safety concept have been defined:

- The CRZ shall remain intact during the whole demonstration period (1 myr), and its barrier function shall not be impaired by internal or external processes and incidents:
 - protection of the CRZ from external impacts: the overburden and adjoining rock will protect the CRZ by their hydraulic, chemical and mechanical properties;
 - stabilization of the host rock: the supporting pressure of the backfill and the geotechnical barriers in the mine openings will stabilize the host rock.
- When harmful substances have been mobilized from the waste, their release from the CRZ will be retarded and impeded by the following chemical and physical safety functions:
 - restriction of advective mass transport: the geotechnical barriers, the backfill and the host rock have a very low permeability; mine construction will partially disturb the host rock. The resulting potential pathways will be sealed with backfill and geotechnical barriers. The excavation damaged zone (EDZ) will be

- closed by the self-sealing properties of the clay;
- restriction of diffusive mass transport: the pore volume of the host rock and clay construction materials have low diffusion coefficients of harmful substances;
 - retardation of harmful substances: clay in the host rock and construction materials will have a high sorption capacity and the hydro-chemical conditions will define favourable solubility limits.
- The temperature burden of the host rock will be limited to a maximum of 150°C by safety functions of the waste packages and repository design:
 - limit of the surface temperature of the waste packages: adequate loading of the disposal canisters (e.g. decay time, mixture of spent fuel);
 - limit of the temperature in the disposal fields: the geometry of the disposal fields (distances between containers, disposal boreholes and disposal drifts) will be defined based on thermo-mechanical calculations.
 - In accordance with legal requirements, recovery of the disposal containers must be possible for a period of 500 years after repository closure; this will be met by the safety function:
 - stability and tightness of disposal canisters for 500 years (adequate design).
 - Gas generation and gas-pressure build-up rate in the mine excavations will be restricted by the following safety functions of the technical components:
 - limitation of construction materials with a high gas-generation potential (e.g. steel, organic matters).
 - Limitation of microbial processes in the mine openings by safety functions of technical components:
 - sterilization of the near field of waste containers: surface temperature of the waste container up to 150°C;
 - minimization of habitats for microbes: clayish construction and backfill material will have a low porosity;
 - minimization of nutrients for microbes: construction and backfill material will contain very little organic matter.
 - In accordance with legal requirements, criticality will be excluded by safety functions of the waste packages for spent fuel:
 - limitation of radionuclide inventory;
 - moderation of neutron flux by canister design (e.g. internal structure with boron steel sheets, backfilling of containers' void volume with magnetite or with depleted uranium (U_3O_8)).
 - Consequences of unintended 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:
 - caution indications;
 - complication of access.
- Additionally, design requirements and technical measures have been defined that altogether will ensure compliance with the objectives of the safety concept. The following requirements are related to the site-selection procedure (Stand AG 2017):
- construction of the repository will be done in a stable geological region with characteristics that are clearly predictable for the demonstration period (e.g. no active fracture zones, no relevant seismic activity);
 - the disposal fields will be located at a depth that excludes any natural impairment of the CRZ from the surface (e.g. erosion of glacial channels). So, for northern Germany, a depth between 600 and 800 m below sea level has been pursued;
 - the thickness of the host rock has to be 100 m at minimum;
 - due to the low permeability of the undisturbed clay host rock, the groundwater velocity is also very low so that the mass transport of harmful substances by advection will be comparable to that by diffusion.
- For mine construction/operation the following requirements are defined:
- the repository mine is completely surrounded by host rock;
 - construction of disposal fields will be in a well-characterized formation with little lithological variation (e.g. mineralogy, grain size, sedimentary fabric);
 - the void volume to be excavated for the mine will be minimized, and excavation will be done using techniques that disturb the rock as little as possible;
 - filled disposal fields will be backfilled and abandoned (operation in a retreating mode);
 - the clay host rock has favourable properties to meet the containment function: suitable clay rock has a low permeability so that slow diffusion is the dominating process of mass transport and advection is of little relevance. Furthermore, clay minerals have a high sorption capacity for radionuclides, and therefore impede and retard radionuclide transport. Clay plasticity will seal any impairment of the rock due to mechanical impacts. In the host rock surrounding the disposal areas, a CRZ will be defined that will not be affected by any impacts from the surface (e.g. ice ages) or evolutions of geosphere (e.g. fracture zones).

Several of the technical measures have the safety function of sealing the unavoidable perforation of the geological barrier rapidly and effectively. The long-term goal is to restore the host rock's integrity and to avoid evolutions that result in an impairment of the CRZ. In detail, the following technical measures are included:

- Shaft seals, drift seals, borehole seals and buffer:
 - To comply with their safety function, these barriers have a low integral permeability, which minimizes an advective solution flow. The integrity of these barriers has to be demonstrated for at least the transient phase of the thermal, hydraulic and mechanical processes. After approximately 50 000 years, the stable phase has been reached when the temperature, fluid pressure and mechanical stresses are in their original, natural bandwidth. Then, potential flow mechanisms for fluids in the repository come to an end.
- Backfill:
 - The safety functions of the backfill comprise the stabilization of the excavations and the limitation of fluid flow. Therefore the open void volume of the mine will be filled with swellable, compacted backfill with a high sorption capacity. The resaturation of the backfill results in a reduction of porosity and permeability, and the swelling pressure supports the excavation contour and closes the EDZ. The low porosity will limit microbial processes.
- Temperature limit:
 - Jobmann & Meleshyn (2015) analysed the mineralogical, chemical and mechanical impacts of short-term high temperatures on the containment function of the CRZ. The consequences of 'thermal expansion and contraction' will be covered by the integrity criteria 'fluid pressure' and 'dilatancy'. 'Microbial activity' will be limited by sterilization at temperatures above 122°C. Therefore, higher temperatures are favourable to stop microbial corrosion. The investigations have shown that short-term temperatures up to 150°C would not result in any impairment of the safety functions of the buffer or the host rock. Thus, a temperature limit of 150°C at the canister surface has been defined.
- Disposal canisters:
 - The disposal canisters will be designed:
 - to be manageable for 500 years (recovery period of BMU 2010);
 - to keep their integrity for the functional period defined by long-term safety requirements;
 - they will be loaded in such a way that criticality can be excluded.

A penetration of the geological barrier is inevitable during mine construction and will result in its local impairment. In the long term, creep processes promoted by the plastic properties of the clay host rock may lead to the eventual closure of such mine openings, thus restoring the original properties of the geological barrier. But such processing would require time. Therefore, engineered high-performance shaft and drift seals will be built, which will provide the required sealing immediately after construction. To guarantee the long-term sealing of the penetrations, the mine workings will be backfilled with an argillaceous backfill that is stable in the long term. Over time, the properties of the backfill will become similar to the surrounding host rock.

Safety demonstration methodology

The safety demonstration concept has been developed in the course of the R&D projects ISIBEL (Bollingerfehr *et al.* 2017) and VSG (Fischer-Appelt *et al.* 2013) for German salt formations, and was in line with the Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste issued by BMU (2010) and international Safety Case Methodology (NEA 2008, 2012, 2016; IAEA 2012). The objective was to develop a systematic and logical procedure that connects all relevant aspects of a safety case. In the course of the ANSICHT project (Jobmann *et al.* 2016, 2017), it has been analysed whether the safety demonstration methodology developed for salt formations is also applicable to safety demonstrations for clay formations. Therefore, all steps of the proposed safety demonstration procedure have been performed – restricted by the limited data available and partly only by example due to the comprehensive scope of the work. The results demonstrated that the methodology is transferable but that the contents of most of the steps have to be adapted to the specific rock.

The concept of the safety demonstration methodology is summarized in Figure 1. The concept can be roughly separated into the two function fields: 'fundamentals' and 'system analysis'.

The starting point of the 'fundamentals' is the 'safety concept', which defines safety objectives, the requirements for the geology and the repository concept, as well as the safety functions. General conceptual specifications and technical measures are addressed.

The German safety concept is based on a 'containment-providing rock zone' (CRZ) ('Safety Requirements' (BMU 2010); cf. the previous subsection on 'Safety concept' in this paper). To comply with the overall safety objective of 'containment of radionuclides', hydraulic, thermal and mechanical requirements for the CRZ's properties have been defined. They correspond to appropriate safety

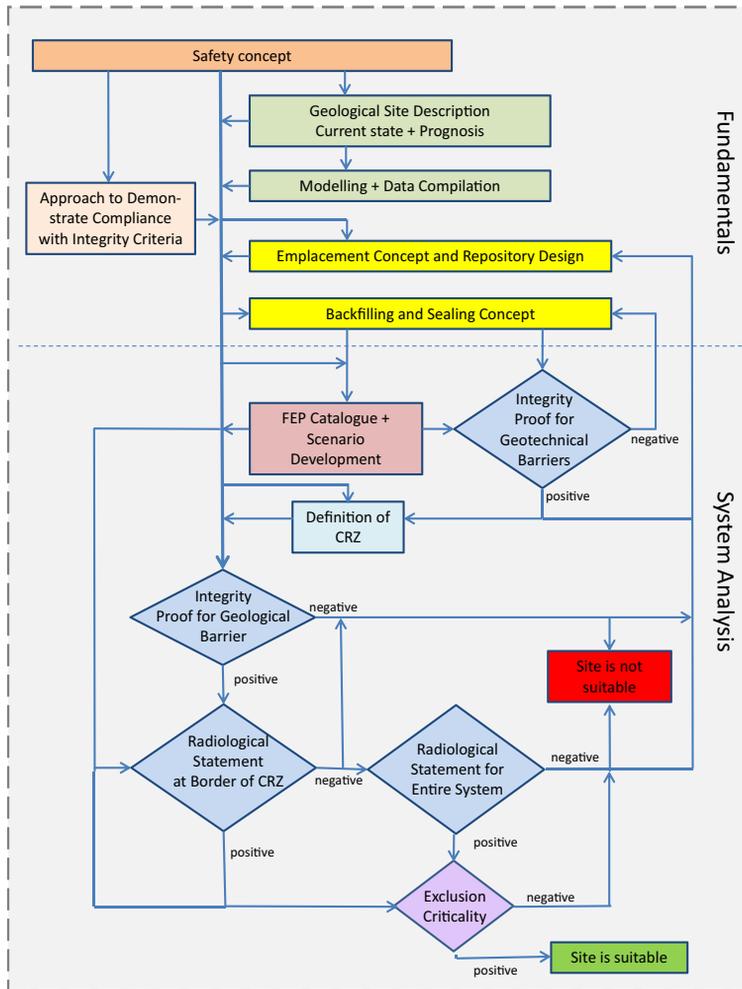


Fig. 1. Safety demonstration methodology (modified after Jobmann *et al.* 2017).

functions of the CRZ. The demonstration of the CRZ's integrity (i.e. retention of the CRZ's containment capabilities) has to be done using suitable integrity criteria. They have been proposed by the Safety Requirements (BMU 2010) but no specifications or numbers for integrity demonstration have been given. Thus, for the integrity demonstration in the context of the R&D work, proposals for the demonstration of compliance with the criteria have been given (quotations from BMU 2010 are in italics):

- The 'advection criterion' (7.2.1, paragraph 3, BMU 2010): *The dispersion of pollutants within the CRZ by advective transport processes is at best comparable with dispersion by diffusive transport processes.* This criterion is 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.
- The 'dilatancy criterion' (7.2.1, paragraph 5, BMU 2010): *The anticipated stresses should not exceed the dilatancy strength of the rock formations in the CRZ outside of the disturbed rock zone.* The criterion is met if the effective stresses do not exceed the damage threshold in the CRZ (excluding the EDZ).
- The 'fluid pressure criterion' (7.2.1, paragraph 6, BMU 2010): *The anticipated fluid pressures must not exceed the fluid pressure capacity of the rock formations in the CRZ in a manner that could lead to the increased ingress of*

groundwater into CRZ. This criterion is met if the fluid pressure is below the compressive strength of the rock and if no tensile stresses occur in the CRZ.

- The ‘temperature criterion’ (7.2.1, paragraph 7, BMU 2010): *The barrier effect of the CRZ must not be inadmissibly influenced by the temperature development.* An analysis of the mineralogical, chemical and mechanical consequences of the short-term thermal impact on the host rock induced by the heat generating waste has shown that this criterion is met if a temperature of 150°C is not exceeded.

The fundamentals of the safety demonstration are the ‘geological site descriptions’ and the development of two generic geological models that are representative of the geology in northern and southern Germany (‘modeling and data compilation’).

‘Emplacement model and repository design’ and ‘Backfilling and sealing concept’ are based on the safety concept, the radioactive inventory, the geology, regulatory requirements and technical/operational constraints (Pöhler 2010; Lommerzheim *et al.* 2016). The safety functions of the different repository system’s components will guarantee compliance with the safety-related requirements. This technical module will compile all information necessary for the following steps of the system analysis.

Starting points for the ‘system analysis’ are the features, events and processes (FEP) (which give a comprehensive description of the repository system) and the derived scenario development (which is a development of probable and less probable future evolutions).

As stipulated in the Safety Requirements (BMU 2010), the ‘system analysis’ has to include the following proofs:

- integrity proof for the geological barrier;
- integrity proof for the geotechnical barriers;
- long-term radiological statement;
- subcriticality proof.

The definition of the ‘containment-providing rock zone’ (CRZ) is a legal requirement (BMU 2010) and therefore essential for the numerical integrity proof of the geological barrier. The dimensions of the CRZ will be derived from the repository site model.

The integrity proofs for the geological and geotechnical barriers, as well as the long-term radiological statement, are based on numerical calculations at different scales, while the results are analysed using integrity/radiological criteria (Jobmann *et al.* 2017). The model calculations need comprehensive data that cover all components and processes of the repository system, as well as the identification of probable and less probable developments that reflect the future evolution of the repository system. This information

is offered by the FEP catalogue and the corresponding scenario development.

In the long-term radiological statement, compliance with dose constraints for probable and less probable evolutions defined in the Safety Requirements has to be demonstrated. If reliable statements can be made for the reference period of 1 myr regarding the integrity of the CRZ, a radiological long-term radiological statement for the border of the CRZ can be performed. This statement does not need modelling of the dispersion of substances in the overburden and adjoining rock. This procedure is permissible if the radioactive substances released from the CRZ led to a maximum of 0.1 mSv/year for probable evolutions and a maximum of 1 mSv/year for less probable evolutions (BMU 2010). This ensures that only very low overall amounts of radioactive substances can be released into the biosphere.

If the repository system does not comply with this requirement and an optimization of the emplacement and sealing concept is not reasonable or possible under existing conditions, a long-term radiological statement for the entire system can be performed.

The exclusion of criticality will be demonstrated by numerical calculations for a conservative, stylized scenario and was not specially addressed in the R&D project ANSICHT.

Geological situation and future evolution. The geology defines the properties of the host rock and very important boundary conditions for the future development of the repository site. As a basis for geological reference models, results from the clay study of the Federal Institute for Geosciences and Natural Resources (Hoth *et al.* 2007) were taken. In this study, the existing data of German clay formations were evaluated in order to identify regions that may be suitable as repository sites. The criteria for rock evaluation include hydraulic conductivity, depth, extent, thickness, dip of the formation, frequency of fractures and the existence of resources, and are compatible with the criteria defined in Stand AG (2017) for repository site selection. As a result, several regions in northern and southern Germany have been identified, and the description shows that the boundary conditions are significantly different in these regions. Part of the North German Basin and the Molasse Basin have been selected as references for defining two 3D generic site models (Fig. 2): For the model north, Lower Cretaceous clays (Hauterivian + Barremian, *c.* 550 m thickness) have been selected as the potential host rock; and for the model south, the Jurassic Opalinus Clay (*c.* 110 m thickness) has been chosen as the potential host rock (Reinhold & Söhnke 2012). Reference data for the host rocks have been taken from German exploration drillings, geophysics and mines (e.g. the

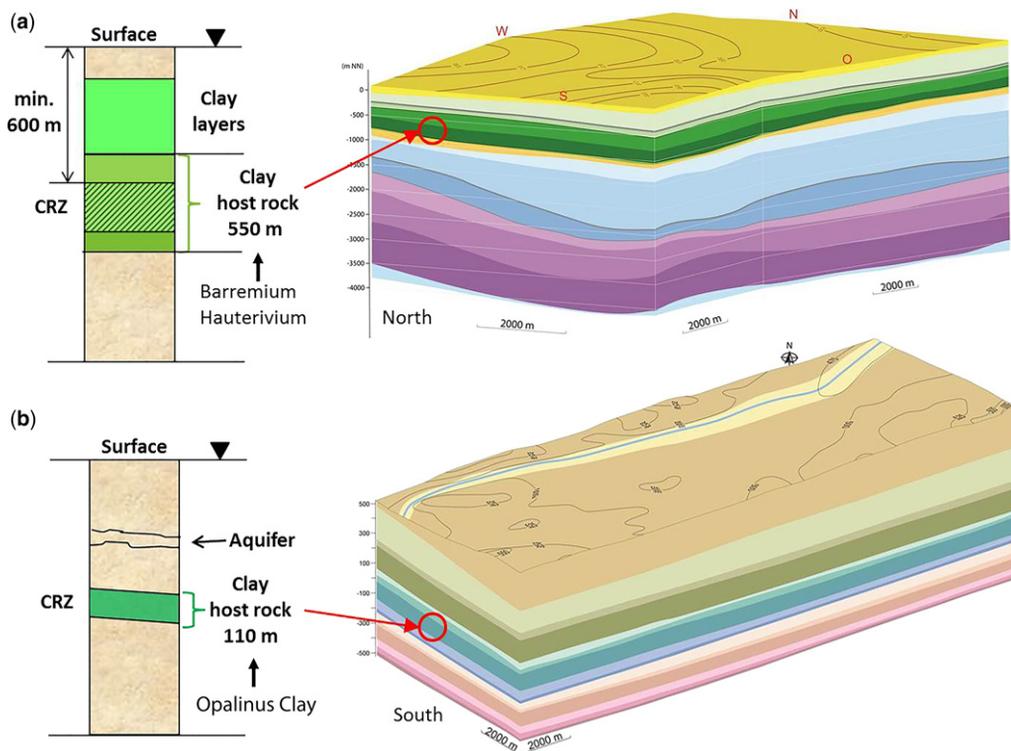


Fig. 2. Geological models for northern (a) and southern Germany (b).

Konrad mine), as well as from Swiss and French underground research laboratories. As the long-term safety assessment has to cover a period of 1 myr, a geological long-term forecast has been carried out for both areas (Mrugalla 2014; Stark 2014). Important aspects of these prognoses include the consequences of climate change (glaciation), the tectonic development and the hydrogeology.

Repository concept

The repository concept includes an implementation of requirements from repository operation, and from the safety concepts for the operation and the post-closure phases taking into account the waste inventory and the site-specific geological boundary conditions (especially geology). The technical components perform significant safety functions with regard to long-term safety. The space requirements for vertical borehole disposal (compact 3D waste arrangement) and drift disposal (plane waste arrangement) are significantly different. Therefore, a vertical borehole disposal concept is provided for the thick Lower Cretaceous clays (Fig. 3) and a drift disposal concept (Fig. 4) for the thinner Opalinus Clay (Lommerzhim *et al.* 2016).

The emplacement levels of both repositories will be completely surrounded by the host-rock formation, and arranged at a depth of between 600 and 800 m to avoid any adverse impact from the surface (e.g. during ice ages). The emplacement concepts are adapted to the thickness, the characteristics and the extent of the host rock. To reduce disturbance and to re-establish the properties of the host rock, the volumes of the excavations and the periods they are kept open will be minimized. Operations will be carried out in retreating mode; that is, when an emplacement field has been completely filled with waste packages, it will be backfilled immediately with swellable material, sealed and abandoned to stabilize the host rock. After the emplacement operations have been concluded, the shafts, drifts and boreholes will be sealed. The heating of the host rock by the disposal of heat-generating waste will be limited to temperatures below 150°C to avoid thermally-induced impairments of clay barriers and host rock (Jobmann *et al.* 2017).

Each repository will comprise two shafts and one emplacement level with an infrastructure area, and the areas of drifts for mining work, waste transport, ventilation and emplacement. The general layout is based on former designs developed by

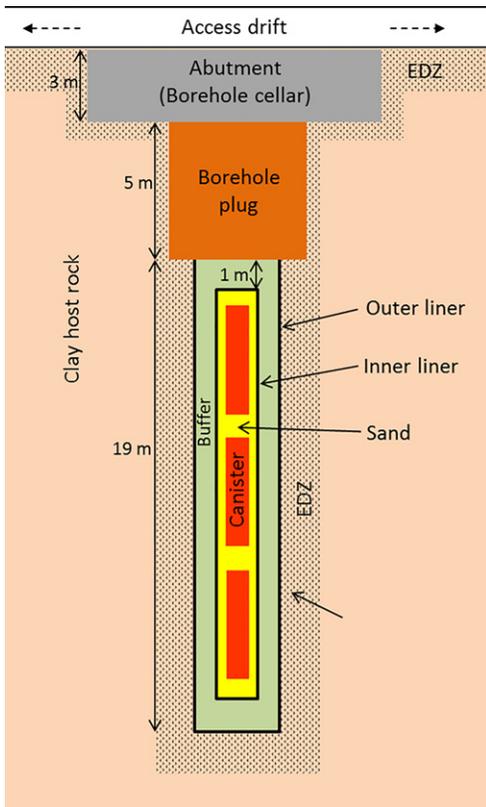


Fig. 3. Schematic drawing of the borehole disposal concept.

Pöhler (2010), which considered radiation protection (controlled) areas and supervised 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 thermo-mechanical calculations and will be arranged in a modular way. The vertical

boreholes for the concept north have a depth of 27 m, and will be furnished with two liners and filled with three disposal canisters. The latter will be surrounded by a bentonite buffer. The boreholes are closed by a borehole seal (Fig. 3). Buffer and borehole seal will limit the liquid flow in the near field, buffer hydrochemistry and retard radionuclides. The disposal drifts for the concept south have a length of 400 m and will be filled with POLLUX® casks at a spacing of 23 m. The casks will be surrounded by a buffer (see the safety functions above) (Fig. 4). In canister design and technical measures (e.g. borehole liners), both disposal strategies consider that retrievability has to be ensured during the operating period and that recovery has to be ensured for a period of 500 years after repository closure (Herold & Jobmann 2017).

The closure concepts for both repository concepts consist of shaft seals, drift seals (in emplacement areas and infrastructure areas), seals for the exploration boreholes, seals for the disposal boreholes, buffers and a clayey backfill for all other parts of the mine workings. The safety functions of all these barriers include the limitation of fluid flow, the retention of radionuclides and the stabilization of the host rock. All barriers are built of concrete abutments (in shafts, also of gravel) and sealing elements, which consist of compacted bentonite, sometimes combined with asphalt. The functional time of the sealing constructions will correspond to the transient phase of the thermo-hydraulic-mechanical (THM) processes at minimum (c. 50 000 years). During that time, the backfill will be compacted and saturated, and will then have a sufficiently low permeability. The backfill will ensure the sealing of the mine openings until the end of the safety demonstration period (1 myr).

FEP catalogue

It is an international standard to document the initial state of a repository site and the understanding of

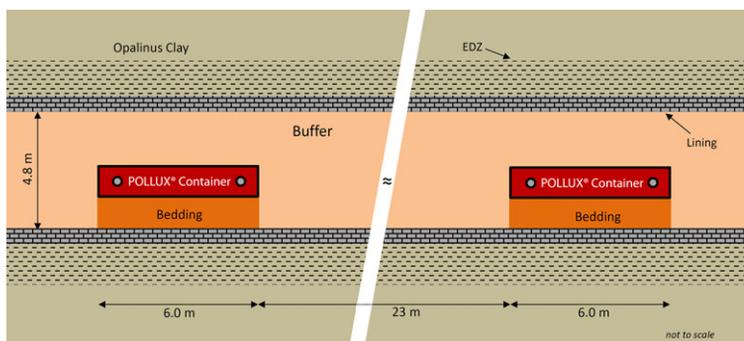


Fig. 4. Schematic drawing of the drift disposal concept.

factors influencing the future development of the site by a compilation of features, events and processes (=FEP). In the context of a safety assessment, the FEP catalogue is highly relevant as it is the connecting link between the fundamentals (site description, geoscientific long-term prognosis and radioactive waste inventory), the repository concept and the system analysis. In addition to the compilation of the most relevant basics, the FEP catalogue reflects the interrelationship between the site-specific conditions and the modifications resulting from the disposal of radioactive waste.

In international projects, the objectives, structures, and contents of a FEP catalogue may be slightly different depending on the safety demonstration methodology. Because of its relevance for long-term safety assessments of repositories, the Nuclear Energy Agency (NEA) has implemented a FEP database, which compiles the international experience of repository projects with different waste inventories and different host rocks (NEA 2014). This FEP catalogue can be used as a starting point for developing a new site-specific FEP catalogue and to check its completeness.

The German R&D project ISIBEL dealt with the development of a safety concept and a safety demonstration methodology for German salt formations. In this context, a first FEP catalogue for salt domes was developed using the NEA database and experience from salt mining, as well as top-down and bottom-up approaches. This FEP catalogue was completed and refined in the course of the 'Preliminary Safety Analysis Gorleben (VSG)' (Wolf *et al.* 2012). To transfer the experience of the salt projects to the generic clay study ANSICHT, several adaptations were necessary with regard to the different safety concept, host rock and repository concept. Furthermore, experience from the VSG project shows that improvements of the FEP catalogue are also necessary with regard to structure and contents. The current status of the safety demonstration methodology is also the basis for preparing relevant documents for the licensing procedure for the closure of the Morsleben repository.

A unique feature of the German FEP catalogue is the objective to use the FEP catalogue as a resource to develop scenarios systematically, stringently and in a transparent manner. As a consequence, several methodological requirements have to be reflected in the structure and contents of the FEP catalogue. Our understanding of the main components of a FEP catalogue is as follows:

- *Features* are interpreted as components of the repository system, including all of its relevant properties.
- *Events* have been defined as short-term incidents and changes in other FEP catalogues (e.g. NRC 2003; Posiva 2012). We do not differentiate

between events and processes as the separation is often weak and ambiguous, and transitions occur: for example, an earthquake can be seen as a special development of the broader process stress change due to mechanical energy transfer modes between solid, liquid and gaseous components. Events composed of chains of events or processes (e.g. failure of a shaft seal) are seen as a kind of small scenario and therefore belong to the scenario development.

- *Processes* are defined as transformations acting within the disposal system that change the state of components (e.g. stress changes, metal corrosion).

Objectives

The German FEP catalogue is a compilation of all information relevant to scenario development and performance assessment modeling. Based on the safety concept, the site characterization, the geoscientific long-term prognosis, the specification of the waste inventory and the repository concept, the FEP catalogue gives a compilation of all features that characterize the initial state of the repository system after repository closure. Furthermore, processes that may influence the future evolution of the site have been identified. So the relationships between site characteristics and evolutions, on the one hand, and environmental conditions and processes that are changed by waste disposal, on the other hand, have been considered. Thus, the FEP catalogue will be a starting point for the design and technical demonstrations of geotechnical barriers (Müller-Hoeppel 2014) and all subsequent steps of system analysis (Jobmann *et al.* 2017).

An important objective of the FEP catalogue is that scenarios can be derived stringently, systematically and transparently from the FEP catalogue. Therefore, there is a close interaction between the methodological approach for scenario development and the structure and contents of the FEP catalogue. So, the FEP catalogue includes assessments of probabilities of occurrence of FEP, identifies important components of the safety concept as 'initial barriers', identifies processes that affect the safety functions of the initial barriers as 'initial FEP' and describes the interactions between FEP.

Other important objectives of the FEP catalogue are to increase transparency and traceability of the information necessary for the safety assessment and to identify open questions.

Structure and contents

To give a useful compilation of all relevant data for site-specific safety assessments, the FEP catalogue includes the following information:

- Definition/short description;

- Reference to the NEA–FEP group;
- Conditional probability of occurrence (i.e. probability of whether the prerequisites for occurrence are given); groups: probable, less probable, and improbable; justification of probability classification will be recorded;
- General information and examples;
- Site-specific characteristics;
- Properties (for components), characteristics (for processes: quantitatively or qualitatively);
- Direct impact on the safety function of initial barriers (only processes); justification will be documented;
- Direct interaction with other FEP (affecting FEP/affected FEP): documents the interaction between component and process by modification of a component's property or change of intensity/mode of the process, the justification of an existence or non-existence of direct interaction will be recorded for transparency reasons;
- Effects on repository subsystems (only for processes): near field, remaining mine openings, host rock, overburden;
- Temporal limitations (e.g. thermal phase of radioactive waste, functional periods of geotechnical barriers, climate changes (ice age));
- References.

To optimize the application of the comprehensive information of the FEP catalogue, all data have been entered into a database.

Development of a FEP catalogue

The structure and contents of the FEP catalogue has been continuously refined based on the application of the methodology in different projects (Stark *et al.* 2015a, b) (Fig. 5). A prominent goal was to structure the FEP catalogue effectively and unambiguously, and to document the information relevant for scenario development as transparently as possible. Several measures are:

- Definitions of FEP must be unambiguous and not overlapping with others.
- A component FEP always covers an entire item (e.g. shaft seal) and not only parts of it (e.g. sealing material: NEA 2012). It should not include a part or the whole of a component that is already included in the FEP catalogue. This is different from the interpretation of FEP in other projects, where a disposal component is used as a wrap for multiple FEP referring to physical properties of a component (drift seal v. porosity and permeability of drift seal) (e.g. Posiva 2012).

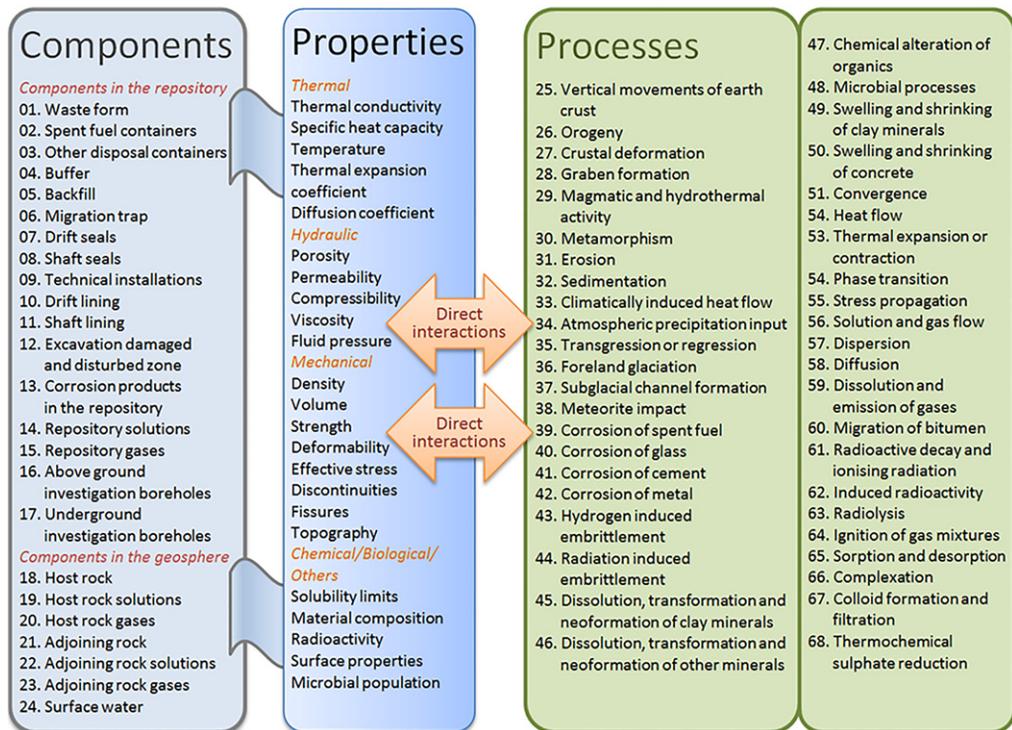


Fig. 5. Example of the structure of a FEP catalogue.

- To optimize the characterization of components and to ensure a comparable level of description, specific properties of a component have to be assigned from a predefined property list, which is an integral part of the FEP catalogue. This property list has been compiled based on expert judgement, and includes 23 mechanical, thermal, hydraulic, chemical, and microbial properties like ‘temperature’, ‘porosity’, ‘fluid pressure’ and ‘effective stress’. These properties can be changed by affecting processes.
- The choice of level of detail for components depends on the scale at which performance assessment modelling for the disposal system can reasonably proceed.
- The total number of components should describe the entire repository system.
- Processes should also be specified to a reasonable level: for example, corrosion of concrete, dissolution, transformation and neof ormation of clay minerals, microbial processes, etc. Aggregating process FEP like ‘alteration of drift seal’ should be avoided.
- With regard to ‘interaction between FEP’, three rules have been defined:
 - An interaction between two components may only occur via processes.
 - An interaction between two processes may only occur by mediation of a component.
 - 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.
- As mentioned above, we define FEP as clearly defined components or processes and not as combinations of FEP. Nevertheless, directly affecting, optional FEP are indicated in the FEP description. Therefore, FEP that reflect incident chains resulting from several succeeding processes are seen as scenarios (e.g. failure of shaft seal) and are not included in the FEP catalogue. These scenarios will be systematically derived during scenario development.

To identify all relevant future evolutions of the repository system, ‘completeness’ is a very important issue of FEP catalogues. To come close to this objective, the first step is site description, including the results of geoscientific long-term prognoses. For a generic study like ANSICHT, all data available from German clay formations and clay sites abroad with a similar geology, as well as experience from clay mining (e.g. at the Konrad repository), have to be compiled.

A plausibility check will identify all FEP that, in principle, may have an impact on the geological evolution of the site or on the repository system (bottom-up approach). Another approach is to analyse the consequences of potential properties of a

component (e.g. integrity of a geotechnical barrier) that may influence the fluid flow in the host rock and the repository mine, as well as the mobilization of radionuclides (top-down approach). Furthermore, a plausibility check of sequences and interdependencies of the FEP may identify missing FEP. In order to check whether any relevant aspect has been overlooked, the consolidated FEP list will be checked against the generic NEA I-FEP list (NEA 2014). All FEP have to be analysed with regard to their relevance at the considered site (FEP screening).

Because of significant differences in the geologies and repository concepts, separate FEP catalogues have been developed for the two generic model regions. Many FEP are similar but have different site-specific characteristics and relevance. Furthermore, the differences in the geological boundary conditions and repository concepts have to be considered.

Scenario development

The fundamentals of scenario development were comprehensively described in Beuth *et al.* (2012). Therefore, only a short summary will be given here. Special focus is set on the modifications resulting from the improvement of the methodology of FEP characterization.

Fundamentals

The site and the repository system will undergo a specific evolution, which will be controlled both by climatic and geological processes at the site and processes induced by the repository construction and by the emplacement of heat-generating waste. Although the various influencing factors are widely understood, this real evolution cannot be predicted unequivocally in all detail.

Developing and investigating several scenarios is an internationally recognized and accepted means to address this uncertainty (NEA 2016). In accordance with the Safety Requirements (BMU 2010), different kinds of scenarios have to be considered as a basis for the safety assessment of a repository system (Beuth *et al.* 2012; Lommerzheim *et al.* 2016). Probable, less probable and improbable scenarios reflect the variations of future site evolutions (Fig. 6):

- ‘Probable scenarios’ refer to normal evolution forecasted for this site, and evolutions normally observed at comparable locations or similar geological situations.
- ‘Less probable scenarios’ refer to evolutions that may occur for the site under unfavourable geological or climatic assumptions and that have rarely occurred in comparable locations or comparable

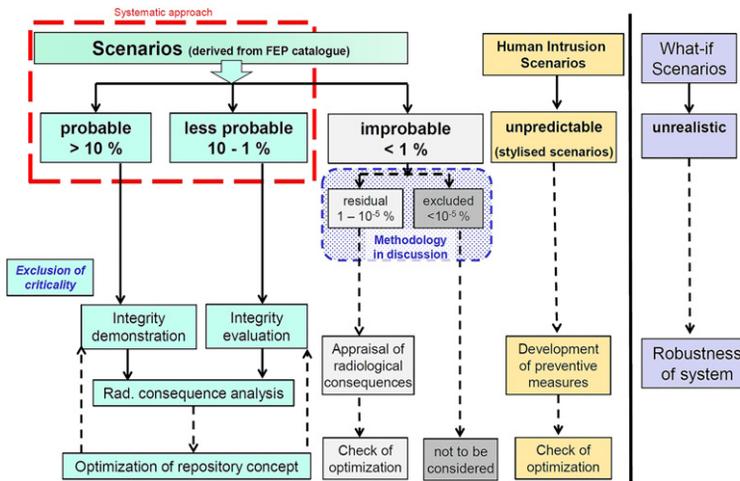


Fig. 6. Classification of scenarios and safety demonstration methodology.

geological situations. Probable and less probable scenarios will be systematically derived from the FEP catalogue.

- ‘Improbable scenarios’ include evolutions with a residual probability of occurrence of below 1%, and these have to be analysed and evaluated (Fig. 6). A methodology to handle these scenarios is currently under discussion. It is consensus that it is reasonable to consider only scenarios that have at least a residual probability of occurrence.
- Unrealistic scenarios must be excluded. ‘Human intrusion scenarios’ are unpredictable and will be handled by stylized scenarios (Fig. 6). ‘What-if scenarios’ are unrealistic evolutions that are used to test the robustness of the system.

Conceptions concerning the future evolution of a repository system are prerequisites for numerical long-term safety assessments. Therefore, the scenario development methodology aims at systematically deriving one reference scenario and a number of alternative scenarios that are to comprehensively represent the reasonable range of repository system evolutions (Beuth *et al.* 2012; Lommerzheim *et al.* 2015). The scenarios are characterized by FEP that will influence the future evolution of the final repository system at the reference site and their associated characteristics. The scenario development methodology is shown in Figure 6.

In the scenarios, possible future evolutions of the repository system during the safety demonstration period are described comprehensively. The methodology applied relies on fundamentals (i.e. regulatory framework, the safety concept, basic assumptions, the geological data, the waste data and the repository concept) and integrates all data relevant to scenario development into the FEP catalogue.

There are two key issues that rely directly on the guiding principles of the safety concept to start scenario development:

- ‘Initial barriers’ are important components of the safety concept and are characterized by the safety functions ‘restriction of advective and diffusive mass transport’, as well as ‘retardation of radionuclides’. They have defined properties just after repository closure and will be modified in different time frames.
- ‘Initial FEP’ are probable process FEP that could impair the safety functions of the initial barriers. They provide the first starting point for scenario development.
- In addition, all possible system evolutions that involve a release of radionuclides from the waste form need to be considered. Those FEP that are related to the mobilization of radionuclides and their transport are the second starting points for scenario development.

Methodological upgrades

The clay-specific adaptations of the safety concept, as well as the modifications of FEP definitions and their interactions, need adaptations in scenario development methodology. So, in contrast to salt formations, in clay rock, a release of radionuclides may occur everywhere in the repository system. Therefore, it is necessary to broaden the focus from single barriers to all relevant components of the repository system for scenario development. The first approach is to handle this aspect in the discussion of radionuclide transport. Another, not yet tested, approach would be to substitute ‘initial barriers’ by ‘initial groups’ that characterize all components relevant

for specific locations. This would result in a comprehensive, broader description of repository system development.

The new rules for FEP interaction also result in a modified definition of the term ‘initial FEP’ (see earlier). In the VSG methodology, the initial FEP include processes as well as properties of components (e.g. fractures and faults of the host rock, fluid pressure of liquids and gas) (Beuth *et al.* 2012). Following the new approach, a component can only be impaired by a process and not directly by another component. Therefore, all initial FEP are processes now. As a consequence, the number of initial FEP (and the number of resulting alternative scenarios) is reduced. Nevertheless, an analysis has shown that there is no deficiency compared with VSG because those items that are no more addressed as initial FEP are now discussed in the context of other starting points for scenario development.

The new, systematic and stringent approach for FEP description (component–process–causal chains) results in longer, but clearer, causal chains to address important aspects of system development. To facilitate the generation of adequate dependence trees, a tool with stop criteria has been developed.

Reference scenario

A reference scenario does not include one specific evolution but describes as broadly as possible the spectrum of probable future evolutions of a repository system.

The ‘initial barriers’ considered in clay formations include the host rock, the shaft and drift seals, the plugs of exploration drillings, the buffer, the

backfill, and the disposal canisters, plus the borehole seals and the inner liners of the disposal boreholes.

The following FEP that may directly affect the safety functions of the initial barriers (=initial FEP) have been identified: earthquakes, stress change, thermal expansion or contraction, convergence, gas-frack, metal corrosion, corrosion of concrete, hydrogen-induced embrittlement, dissolution, transformation and neof ormation of clay minerals, dissolution, transformation and neof ormation of other minerals, microbial processes, swelling and shrinking of clay minerals, swelling and shrinking of concrete, and migration of bitumen.

The starting points for developing reference scenarios are (Fig. 7):

- Specific assumptions: provide a means to deal in a transparent and traceable way with particular uncertainties, some of which may be minimized in the future while others may never be reduced at all. They especially address three aspects with high uncertainty and assume for the reference scenario:
 - Geology: the available geological data are representative and there are no undetected geological characteristics. Has to be verified in the future with proceeding exploration.
 - Safety function of technical/geotechnical barriers: all barriers work as designed. The functionality of engineered barriers has to be verified by an integrity proof.
 - Future climatic evolution: because of the persisting uncertainties in this issue, all reasonable climatic evolutions have to be considered as ‘probable’. The evolution with highest

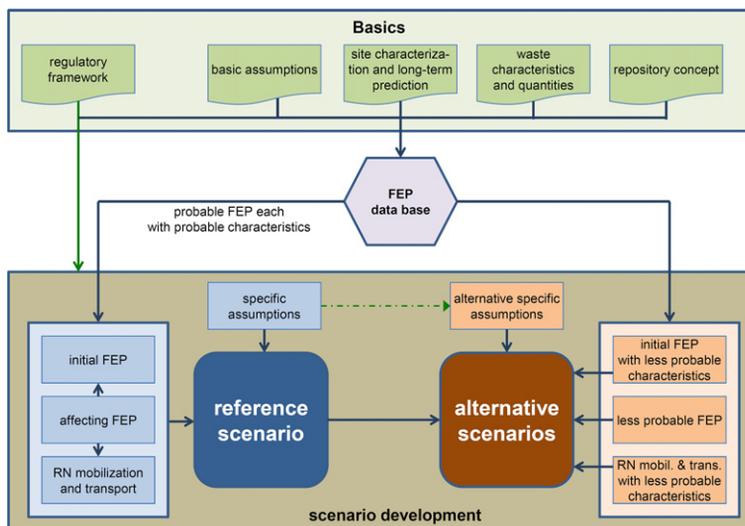


Fig. 7. Scenario development methodology (modified after Mönig *et al.* 2013).

plausibility will be attributed to the reference scenario. Other probable climate evolutions will be analysed as probable alternative scenarios.

- Probable initial FEP with their probable characteristics: if appropriate information is available in the FEP catalogue, the probable or representative characteristics of those initial FEP have been taken for scenario description. Otherwise, the characteristics of the initial FEP have to be derived from their interaction with other FEP (causal chains) in combination with orientating process modelling.
- Probable FEP characterizing the mobilization and transport of radionuclides with probable characteristics: the characteristics will be derived as described above.

Because the reference scenario results from the interaction between probable FEP, it will be probable as well.

The relevant process FEP may have different characteristics at different times and at different locations in the repository system. Therefore, it is useful to subdivide the description of the reference scenario into subsystems such as near field, remaining mine excavations, host rock and overburden to optimize the clarity and traceability of the description, and to consider the interrelationships between the subsystems and possible chronological limits of the initial FEP.

Alternative scenarios

Alternative scenarios are evolutions that differ in exactly one aspect from the reference scenario. Alternative scenarios are developed from the following starting points (Fig. 7):

- Alternatives concerning the specific assumptions: this approach may yield fewer probable scenarios and probable scenarios – not covered by the reference scenario. Possible alternative scenarios for the three key issues of specific assumptions are:
 - undetected fracture zones or undetected fluid reservoirs;
 - early failure of shaft seal (drift seal, borehole seal, etc.);
 - modifications of the future climate evolutions: for example, changed characteristics of glacial periods (thickness of glaciers, depth of permafrost, dimensions of glacial channels, modified duration of glacial cycles).
- Less probable characteristics of the initial FEP: for the 15 initial FEP (see earlier), less probable characteristics have to be defined, and the consequences on the repository system analysis have to be evaluated. If a significant impact was to be

expected and the consequences are not yet covered by any other alternative scenario, then a new alternative scenario will be proposed. So, for the process FEP ‘metal corrosion’, a corrosion rate twice as high as for normal evolution would be a less probable characteristic. Metal corrosion is a key issue for gas generation and therefore not only relevant with regard to the function of the disposal canisters. Therefore, the consequences of a high corrosion rate are not covered by the ‘early failure of a disposal canister’ and an additional alternative scenario is necessary.

- Less probable characteristics of the process FEP mobilization and transport of radionuclides: for the procedure to identify less probable characteristics of these processes see above. For example, for the less probable characteristics of radionuclide transport, flow processes and the hydraulic properties of the materials in the repository system and the host rock have to be considered. So, for the less probable radionuclide transport by diffusion, less probable diffusion coefficients for the materials and the host rock have to be evaluated. An adequate alternative scenario has to be defined.
- Less probable FEP: in the FEP catalogue two technical FEP (‘Piping in sealing elements’ and ‘Flow paths in exploration drillings’) have been classified as having a low probability due to the comprehensive quality assurance measures for the preparation of construction materials and the performance of construction work. ‘Gas fracks in the host rock’ are less probable because of the limited gas generation by reduction of materials with a high gas-generation potential. For the three FEP with low probability, alternative scenarios have been defined.

It is possible that similar alternative evolutions result from the different starting points. In this case, various evolutions may be abstracted into one representative alternative scenario that covers the characteristics of the various evolutions.

Over the course of the R&D project ANSICHT, an alternative scenario for each starting point was derived and discussed to verify the applicability of the methodology.

Conclusions

In the course of the R&D project ANSICHT, fundamental investigations have been made for developing a safety concept and a safety demonstration methodology. With regard to the safety demonstration methodology, the study relies on corresponding research for German salt formations carried out in the Preliminary Safety Analysis of the Gorleben Site (VSG). It has been demonstrated that this

methodology can, in principle, also be applied to clay formations. Some adaptations of the FEP catalogue and the scenario development methodology are necessary because of the significant host-rock-specific differences in the safety concept, the geology, the repository design and the integrity criteria of the geological barrier. A safety demonstration methodology applicable to different host rocks will be an important means for the comparison of the safety levels of different sites (Stand AG 2017).

The guiding principle of the safety concept for German clay formations is the safe containment of radionuclides by retarding radionuclide transport. This strategy is based on the 'containment-providing rock zone' (CRZ) that surrounds the repository. The CRZ together with the geotechnical barriers will provide the safety function 'limitation of advective and diffusive mass transport'. Furthermore, the backfilling and sealing of the mine openings will contribute to the safety function 'restoration of the low permeability of the host rock'. To comply with guiding principles, several objectives and safety functions for the geological and geotechnical barriers are defined, including protection and stabilization of the CRZ, restriction of advective and diffusive mass transport, retardation of harmful substances, temperature limit, minimization of gas generation and microbial processes, subcriticality, etc. In addition, design requirements and technical measures have been derived.

As fundamentals to test the further steps of the system analysis, two geological reference models for northern and southern Germany, as well as suitable disposal concepts and repository designs, have been developed.

FEP catalogues for high-level waste (HLW) repository systems in two reference regions in German clay formations have been developed. The clay FEP catalogues were adapted to clay-specific issues and design concepts where necessary. Furthermore, the structures and contents of the FEP catalogues, as well as the procedures for FEP descriptions and interactions, have been significantly improved. Important modifications included the application of stringent, non-overlapping FEP definitions and systematized component descriptions based on property lists, as well as rules for FEP interactions. Information necessary for scenario development was also included in the FEP descriptions.

The methodology for scenario development has been successfully applied to the clay formations. In compliance with the legal requirements, a reference scenario and exemplary alternative scenarios were derived. The reference scenario is based on specific assumptions, initial FEP (=probable FEP with probable characteristics that may impair the safety functions of barriers) and probable FEP, with probable characteristics describing radionuclide mobilization

and transport. It embraces a set of probable evolutions of the repository system that is as large as possible. Alternative scenarios are evolutions that differ in exactly one aspect from the reference scenario. They are based on alternatives for specific assumptions, less probable characteristics of initial FEP, and FEP for radionuclide migration and transport, as well as FEP with low probabilities. Since the methodological approach systematically covers all aspects, it is concluded that the scenarios in their entirety cover the uncertainty regarding the future evolution of the repository system. Each scenario is described in detail by FEP, and their characteristics and interactions.

Further broadening of the methodology and their application is under discussion:

- Thus, the enlargement of information included in the FEP catalogue by the systematic integration of all characteristics of the components and their impact by different processes would also allow the development of scenarios to investigate specific aspects in system evolution.
- Furthermore, in contrast to salt formations, in clay host rock, a release of radionuclides may occur everywhere in the repository system. Therefore, a modification of the starting points for scenario development may be reasonable: to switch the focus from single barriers to FEP groups characterizing all components relevant for specific locations. An adequate methodology is still under discussion and not yet tested.

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