BGE TECHNOLOGY GmbH

FEP-Catalogue and Scenario Development for a Generic HLW Repository in a Salt Dome

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Technical Report

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Abbreviations

ANVS	Authority for Nuclear Safety and Radiation Protection
BE	Brennelement (German), in English “Spent Fuel Element”
CRZ	Containment-Providing Rock Zone
CSD-C	Conteneur Standard de Déchets – Compactés (French), in English „Standard Waste Packages – Compacted”
COVRA	Centrale Organisatie Voor Radioactief Afval (Dutch), in English “Central Organisation for Radioactive Waste”
EBS	Engineered Barrier System
EDZ	Excavation-Damaged Zone
ETDA	Ethylendiamintetra acetic acid
FEP	Features, Events and Processes
DWP	Disposal Waste Package
HLW	High–Level Waste
IAEA	International Atomic Energy Agency
IFEP	international FEP
ISIBEL	Revision and Appraisal of the Instruments for the Safety Assessment of Final Repositories for HLW
LILW	Low- and Intermediate–Level Waste
NEA	Nuclear Energy Agency (OECD)
NTA	Nitrilotri acetic acid
TE(NORM)	Waste from ores – and other raw materials – generated in processing industries sometimes have a high natural radioactivity concentrations: (TE)NORM includes radioactive waste originating from the uranium enrichment facility of URENCO.
RESUS	Grundlagenentwicklung für repräsentative vorläufige Sicherheitsuntersuchungen und sicherheitsgerichtete Abwägung von Teilgebieten mit besonders günstigen geologischen Voraussetzungen für die sichere Endlagerung wärmeentwickelnder radioaktiver Abfälle (German), Acronym of a German R&D project, in English "Development of the basis for representative preliminary safety studies and safety-oriented consideration of subareas with particularly favourable geological conditions for the safe disposal of heat-generating radioactive waste“
R&D	Research and Development
THMC	Thermo-hydro-mechanic-chemical
VSG	Preliminary Safety Analysis of the Gorleben Site

1 Introduction

Today, the Netherlands follow the strategy of long-term interim storage of radioactive waste and an eventual disposal in a repository. COVRA N.V. (hereafter COVRA) considers a multi-national repository and two national repository concepts as options for radioactive waste management as part of the Dutch policy The two national repository concepts include the disposal of the radioactive waste in poorly indurated clay and the disposal in rock salt, either in bedded salt or in a salt dome. The present waste inventory includes non-heat-generating and heat-generating waste (HLW, LILW, (TE)NORM). Today's preference is to dispose of all categories of waste in a single repository (Ministry of Infrastructure and the Environment, 2016). Currently, the waste is stored in a long-term surface storage facility. It is expected that a repository will be operational around 2130 as stated by (Ministry of Infrastructure and the Environment, 2016). Today's work of COVRA focusses on generic investigations considering potential host rock types, the development of safety and repository concepts (incl. container and barrier concepts) and corresponding generic safety assessments. FEP and scenarios are fundamentals for any numerical modelling and safety evaluation.

The Netherlands have not yet selected any potentially suitable site for hosting a repository. But even a generic safety assessment needs specific boundary conditions and specific characteristics of important processes. Therefore, a plausible generic site model has to be defined, incl. a specific geosphere and biosphere, a repository model and plausible processes reflecting the interaction between geosphere and the repository in the long-term. To close data gaps in the site model, data from the German salt projects have been taken in the present study.

COVRA commissioned BGE TECHNOLOGY GmbH with a study to develop a generic FEP catalogue and a resulting scenario development for the generic site model incl. the radioactive waste inventory and the repository concept mentioned above. The overall objectives of the project are to:

- Develop a FEP list (documented in an Excel file) comprising:
  - FEP No. and name and corresponding NEA-FEP No. (NEA 2019)
  - short FEP definition/description
  - relevance of FEP to performance and safety
  - interaction with other FEP (affecting / affected FEP)
- Describe and apply a methodology for developing base and alternative evolution scenarios as well as inadvertent human intrusion scenarios

2 Fundamentals

2.1 Regulatory requirements

The Tweede Kamer (1992) has specified a reversibility in principle of the waste disposal process in the deep underground. As a result, retrieval of the waste must be possible at least during the operating phase of the disposal facility. Based on NEA (2011), it is assumed that *"Retrievability is the ability in principle to recover waste or entire waste packages once they have been emplaced in a repository. Retrievability implies making provisions in order to allow retrieval should it be required."* The actual process of removing the waste packages is called retrieval. However, it has not yet been decided how long retrievability must be possible after the end of disposal operation or which technical requirements must be fulfilled in regard to retrievability/retrieval (Ministry of Infrastructure and the Environment, 2016). Thus, for this study, a detailed technical concept how to retrieve or how to ease retrievability is not considered. The current disposal concept considers the optional retrieval of waste packages.

2.2 Safety und containment strategy

The Dutch safety concept relies on a multi-barrier system, which consists of a geologic (natural) barrier in combination with an engineered barrier system (EBS). This concept is very close to the German safety concept defined in Mönig et al. (2013).

The main barrier for the long-term safety are salt formations accumulated in salt domes and bedded salt. In heterogeneous salt formations (anhydrite, carbonate, clay and different types of salt), thick homogeneous halite layers are most important for the barrier function.

The engineered barrier system consists of shaft seals, ramp seal, drift seals, borehole seals, and the backfill. All engineered barriers (hereafter called geotechnical barriers) must be designed to be compatible with the properties of the surrounding rock and the hydrochemistry of impacting brines. Because the hydrochemical evolution can only be predicted up to the next glacial period, the performance assessment will only consider a functional lifetime of the engineered barriers of 50,000 years (Mönig et al. 2013, Müller-Hoeppe et al. 2012a). The barriers will influence the development of the repository system for a longer period, but the properties of the barriers are difficult to predict at later stages.

Initially, backfill (crushed salt) will have a high porosity and permeability. But after completion of compaction (which is influenced by the geological properties (creep rate), the geometry of the excavations, and the properties of the backfill (dry, wet)), the backfill will provide long-term sealing of the underground excavations. There are still some uncertainties with regard to long-term compaction and remaining residual porosity, but it is expected, that finally compacted crushed salt will have hydraulic properties similar to those of undisturbed salt rock. Furthermore, backfill has the same mineralogical composition as the surrounding rock formations, and therefore will be long-time stable. Following the model of Popp et al. (2012), the final level of residual porosity of the backfill will be 1 ± 1 %. But there are uncertainties with regard to possible hydraulic connections between the pores and the resulting mobility of the fluids. Assuming the boundary conditions of the simplified model (Popp et al. 2012), compaction will be completed after approx. 1,000 years. But many THMC processes during system development will influence the backfill compaction, e.g. convergence, fluid pressure change and flow processes, thermal volume changes, dissolution and precipitation of salt minerals. Many uncertainties are linked with those processes and complicate the compaction prognosis. Therefore a broad overlap between the minimum functional lifetime of 50,000 years for the geotechnical barriers and the expected completion of backfill compaction has been defined to cover the uncertainties.

Waste containers and the waste matrices are additional technical barriers of the EBS. The waste containers will be most relevant for the operating phase and must cover the potential period of retrieval (which is not clearly defined). The waste matrices will influence the radionuclide mobilisation during all phases of repository system evolution.

2.3 Geosphere

In Germany and in the Netherlands, similar salt formations have been deposited several times during geological evolution. The salt formations of the Zechstein group (Permian) have the largest thickness and can be found at depths that make them potentially suitable for a repository. If subsided and buried in greater depths, salt formations with a high content of rock salt have often been converted by halokinesis to salt domes because of their low density and the high plasticity in combination with tectonics. An overview of cross sections through salt diapirs can be found in Kockel (2000). During halokinesis, the salt formations have been plastically deformed while the brittle carbonate and anhydrite layers have been fractured and enclosed as discrete blocks in salt. The mineralogical and geochemical characteristics and the resulting thermo-hydro-mechanical properties of these salt formations are comparable in both countries. The Dutch Zechstein salt formations are subdivided into 5 main cycles, of which the second cycle, called Staßfurt formation, includes the thickest layers of halite deposits (> 600 m, e.g., Van Adrichem Boogaert & Burgers 1982). Geluk (1995) describes the sedimentary characteristics and the structure of the Staßfurt formations in the Netherlands. Due to the favourable rock properties and the suitable structural conditions, the Staßfurt formation has been selected as a potential host-rock in Germany and will also be taken as a reference in the present study. But, of course, other Zechstein formations may also include thick halite formations and in this case, they are also potential host rocks.

Because no location has been selected in the Netherlands, COVRA has developed a generic model of a salt dome based on data from the Netherlands (Figure 2.1). In this model, the center of the salt consist of thick Stassfurt rock salt. Towards the flanks of the salt dome, different younger salt formations, e.g., potash salt, main anhydrite, and other sedimentary units of the Leine sequence occur. The assumed permeabilities vary from $<10^{-22}$ m² in the rock salt, to $<10^{-20}$ m² in clay and anhydrite. The geothermal temperature is 38°C at a depth of 1,000 m.

Due to *subrosion* at the salt table, the top of the generic salt dome is covered by a caprock (thickness 55 m to 80 m), which is overlain by the Chalk Group, the Lower and Upper North Sea Group (Paleogene, Neogene and Quaternary). The Upper North Sea group includes several aquifers with fresh water near surface and increasing salinity towards the top of the salt dome. The overburden formations on top of the salt dome have a thickness of 340 m.
In the adjacent rim basins, thick Germanic Triassic Group, Altena Group (early to middle Jurassic), Niedersachsen Group (Upper Jurassic to early Cretaceous), Rijnland-Group (early

Cretaceous), Chalk Group Upper Cretaceous to early Paleogene), and North Sea Group (Paleogene and Neogene) have been sedimented. The Triassic formations include sandstones (Buntsandstein) and karstified limestones with a medium permeability of 10^{-10} m² and groundwater with a salinity of 300 g/l.

The surface above the generic salt dome model is at 30 m above sea level. The base of the model is 2,700 m below sea level. Overall, the salt dome provides enough space to host a repository. The lower disposal level for HLW will be located at around 850 m below sea level, the upper disposal level for LILW and (TE)NORM at 750 m below sea level. The disposal galleries will be placed in the central rock salt layers. In addition to the main component halite (NaCl), the sulphates anhydrite ($CaSO_4$) and polyhalite ($K_2Ca_2Mg[SO_4]_4{\cdot}2H_2O$) can occur as secondary components (Biehl et al., 2014; Engelhardt et al., 2000).

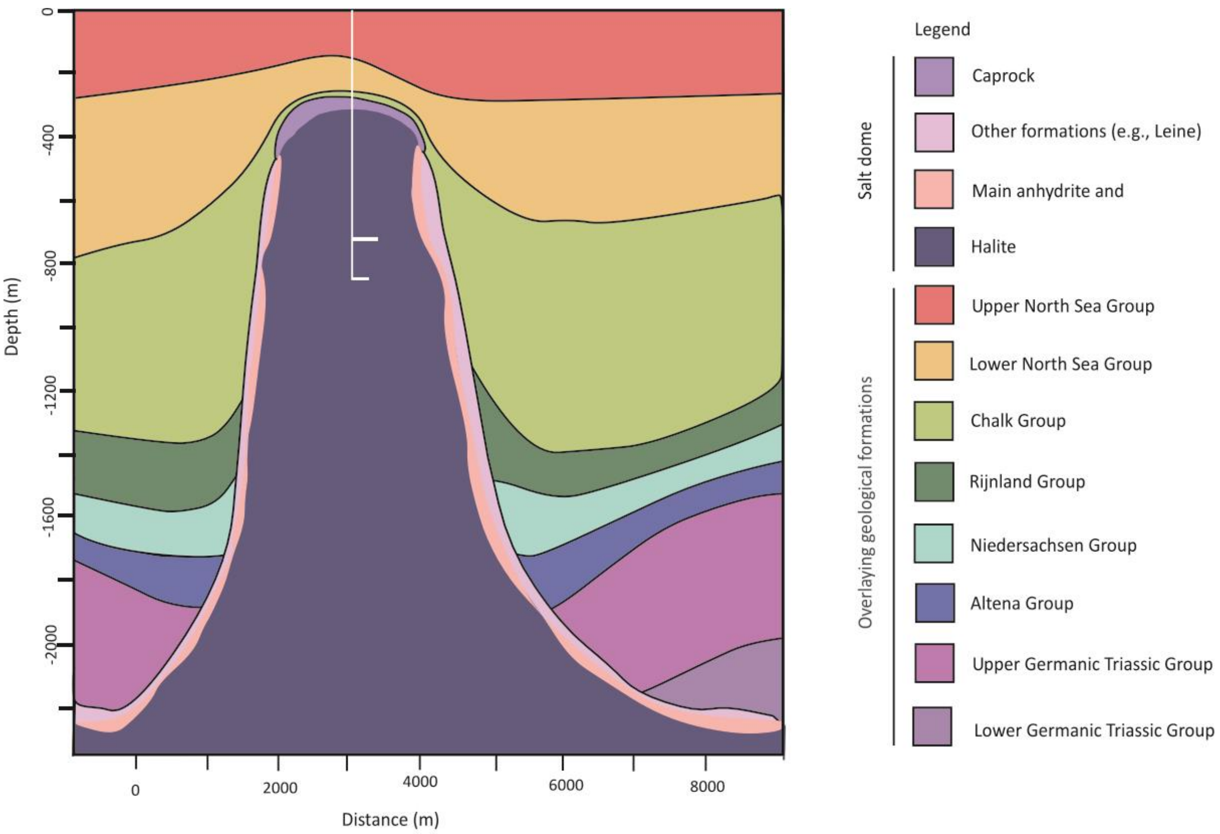

Figure 2.1: Simple generic model of a salt dome (information from Bartol 2023)

2.4 Waste inventory

A compilation of the Dutch radioactive waste inventory is given in COVRA (2020). The waste includes low- and intermediate-level radioactive waste (LILW), (TE)NORM-waste, and HLW.

The LILW arises from the operation and decommissioning of nuclear facilities and from radioactive materials in medicine, industry, and research. It includes contaminated plastic, metals, glass, tissues, and cloths. They are packaged in approx. 100,000 steel drums with volumes of 200 l, and magnetite or concrete containers with volumes of volumes of 1,000 l and 826 KONRAD Type II containers (Figure 2.2).

Some waste from ore processing or other raw materials (incl. depleted uranium) contains high concentrations of natural radionuclides. This waste will be stored in 12,600 KONRAD Type II containers (Figure 2.2).

The HLW is subdivided into heat-generating waste (HLW from reprocessing, spent nuclear fuels) and non-heat-generating waste (CSD-C from reprocessing, spent fuel from research reactors and spent uranium targets from molybdenum production (Figure 2.2)). The primary steel containers from reprocessing as well as the spent fuel elements have to be repackaged into 286 steel disposal overpacks (design concept see Wunderlich et al. 2023) with a minimum functional lifetime of 1,000 years to ensure that full containment is provided until the backfill has become essentially impermeable.

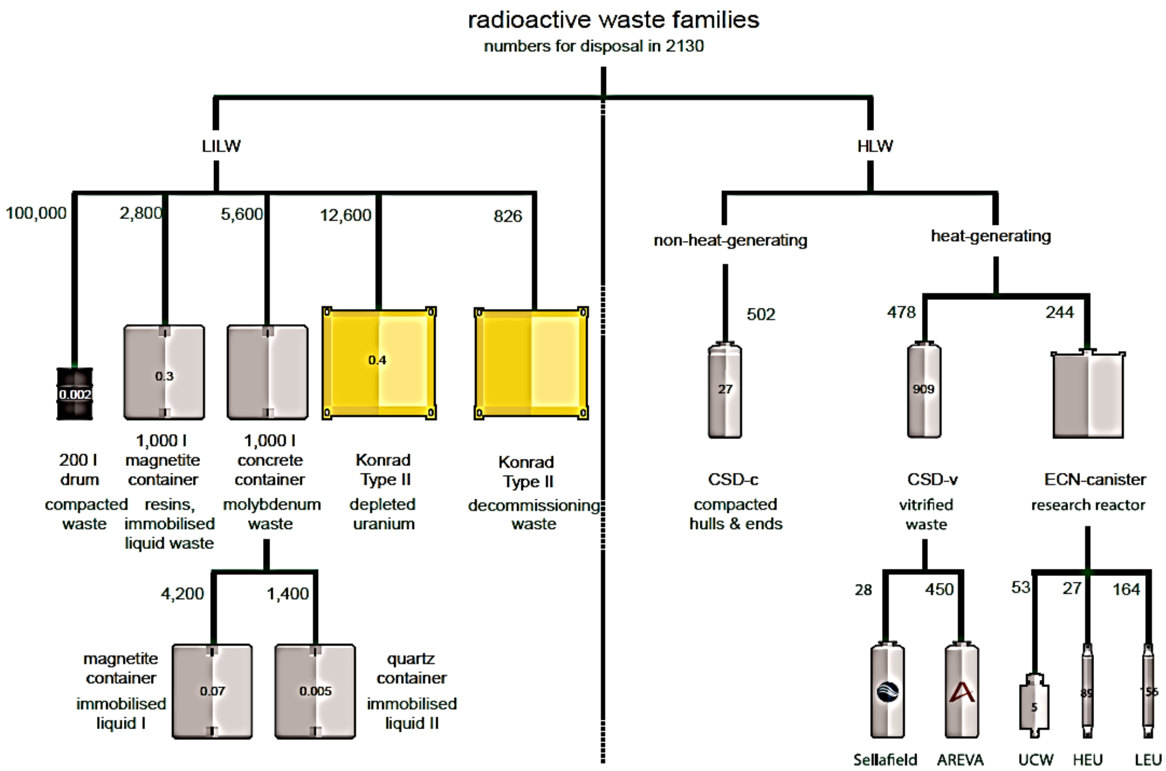

Figure 2.2: Dutch radioactive waste inventory (COVRA 2020).

2.5 Repository concept

This study is based on the generic Dutch repository concept for rock salt in a salt dome. The underground facility consists of two separate disposal levels. The lower disposal level, at a depth of approximately 850 m, is for disposal of HLW. In the upper disposal level, at a depth of approximately 750 m, LILW and (TE)NORM waste will be emplaced. The two levels are connected by 3 shafts (1 large waste hoisting shaft (exhaust air), 2 smaller mining and air intake shafts) and a ramp. At the end of the operating period, the shafts have to be sealed by large, redundant, and divers shaft seals. The corresponding barrier layout and the construction materials have to be adapted to the geology of the surrounding salt formation, the caprock, and the overburden formation (cf. Bollingerfehr et al. 2012, 2013).

The underground facilities will consist of two levels in order use of the vertical extent of the salt dome to its optimum capacity and to separate the different types of waste and thus avoid/minimise chemical interactions. At the end of the operating period, the connecting ramp will be sealed by a ramp seal. Near the shaft landings, an infrastructure area is provided at the upper level. At the lower level, a service tunnel is planned close to the access via the ramp.

The first draft concept for the upper LILW/(TE)NORM-level (-750 mNN) provides transport, disposal, and ventilation tunnels. The cross sections for the disposal chambers and the transport tunnels will be 10.2 m x 6.0 m and 10.2 m x 4.0 m respectively, and for the service and ventilation tunnels 5.6 m x 4.0 m (Figure 2.3). After completion of waste disposal, the disposal chambers will be backfilled (if needed) and sealed by drift seals at the ends. The transport and ventilation tunnels will also be backfilled with crushed salt, while the infrastructure rooms and salt bunker will be backfilled with gravel, which will be used as a fluid reservoir. Because of the humidity and the waste inventory, significant gas generation might occur in the LILW/(TE)NORM disposal area.

The draft layout of the lower HLW disposal area (-850 mNN) is shown in Figure 2.4. From a central transport gallery, the emplacement galleries will branch off to both sides. The transfer from the surface to underground will be performed through the waste hoisting shaft, which is next to the infrastructure area. Underground, the waste packages will be transported by trucks through the transport tunnel to the emplacement tunnels and then emplaced by appropriate waste handling equipment. The emplacement galleries for the HLW are expected to have an effective length of 100 m, a height of 4 m, and a width of 5 m. The cross section is characterised by slightly rounded edges. The ventilation galleries have the same dimensions but differ in length. The transport gallery has an increased width of 10 m and the same height (4 m). All emplacement galleries are connected to a ventilation gallery opposite to the transport gallery. The exhaust air from the disposal areas will be released via ventilation galleries and the waste transport and exhaust air shaft.

To facilitate waste package retrieval, the HLW containers will be disposed in short vertical boreholes arranged in the emplacement galleries (Fig. 2.5). The boreholes will stabilise the lower part of the waste packages and prevent tilting of the containers. After positioning of a waste disposal overpack, the surrounding void volume in the disposal tunnel will be backfilled with dry crushed salt. When emplacement and backfilling in a disposal tunnel has been finished, drift seals will be constructed of Mg-oxychloride concrete at both ends of the tunnel.

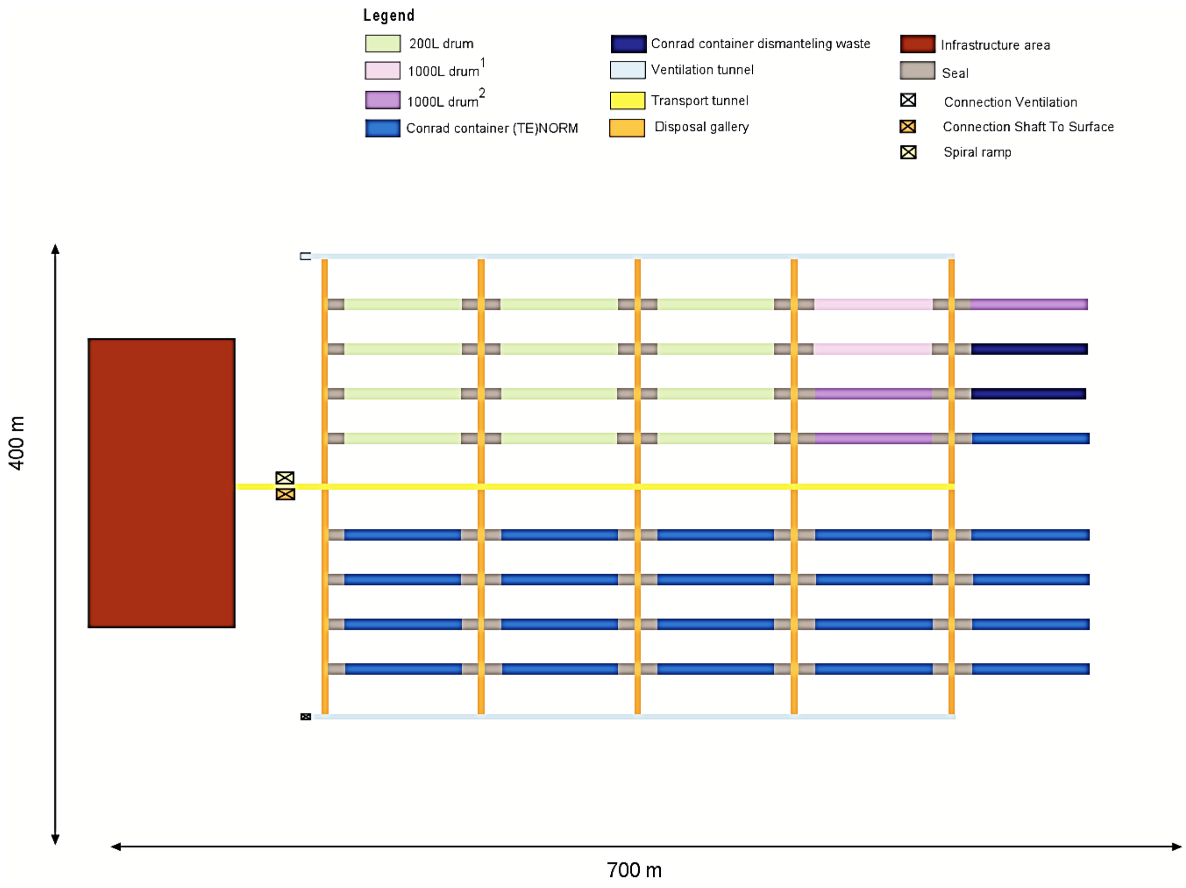

Figure 2.3: Draft layout of the LILW/(TE) NORM disposal level (-750 mNN) of the generic Dutch repository concept. Disposal chambers for small drums are green, for large 1000-l-containers violett, and for KONRAD containers dark blue. Central transport tunnel is yellow, access tunnels for disposal chambers are orange and marginal ventilation tunnels are marked light blue.

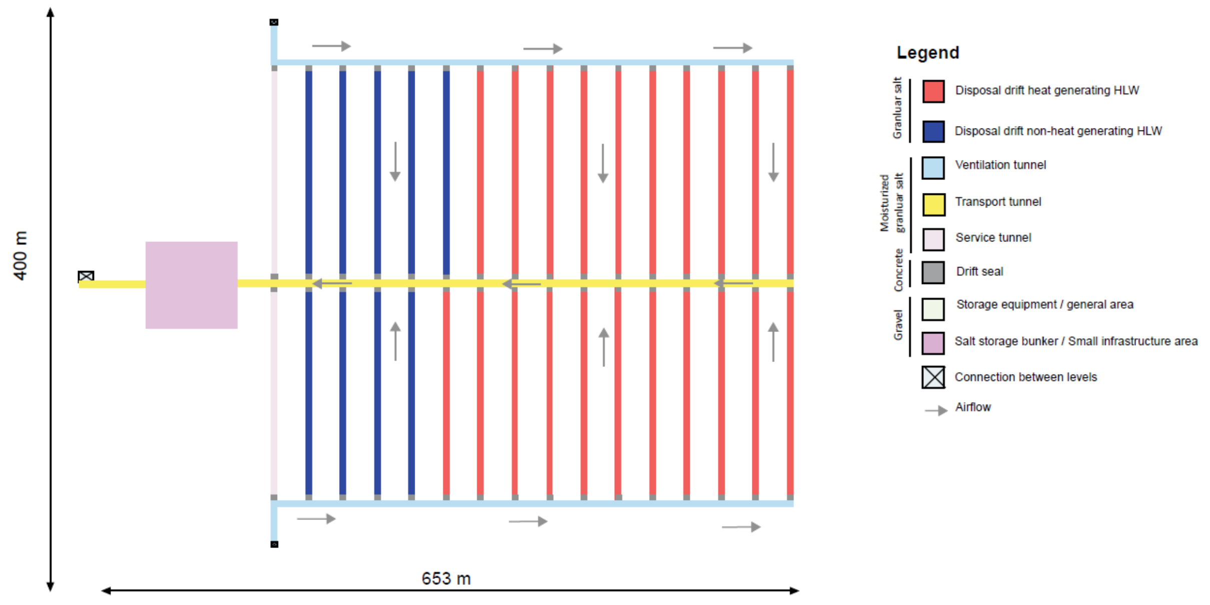

Figure 2.4: Draft layout of the HLW disposal level (-850 mNN) of the generic Dutch repository concept. Disposal drifts with heat-generating waste (red) and with non-heat-generating waste (blue). Central transport tunnel (yellow), marginal ventilation tunnels (light blue), and a service tunnel at the ramp side (gray, left)

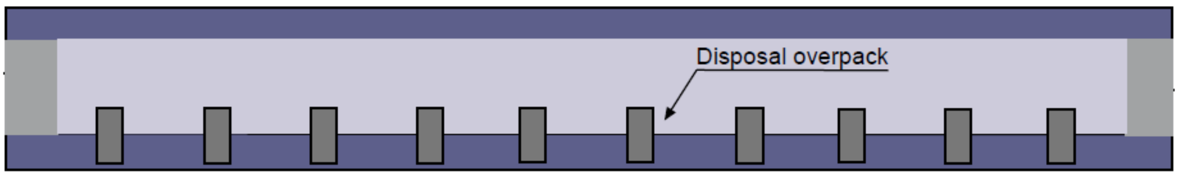

Figure 2.5: Dutch disposal strategy for HLW packages

3 Methodology

3.1 Introduction

Based on the generic FEP list, scenarios for the normal (= expected) and alternative (= deviating) long-term evolutions will be systematically developed. It has been agreed with COVRA that the German approach will be used for the scenario development. The German approach is based on comprehensive experience gained in salt mining, repository operation, and R&D work. The methodology will be described and explained below. The normal and alternative evolution scenarios will serve as basis for the future performance assessment within a rock salt safety case. The scenarios will be documented in text form and discussed with COVRA.

Fundamental issues of safety objectives and safety demonstrations have been compiled in recommendations of IAEA (2011) and NEA (2013). Most of these recommendations are also reflected in national regulations and were fundamentals for developing a national safety strategy for repositories, e.g. in Germany (Atomic Energy Act, Radiation Protection Act, Mining Act, Ordinance on Safety Requirements and Preliminary Safety Assessments for the Disposal of Heat-Generating Radioactive Waste (BMU 2020). The Dutch initial safety case in the OPERA project also refers to these IAEA/NEA recommendations (Verhoef et al. 2017).

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*". Based on these protection goals, 3 safety principles are of particular relevance (e.g. BMU (2020)):

- the radionuclides and other pollutants in the waste must be concentrated and contained in the host rock (called Containment-providing Rock Zone (CRZ) in Germany[1]), and thus kept away from the biosphere as long as possible;
- disposal must ensure that in the long term, any release of radioactive substances from the repository only negligibly increases the risks associated with natural radiation exposure;
- the repository shall be constructed and operated in such a way that no intervention or maintenance work is required during the post-operational phase in order to ensure the reliable long-term containment of the radioactive waste in the CRZ.

The key safety functions for the safety concept are

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

For potential HLW repositories in German salt formations, a safety concept and a safety demonstration methodology have been developed on a generic level in the R&D project ISIBEL (= Safety assessment methodology for a German high-level waste repository in salt formations) and site-specifically optimised as part of the 'Preliminary Safety Analysis of the Gorleben Site (VSG)' (Bollingerfehr et al. 2013, Fischer-Appelt et al. 2013). In the R&D project

[1] A CRZ must be identified in salt, argillaceous rock and suitable crystalline rock. For crystalline rock, a concept relying on geotechnical barriers as a substantial barrier instead is an accepted exemption.

ANSICHT (= Safety assessment methodology for a German high-level waste repository in clay formations), it has been demonstrated that this methodology can be used in argillaceous rocks, too (Jobmann et al., 2017, Lommerzheim et al., 2018). Moreover, the methodology was upgraded taking into account questions that were identified during its application in the former projects. The latest state of this methodology is currently applied in the safety case for the licensing procedure for the closure of the German Morsleben LILW repository.

The safety demonstration methodology is summarised in Figure 3.1. This methodology can roughly be divided 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 of the barriers. General conceptual specifications and technical measures are addressed.

The German safety concept is based on a “Containment-providing rock zone” (CRZ) (BMU 2020), which means that at least a defined rock area surrounding the disposal areas has to remain stable for the whole demonstration period and thus ensure radionuclide containment. To comply with this safety objective, hydraulic, thermal, and mechanical requirements for the CRZ’s properties have been defined. They correspond to suitable safety functions of the CRZ. The demonstration of the CRZ’s barrier function (i.e., retention of the CRZ’s containment capabilities) must verify that most of the radionuclide inventory will remain within the CRZ. Different constraints have been defined in international projects to evaluate the radionuclide release.

To check the CRZ’s integrity, the German safety demonstration methodology includes several criteria (BMU 2020). Thus, the following procedures for the integrity demonstration of the CRZ have been developed:

- the “*dilatancy criterion*”: The anticipated stresses should not exceed the dilatancy strength of the rock formations in the CRZ surrounding the Excavation-damaged Zone (EDZ). The criterion is met, if the effective stresses do not exceed the damage threshold in the CRZ (excl. the EDZ);
- the “fluid pressure *criterion*”: 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 an increased ingress of groundwater into the 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*”: The barrier effect of the CRZ must not be inadmissibly influenced by the temperature development. Compliance with this criterion can be proven by a thermomechanical analysis of the thermal impact induced by the heat-generating waste on the host rock. Thermo-mechanically induced fractures should not bypass the CRZ.
- the “*chemistry criterion*”: modifications of hydrochemistry by the construction materials of technical and geotechnical barriers should not impair the safety function of the host rock. Compliance checks can be made by chemical analyses of the interaction between the construction materials in different parts of the repository and the surrounding rocks.

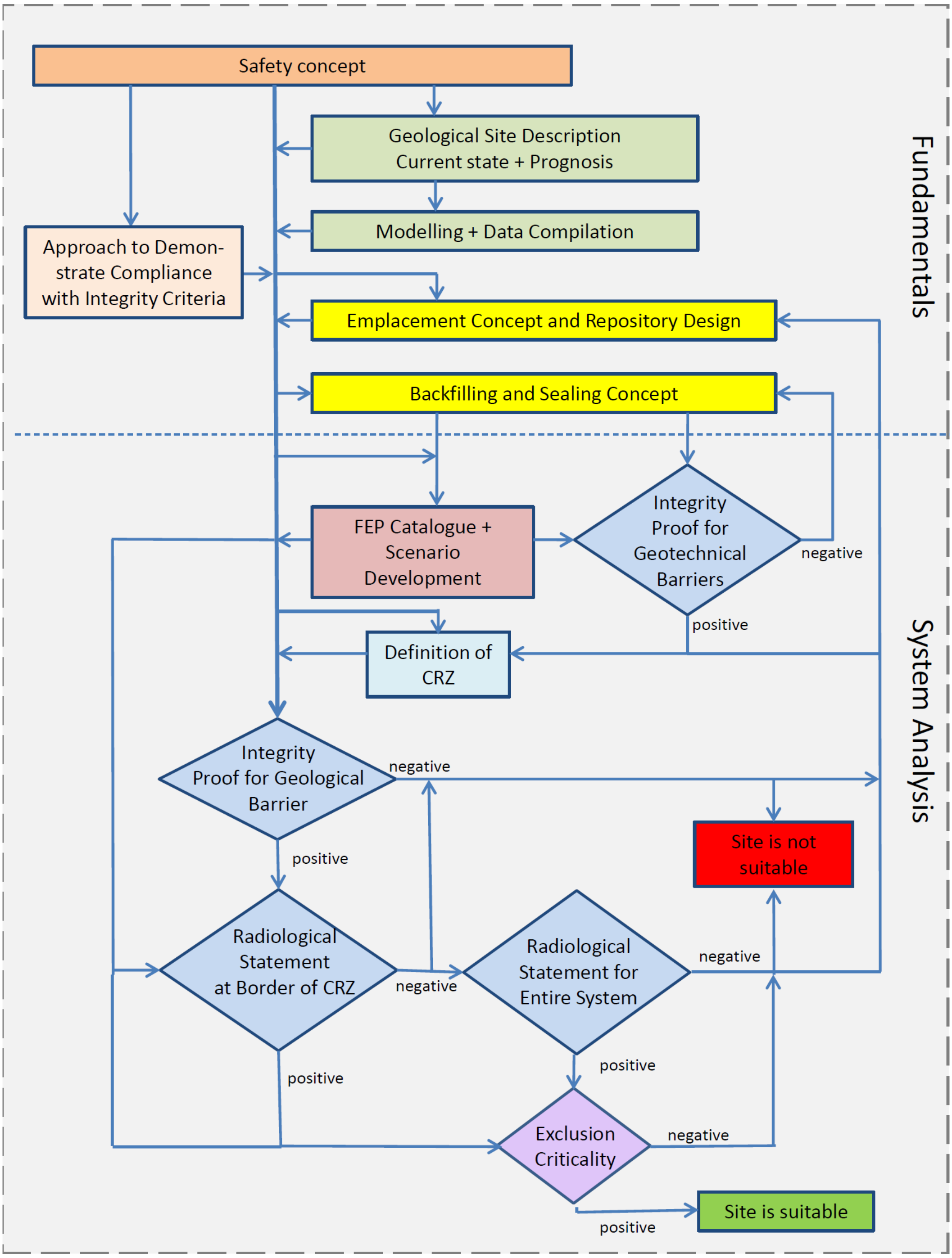

Figure 3.1: Flow diagram of safety demonstration methodology (modified after Jobmann et al. 2017)

The "geological site description" is a basis for the safety demonstration. Fundamental information on salt formations in the Netherlands and their potential impairment by natural processes (e.g. diapirism, subrosion, earthquakes, glacial channels, permafrost etc.) are compiled in Grupa et al. (2017) and COVRA (2020). As an example for a generic safety evaluation, a geological model for a salt dome that has been developed for the RESUS project (= fundamentals for representative preliminary safety assessments and safety related evaluations of sub-areas with suitable geological properties for final disposal of high level radioactive waste) (Bertrams et al. 2020) was used. The following report will refer to this model. The “emplacement model and repository design” as well as the “backfilling and sealing concept” rely on the safety concept, the radioactive inventory, the geology, regulatory requirements, and technical / operational constraints (for Germany: Bollingerfehr et al. 2011, 2012, 2016; for the Netherlands: COVRA 2020). 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. The broad outlines of the Dutch disposal concept in domal salt formations have been compiled in COVRA (2020). The recent Dutch repository and closure concepts are still generic and not yet comprehensive. Therefore, for safety assessments it is intended to refer at open questions to the detailed German repository and closure concepts and experiences from in-situ-tests.

Starting points for the “system analysis” are the **f**eatures, **e**vents, and **p**rocesses (FEP) (which give a comprehensive description of the repository system) and the derived scenario development (which is a development of normal and alternative evolution scenarios). The FEP catalogue prepared for the present study has been developed by an adaption of the German FEP catalogue for the Preliminary Safety Assessment of the Gorleben salt dome (Wolf et al., 2012) to the Dutch specific boundary conditions incl. a Dutch generic model for a salt dome (chapter 2.23), the waste inventory (chapter 2.3), and the disposal concept (chapter 2.4).

The further steps of the “system analysis” (which are not part of the present study) will include the performance assessment of the repository system, the radiological consequence analysis, and the demonstration of subcriticality.

Corresponding to the German approach, the “Containment-providing rock zone (CRZ)” of the salt dome will ensure the long-term containment of the radionuclides. Therefore, this barrier should not be impaired during the demonstration period of 1 million years. The integrity demonstrations for the geological barrier and for the required geotechnical barriers as well as the long-term radiological statement will be based on numerical calculations at different scales. The results have to be analysed using integrity / radiological criteria. The model calculations need comprehensive data that cover all components and processes of the repository system as well as the identification of expected and alternative evolutions that reflect the future evolution of the repository system. This information will be offered by the FEP catalogue and the corresponding scenario development.

The safety assessment includes modelling of the potential dispersion of radionuclides in the overburden and adjoining rock as well as in the biosphere. The resulting doses should be negligible in comparison to natural radioactivity. For evaluation of the consequences, it is necessary to identify the surface areas with radionuclide release. A criterion for the safe containment of radionuclides is the demonstration of compliance with radiological constraints. E.g. different dose constraints for the normal and alternative system evolutions have been defined in German regulations (BMU 2020). The radiological burden for the reference person of population has to be estimated in stylised scenarios assuming similar living conditions as at the time of license application. The exclusion of criticality has also to be demonstrated by a stylised conservative scenario.

The geology defines the properties of the host rock (chapter 2.23) and thus defines important boundary conditions for many future processes occurring in the repository. At an early stage of the safety evaluation for salt formations, geological models can be defined to describe a generic potential site. The generic Dutch model of a salt dome reflects experiences from salt mining and exploration in the Netherlands and considers German experiences (e.g. Gorleben exploration mine, Morsleben repository, Asse mine) (Figure 2.1). COVRA (2020) gives a compilation of representative properties of salt formations in the Netherlands.

To evaluate the long-term barrier function of the salt formations, a geoscientific and climatic long-term prognosis gives important indications. Many geological processes are very slow and long-lasting, and therefore, an analysis of the former site evolution can be used for a prognosis of the future system evolution (actualism principle). A comprehensive long-term prognosis for the Netherlands has not yet been carried out, but some important aspects of these prognoses (e.g. climate change (glaciation), tectonic developments, and the hydrogeology) have been described in COVRA (2020) and Grupa et al. (2017).

The repository concept must implement 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 geologic boundary conditions (Bollingerfehr et al. 2011, 2012). The geological barrier has been perforated by the mine excavations and therefore, the integrity of the barrier has to be restored by the engineered barrier system (EBS). The EBS will provide important safety functions with regard to long-term safety.

The selection of a disposal concept will be influenced by the safety strategy on the one hand and the geological properties (e.g. folding of internal structures, geometrical extent and thickness of the salt formations) on the other hand. So, in salt formations with a large extent but a smaller thickness, drift disposal or horizontal boreholes are favourable, in salt domes with high thicknesses but limited extensions, vertical disposal boreholes may be an option (Bollingerfehr et al. 2016).

The repository excavation strategy and the closure measures define the intensity of host rock impairment and therefore, they are key issues for long-term safety. E.g. careful excavation by road headers is an effective measure to minimise rock disturbance and the mining-induced loosening of the drift contour (EDZ). Furthermore, the reduction of volumes of the excavations, shortening of “keep-open-periods” and timely decommissioning and backfilling and sealing of filled disposal areas (operations in retreating mode) will contribute to the minimisation of rock disturbance. After completion of emplacement operations, the remaining mine openings (e.g., shafts, ramps, drifts, and boreholes) will be sealed and backfilled as well. To avoid thermally-induced impairments of the waste matrices, the disposal overpacks[2], and the host rock, the maximum temperatures of the waste packages will be restricted adequately.

The Dutch repository design comprises three shafts and two emplacement levels that will be connected by a ramp (chapter 2.4). An infrastructure area is provided at the -750 m level.

[2] There are different definitions of “disposal overpacks”: on one hand, it may be a protective, shielded container to transport unshielded disposal containers in the repository (will not be disposed), or, as for the Dutch concept, it’s a disposal container that includes several primary containers from waste conditioning (will be disposed).

Furthermore, drifts for mining work, waste transport, ventilation, and emplacement have to be constructed.

Basic operational requirements for the repository layout include the consideration of radiation protection (controlled) areas and supervised areas, a corresponding air ventilation system, as well as the transport logistics for parallel work of mining and radioactive waste transport. The emplacement areas' dimensions and arrangements will be based on thermo-mechanical calculations as well as on geological and operational requirements.

For radionuclide containment in a repository in salt formations, the host rock is the main barrier in combination with shaft, drift, and borehole seals and backfill for sealing the mine excavations. The safety functions of the EBS include the limitation of fluid flow, the retention of radionuclides, and the stabilisation of the host rock. During the ten glacial periods expected for the demonstration period, the hydro-chemical boundary conditions will change several times. These evolutions are not predictable in detail. Therefore, the German safety concept and the performance assessment only consider a functional lifetime of 50.000 years for the geotechnical barriers (corresponding to the period with predictable boundary conditions up to the first glacial period). In addition, this lifetime covers – with a very conservative time addition – the uncertainties in the prognosis of the development of the backfill properties. After completion of the backfill compaction, the permeability of the backfill will be sufficiently low to ensure radionuclide containment until the end of the safety demonstration period (1 million years) and most likely much longer.

Due to the safety concept for salt formations, the disposal overpacks are mainly relevant for operational requirements (incl. retrievability) and for reversibility during the initial period after repository closure (500 years in Germany, not defined in the Netherlands).

3.2 Identification of FEP

It is international standard to document the initial state of a repository site and compile the understanding of evolutions 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 interrelations between the site-specific conditions and the modifications resulting from the disposal of radioactive waste as well as their development over time (Figure 3.2).

In international projects, the objectives, structures, and contents of a FEP catalogue may be slightly different depending on legal requirements and the safety demonstration methodology. Because of its relevance for long-term safety assessments of repositories, NEA has implemented a FEP database, which compiles the international experience of repository projects with heterogeneous waste inventories and different host rocks (NEA 2019). This FEP catalogue can be used as a starting point for developing a new site-specific FEP catalogue and to check its completeness.

The generic FEP catalogue compiled for the salt option in the Netherlands is based on the German FEP catalogue that has been prepared for the “Preliminary Safety Analysis of the Gorleben Site (VSG)” (Wolf et al. 2012). Furthermore, the optimisations of the FEP catalogue structure and content during the ANSICHT project (Lommerzheim et al. 2018) and during the licensing procedure for the closure of the Morsleben repository have been considered (Figure 3.2). Due to the early stage of the generic safety assessments in the Netherlands, the FEP catalogue prepared for COVRA has a low level of detail and cannot (yet) comprise all the (site-specific) information included in the German FEP catalogue(s). Dutch data for geology, the waste inventory, and the repository concept have been included in the corresponding FEP when available.

A key issue of the German approach is the objective to use the FEP catalogue as a resource to develop scenarios systematically, stringently, and in a transparent manner. Consequently, several methodological requirements have been reflected in the structure and contents of the FEP catalogue. The 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-time incidents and changes in other FEP catalogues (e.g., NRC (2003), POSIVA (2012)). The German FEP catalogues and the present study abdicates from a separation between events and processes because the differences are often weak and ambiguous, and transitions occur. Events composed of chains of events or processes, e.g., failure of a shaft seal, are not seen as FEP but as a kind of small scenario and therefore belong to scenario development.

Processes are defined as successions and transformations acting within the disposal system that change the state of components, e.g. stress changes, metal corrosion.

The FEP catalogue will compile all information relevant to scenario development and performance assessment modelling (Beuth et al 2012, Wolf et al. 2012). The FEP summarise all features that characterise the initial state of the repository system after repository closure and identify processes that may influence the future evolution of the site. So, the relationship between site characteristics and evolutions on the one hand and environmental conditions and natural processes or processes that are initiated by waste disposal on the other hand are considered. Thus, the FEP catalogue will be a starting point for the design and performance assessment of geotechnical barriers (Müller-Hoeppe 2014) and all subsequent steps of system analysis (Müller-Hoeppe et al. 2012a,b, Fischer-Appelt et al. 2013).

The Dutch FEP catalogue includes

- FEP No in project , FEP No in NEA-IFEP list, FEP name
- FEP description
- relevance to performance and safety: indications to importance for safety evaluation
- impact on barrier function: processes that will directly impact the properties of a barrier
- relevance to radionuclide mobilisation and transport: processes that directly alternate waste matrices or waste containers (and thus cause RN mobilisation) or influence the transport of fluids and dissolved components
- affected FEP: FEP that are directly influenced by the property of a feature or the intensity of a process
- affecting FEP: FEP that may directly change the properties of a feature or the intensity of a process
- FEP screened out: indications for some common FEP that have been screened out due to different boundary conditions (e.g. geologic or site-specific) or low relevance (plausibility check). It was not possible to discuss all NEA-IFEP at this point. Many FEP of the NEA IFEP-list can be excluded because they refer to another host rock, different boundary conditions, waste inventory, disposal concept etc.

There is a close interaction between the methodological approach for scenario development and the structure and contents of the FEP catalogue (Figure 3.2). The FEP catalogue includes assessments of probabilities of occurrence of FEP, identifies important components of the safety concept as “initial barriers” (also see Table 3.1), highlights processes that affect the safety functions of the initial barriers as “initial FEP”, and describes the interactions between FEP.

Furthermore, FEP describing radionuclide mobilisation or transport are starting points for scenario development as well.

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.

The structure and contents of the FEP catalogue have been continuously refined based on the experience with the application of the methodology in different projects (Wolf et al. 2012, Stark 2015a, b) (Figure 3.2).

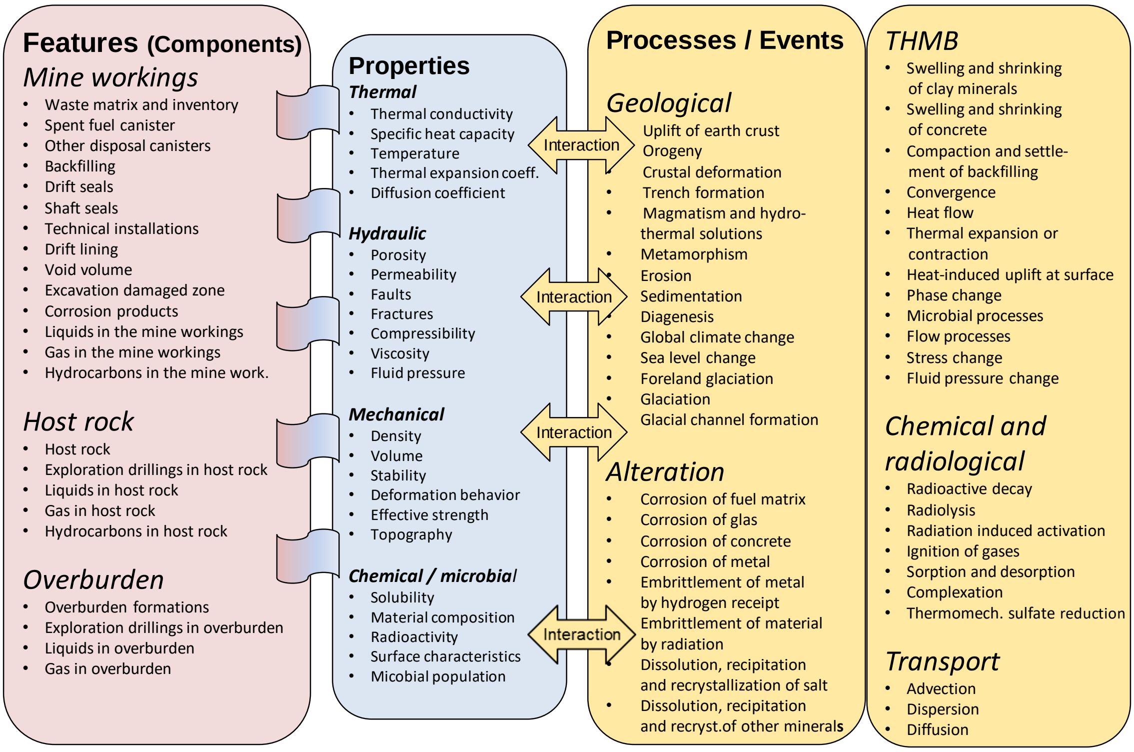

Figure 3.2: Example of the structure of a FEP catalogue (Lommerzheim et al. 2018)

A prominent goal of data management was to structure the FEP catalogue effectively and unambiguously and to document the information relevant for scenario development as transparently as possible. The corresponding measures include:

- 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 parts of it (e.g. sealing material or abutment, NEA 2019). Furthermore, 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 some other projects, where a disposal component is used as a wrap for multiple FEP referring to physical properties of a component (drift seal > porosity and permeability of drift seal, e.g. POSIVA 2012). These properties of the components can be changed by affecting processes. Due to the early stage of the project, the COVRA FEP catalogue could not include descriptions of all component properties as mentioned in Figure 3.2.
- The choice of level of detail for component description 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. Because processes occurring in several sub-systems have different site-specific properties, it is useful to split them into subsystem-specific FEP, e.g. mechanical stress change in host rock (in overburden formations, in mine openings). This increases transparency in the discussion of FEP interactions.
- Accumulative process FEP are only used exceptionally if a more specific description is not possible or not necessary for future system evolution, e.g. microbial processes.
- The interaction between FEP considers directly affecting FEP and affected FEP. Three basic rules have been defined for these interactions:

  - An interaction between two components (features) may only occur via processes.
  - An interaction between two processes may only occur by mediation of a component. Exceptions are process FEP that are split into different subsystems – they can directly interact with each other.
  - 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.
- In some FEP catalogues, incident chains resulting from several succeeding processes are subsumed in FEP (e.g. failure of shaft seal). In the current study, they are seen as scenarios and therefore not included in the FEP catalogue. These scenarios will be systematically derived during scenario development procedure.

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 a site description (or description of a generic site model), including the results of geoscientific long-term prognoses. Furthermore, the German FEP catalogue for salt formations compiles all data and experiences from salt mining (e.g., potash and halite mines), site exploration (e.g. Gorleben site) and two LILW repositories (e.g. Morsleben repository, Asse mine).

A plausibility check identifies all FEP that, in principle, may have an impact on the geologic evolution of the site or on the repository system evolution (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 mobilisation of radionuclides (top-down approach). Furthermore, a plausibility check of sequences and interdependences of the FEP may identify missing FEP. In order to check whether any relevant aspect has been overlooked, the consolidated FEP list can be checked against the generic NEA I-FEP list (NEA 2019). All FEP must be analysed with regard to their relevance at the considered site (FEP screening).

Comparing the FEP catalogues of different salt sites (e.g., Gorleben site and Morsleben site vs. WIPP site), many FEP are similar but have different site-specific characteristics and relevance. In this context, the differences in the geological boundary conditions and repository concepts must be considered.

3.3 Screening of FEP

A starting point for the development of a FEP catalogue for salt formations is – on the one hand – the compilation of all common data from national (mining and scientific) experience and – on the other hand – the comparison with the NEA-IFEP-list. When comparing different sites of salt formations, many properties and processes are common, while others are site-specific. Because the NEA-IFEP-list compiles the FEP lists from different host rocks and different boundary conditions, there are many FEP that are not relevant for salt formations and the surrounding geosphere as well as the disposal concept or the radionuclide inventory. Therefore, for both steps, FEP screening is necessary to focus on the relevant FEP. Due to the site selection procedure, many geological processes that may impair the geological barrier, are excluded at the repository site. Examples are "volcanism and magmatism", "active fracture zones" and "orogensis". Another reason for excluding a FEP may be that a process FEP will occur but will not have a significant impact on the repository system evolution, e.g., "vertical uplift of geosphere" (if it is a large-scale, uniform movement).

Common FEP exclusion criteria are based on:

- Exclusion by regulation – Some FEP may be excluded by regulations. For example, FEP related to the characteristics, concepts, and definitions pertaining to the biosphere, receptor, long-term geologic processes, and disruptive events (e.g., human intrusion) are commonly addressed by regulations.
- Exclusion by probability – FEP having less than a specified probability of occurrence may be excluded from consideration based on low probability.
- Exclusion by consequence – FEP that have little or no effect on disposal system performance, as defined by specified metrics, may be excluded from consideration on the basis of low consequence.

The FEP screening and the corresponding justification of decisions should be documented in the FEP catalogue.

3.4 Scenario development

The fundamentals of the German approach for scenario development have been developed and have comprehensively been described in Beuth et al (2012) and Lommerzheim et al. (2018). 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 characterisation.

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

Developing and investigating several scenarios is an internationally recognised and accepted approach to address this uncertainty (NEA 2016). Different kinds of scenarios must be considered as a basis for the safety assessment of a repository system. Expected (base), alternative, hypothetical, and human intrusion scenarios reflect the variations of potential future site evolutions.

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 (or more) normal evolution scenario(s) and a number of alternative evolution scenarios that are to comprehensively represent the reasonable range of repository system evolutions (Beuth et al. 2012, Lommerzheim et al. 2018) (Figure 3.3). These scenarios are characterised by FEP that will influence the future evolution of the final repository system at the reference site and their associated characteristics. Examples for different evolutions with the same probability of occurrence are various potential climate evolutions (warm vs. glacial). Because of the high uncertainties in climate prognosis, all of them have to be considered as “normal (= expected) evolutions” and result in different repository system evolutions, that may not be covered by bandwidths of parameters. Basing on an evaluation of the consequences on repository system evolution, it has to be decided, whether additional normal evolution scenarios are necessary.

The scenario development methodology is shown in Figure 3.4.

“Normal evolution scenario” refer to the expected, normal evolution forecasted for the model site, and evolutions normally observed at comparable locations or similar geologic situations.

“Alternative evolution scenarios” refer to evolutions that are not expected for the model site, but which may occur with regard to geological or climatic boundary conditions, the technical and geotechnical barriers, and the radioactive inventory.

Normal and alternative evolution scenarios will be systematically derived from the FEP catalogue.

Other groups of scenarios include “hypothetical scenarios” and “inadvertent human intrusion scenarios”. These scenarios will be analysed with stylised scenarios and can be addressed to optimise the repository system and to assess the robustness of the system.

“Hypothetical scenarios” include evolutions that can be excluded even for most unfavourable assumptions based on human judgement. This scenario group includes “what-if-cases”. They may be considered to evaluate the robustness of the repository system and to indicate the aspects for optimisation. These scenarios have not been considered here.

“Inadvertent human intrusion scenarios” describe consequences resulting from future human actions intruding into the repository that may be relevant for the safety of the repository system (Figure 3.3). “Representative scenarios” for these evolutions can be derived from common recent human activities.

A fundamental objective of scenario development is to describe the spectrum of potential future system evolutions for the demonstration period (1 mio. years) as comprehensively as possible. 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.

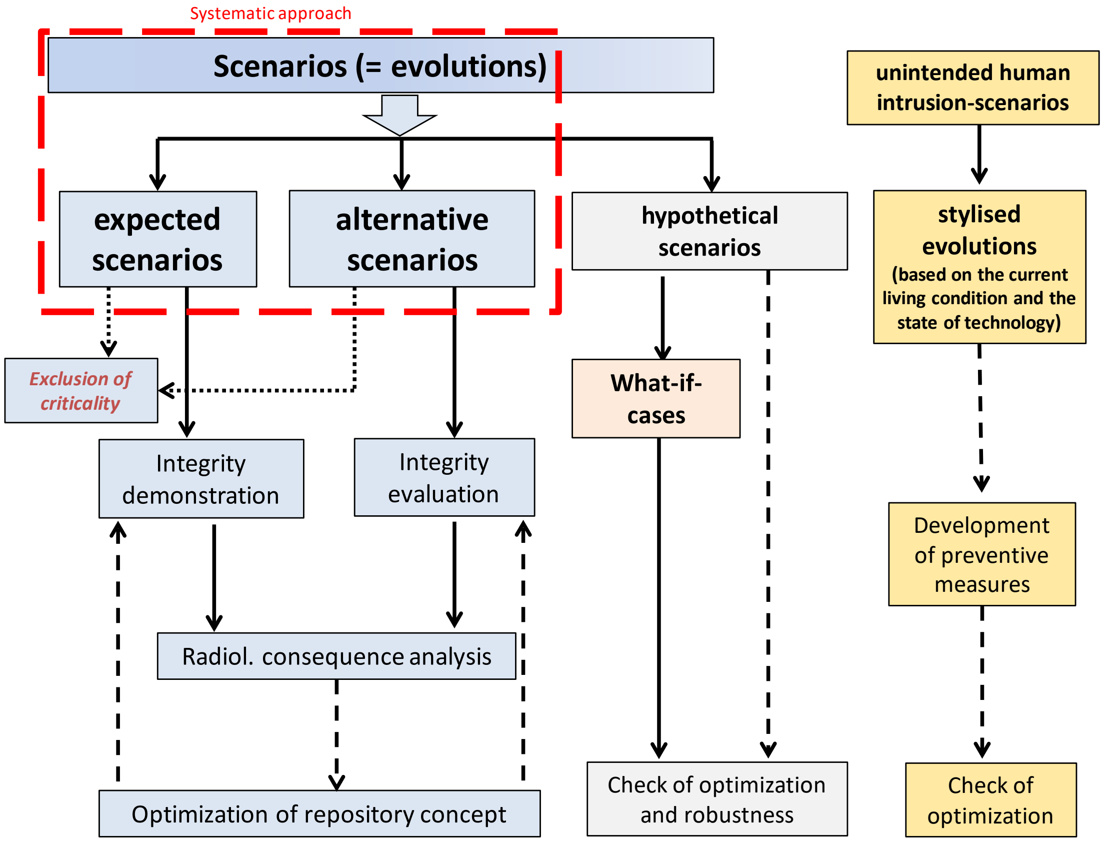

Figure 3.3: Classification of scenarios and safety demonstration methodology (German approach)

There are two key issues that rely directly on the guiding principles of the safety concept to start scenario development (Figure 3.4):

- Impairment of "Initial barriers" by different processes (Table 3.1). Initial barriers are important components of the safety concept and are characterised 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 their properties will be modified in different time frames.
- "Initial FEP" are expected processes that could impair the safety functions of the initial barriers. They provide the first group of starting points for scenario development.
- In addition, all possible system evolutions that influence a release of radionuclides from the waste form need to be considered. These FEP, which are related to the mobilisation of radionuclides and their transport, are the second group of starting points for scenario development.

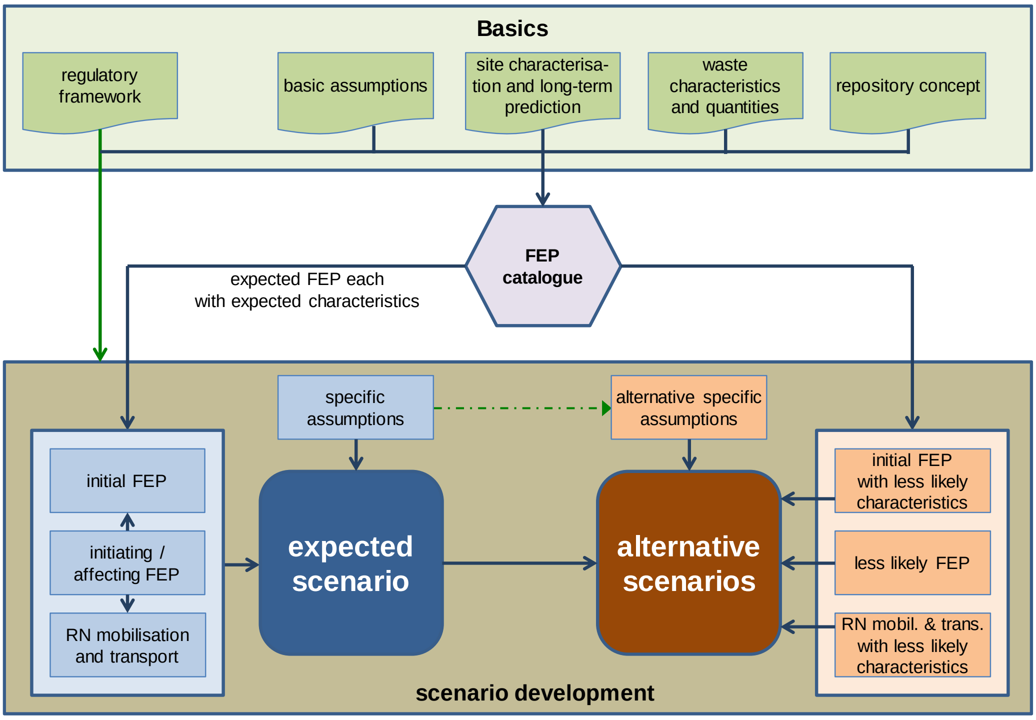

Figure 3.4: *Scenario development methodology (modified after Mönig et al. 2013). The "expected scenario" corresponds to the "normal evolution scenario" in the present report, alternative scenarios" to "alternative evolution scenarios".*

Table 3.1: Initial barriers and barrier-impairing initial FEP in the different compartments of the Dutch repository system in salt formations

Compartment	Initial-Barriers	Initial-FEP (Processes)
Disposal Areas	HLW overpack containers LILW overpack containers Backfill (incl. Contact Zone, EDZ), Disposal Drift Seal (incl. Contact Zone, EDZ), Underground exploration drillings (incl. Contact Zone, EDZ)	Seismic activity Salt diaprism Thermal Expansion or Contraction Thermomigration Thermochemical sulphate reduction Alteration of Concrete Metal Corrosion Dissolution and Precipitation of Salt Minerals Microbial Processes Mechanical stress changes Convergence Swelling, Shrinking and Creeping of Concrete Settlement and Compaction of Backfill Fluid Pressure Change Channelling of Backfill Pressure induced permeation of fluids into salt formations
Other underground excavations	Shaft Seal (incl. Contact Zone, EDZ) Ramp Seal (incl. Contact Zone, EDZ) Backfill (incl. Contact Zone, EDZ) Drift Seal (incl. Contact Zone, EDZ) Surface Exploration Drillings (incl. Contact Zone, EDZ) Underground exploration drillings (incl. Contact Zone, EDZ)	Seismic activity Permafrost Glacial channelling Salt Diapirism Thermal Expansion or Contraction Phase Transition Alteration of Concrete Alteration of Bentonite Metal Corrosion Dissolution and Precipitation of Salt Minerals Transformation of Anhydrite to Gypsum Mechanical stress changes Convergence Swelling, Shrinking and Creeping of Concrete Swelling and Shrinking of Bentonite Settlement and Compaction of Backfill Fluid Pressure Change Channelling of Backfill Microbial Processes

Compartment	Initial-Barriers	Initial-FEP (Processes)
Host Rock	Host rock	Seismicity Subrosion Salt diapirism Glacial channelling Cryogenic joints Natural gas intrusion Thermal expansion or contraction Thermomigration Pressure induced permeation of fluids into salt formations Mechanical stress changes Fluid pressure changes Dissolution and Precipitation of salt miner-als Transformation of anhydrite to gypsum

A plausibility check has shown that the initial FEP consider all safety-relevant impacts on the geological and geotechnical barriers (Table 3.1.). Therefore, they are suitable starting points for scenario development. Furthermore, all relevant aspects with regard to radionuclide release will be described by the FEP associated with radionuclides mobilisation and radionuclide transport.

The description of FEP interactions by component-process-causal chains results in long and complex, but clear causal chains to address important aspects of system evolution. To facilitate the generation of suitable dependence trees, FEP screening should also be performed in the causal chains to focus on relevant issues.

3.4.1 Normal evolution scenario

A normal evolution scenario does not include one specific evolution but describes as broadly as possible the spectrum of probable future evolutions of a repository system. Relevant components and relevant processes will have different properties and characteristics in different areas of the repository system and during different periods of system evolution. Therefore, a subdivision of the repository system into the following compartments is useful and increases transparency of description (Table 3.1):

- *Disposal areas*: include the disposal boreholes / chambers and the disposal drifts with drift seals
- *Other underground excavations*: include all mine openings at the 2 emplacement levels (except the disposal areas), the shafts, ramps, and boreholes, and the EDZ resulting from mining work
- *Host* rock: includes the salt formations (except the EDZ), which form the geological barrier
- *Surrounding geosphere*: includes the cap rock, the overburden, and adjacent rock. The safety function of this compartment is the protection of the host rock from external impacts.

- *Biosphere*: includes some characteristics above the surface of geosphere and climate / weather. Due to high uncertainties, a comprehensive description of future biosphere is impossible. Therefore, the FEP catalogue for this compartment only includes potential characteristics and processes that may impact geosphere or that are relevant with regard to radionuclide transport / release.

The starting points for developing normal evolution scenarios are:

Specific assumptions: provide a means to deal in a transparent and traceable way with particular uncertainties, some of which may be minimised in the future while others can never be reduced at all. They especially address three aspects with high uncertainty, that are assumed for the normal evolution scenario:

- *Geology:* the available geological data are representative and there are no undetected geological characteristics. Has to be verified in future with proceeding exploration.
- *Safety function of technical and geotechnical barriers:* all barriers will work as designed. The functionality of engineered barriers must be verified by integrity demonstrations (performance assessment)
- *Future climatic evolution:* Because of the persisting uncertainties in this issue, all reasonable climatic evolutions must be considered as “probable (expected)”. The evolution with the highest plausibility will be attributed to the normal evolution scenario. Other climate evolutions have to be analysed with regard to their safety relevance and then decided, whether additional normal evolution scenarios are necessary.

The description of the normal evolution scenarios is based on a “bottom-up-approach”, i.e. a comprehensive description of the repository system and its evolution.

Expected initial FEP with their probable characteristics: Initial-FEP may impair the “initial barriers” that are the key elements of the safety system. Apart from the host rock, the initial barriers comprise the components of the Engineered Barrier System (EBS) (see Table 3.1). For evaluating the performance of an EBS component, the contact zone and EDZ have to be considered. The EBS is arranged in the two compartments “Disposal areas” and “Other underground excavations”. Initial representative properties of the initial barriers are given in the FEP catalogue resp. in references therein. At early stage of a project, assumptions will be made for characteristics of Initial process FEP. Later on, those assumptions need to be verified and specified by process analyses. For the process analyses the causal chains of interaction with other FEP will give useful indications for modelling.

Expected FEP characterising the mobilisation and transport of radionuclides with probable characteristics: The characteristics will be derived from interaction with other FEP.

The two compartments “Surrounding geosphere” and “Biosphere” do not have a barrier function, but they are important for the evaluation of the radionuclide transport. Furthermore, the “Surrounding geosphere” contributes to the protection of the host rock against impairments from the biosphere (e.g. glacial impacts).

If a scenario results from the interaction between expected (probable) FEP, they will be expected (probable) as well (called "normal evolution scenario").

3.4.2 Alternative evolution scenarios

Alternative evolution scenarios are evolutions that differ in exactly one aspect from the normal evolution scenario (Top-down-approach). The methodological approach is based on the normal evolution scenario and its modification by a different boundary conditions (geology, EBS etc.) or different characteristics of processes. Thus, alternative evolution scenarios can be developed from the following starting points (Figure 3.4):

- Deviations concerning the specific assumptions: This approach may yield alternative evolution scenarios. Examples for deviations from specific assumptions that may result in alternative evolution scenarios are:
  - Undetected geological properties (e.g. fracture zones or fluid reservoirs)
  - Early failure of shaft seal (drift seal, borehole seal, etc.),
  - Modifications of the future climate evolutions, e.g. 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 initial FEP (see Table 3.1), less probable characteristics must be defined, and their consequences on repository system evolutions have to be evaluated. If a significant impact would be expected, and the consequences are not yet covered by any other alternative evolution scenario, a new alternative evolution 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 regarding the function of the disposal overpacks, but due to fluid pressure increase they also impair other technical barriers and the host rock. Therefore, the consequences of a high corrosion rate are not covered by the "early failure of a disposal overpack", but also have to be considered in other alternative evolution scenarios.
- Less probable characteristics of the process FEP *mobilisation 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 must be considered. So, for the less probable radionuclide transport by *diffusion*, less probable diffusion coefficients for the materials and the host rock must be evaluated. A suitable alternative evolution scenario must be defined.
- Less likely FEP: process FEP describing modifications of technical FEP (e.g. *channelling in sealing elements* and flow paths in exploration drillings) will have a lower probability of occurrence due to the comprehensive quality assurance measures for the preparation of construction materials and the performance of construction work. Therefore, these FEP may be starting points for the description of alternative evolution scenarios.

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

3.4.3 Inadvertent human intrusion scenarios

Neither the future evolution of the biosphere nor future human actions are predictable. Therefore, the description of biosphere in the FEP catalogue is rudimentary and vague. Human intrusion scenarios (HI) cannot be derived systematically from the FEP catalogue. Nevertheless, future human actions may significantly impair the repository system and therefore, they have to be considered in long-term safety assessments. In many national regulations, the procedure and the boundary conditions for handling these evolutions are defined. Commonly, stylised scenarios are used that are derived from common recent human activities (IAEA 2017).

4 Normal evolution scenario

As mentioned above, the German reference scenario (corresponding to the Dutch normal evolution scenario), which has been developed for the Preliminary Safety Assessment of the Gorleben Site (VSG) (Beuth et al. 2012), has been taken as an example and has been slightly modified to be compatible with the Dutch concept for repositories in salt formations (COVRA 2020). Apart from the fundamentals described in chapters 2.2, 2.3, and 2.4, the normal evolution scenario is characterised by the following properties and evolutions:

Specific assumptions for the normal evolution scenario include:

- The reference climate development with a 100.000 a-cycle of glacial and warm periods is representative. Recent climate forecasts for the northern hemisphere expect the start of the next cooling period in approx. 50,000 years (Berger & Loutre 2002, Pimenoff et al. 2011). Some time delay may occur due to anthropogenic CO_2 production and warming. Because the intensity of this glacial period is unpredictable, the characteristics (e.g. depth of permafrost, thickness of glaciers, and depth of glacial channels) of the Elster glaciation (which was the glacial period with the highest intensity) will be referred to.
- All components of the EBS will be constructed and function as required. This assumption has to be verified by performance assessment (integrity demonstrations).
- The available geological data are representative and there are no undetected geological characteristics. Has to be verified in the future with proceeding exploration.

A comprehensive geoscientific long-term prognosis is not yet available for the Netherlands, but for many important aspects (e.g. seismicity, tectonics, hydrochemistry, climate evolution), results from specific investigations are available (compilations in Grupa et al. 2017, COVRA 2020). The most import issues are:

Only small changes of the tectonic stress field and a low *seismicity* are expected during the future evolution of the Netherlands. During former glacial periods, the maximum thickness of ice sheets in the Netherlands was only a few hundreds of meters. Therefore, only little *Isostatic movements* occurred. Depending on the site-specific evolution of the salt dome structures, the uplift rates of *salt diapirism* varied between 10^{-3} to 10^{-1} mm/y. The bandwidth of *subrosion* rates will be between 10^{-2} to 10^{-1} mm/y mm/y.

Apart from minor large-scale surface *erosion*, marine and fluviatile processes may contribute to *erosion*. So, a break through the coastal barrier (crevasse) may result in a marine erosion of up to 50 m. In combination of changes of sea-level, tidal currents can give rise to deep incisions with max. depths of 50 m. During glacial periods, fluviatile erosion may result in a maximum depth of 20 m.

Climate development will result in complex consequences for the geosphere evolution, e.g. by modifications of hydrochemistry and geosphere stresses. The intensity of *erosion* will depend on *topography,* geological properties, vegetation and climate (*precipitation)* and will have a higher intensity during ice ages and a lower intensity during warmer climates. If fresh water from melting periods was pressed underground, *subrosion* rates will increase. In summary, important characteristics of future glaciations include a penetration of *permafrost* up to a depth of 100 m, an estimated thickness of glaciers of ca. 200 m and an insertion of *glacial channels* up to a depth of 600 m. As a consequence of climatic developments and their modification by anthropogenic impacts, *regression and transgression* will occur.

For the normal evolution scenario, the expected future evolution of the repository system will be described taking the initial FEP as well as process FEP describing *radionuclide mobilisation and transport* as starting points. In the following chapters, a short compilation of the most important characteristics of the repository system evolution in the different compartments will be given. Because the external factors define the boundary conditions for the repository system evolution, the description starts with the “biosphere” and “surrounding geosphere”, which do not include any barrier but have a protective function for the host rock (surrounding geosphere) and are important for radionuclide transport / release. Subsequently, description proceeds to the “host rock”, the “other underground excavations” and finally the “disposal areas”.

In compliance with the early stage of the Dutch project for developing and evaluating HLW repository options in salt formations, the normal evolution scenario description can only address some broad lines of the expected system evolution in a Dutch salt formation.

FEP names are highlighted in *italics* in the following scenario descriptions.

4.1 Biosphere

It is assumed that the characteristics of biosphere before the first future glacial period (e.g. climate, morphology, vegetation, animals, land use) will persist similar to those of today:

- temperate warm climate,
- little topography / morphology,
- altitude in western region slightly below sea level, in south-eastern region up to 100 m above sea level.

The geological model assumes a medium altitude of 30 m above sea level. Rivers, lakes, precipitations, and resulting groundwater recharge are important for radionuclide transport in the biosphere and influence the hydrogeology (and *radionuclide-transport*) in the underlying geosphere. Furthermore, during glacial periods, intensive *erosion* is initiated in the biosphere and may remove geosphere up to a depth of 50 m. In the long-term, the biosphere will be completely modified during the climatic cycles.

The specific characteristics during the warm and cold periods are unpredictable. Therefore, radionuclide transport and radiological impact on the biosphere will be evaluated by stylised scenarios (IAEA 2017).

Some properties and processes during the glacial periods will have severe impacts on the geosphere:

- *Permafrost* will intrude up to 100 m, minimise groundwater recharge (*liquid flow processes*) and thus influence hydrochemistry (increased salinity) in the underlying geosphere. Melting of glaciers will press fresh water into the underground.
- The medium thickness of glaciers is estimated as ca. 200 m (*continental ice sheet at the site*). Therefore, there will be only moderate glacial loads on the geosphere.

- *Glacial channels* with a depth of up to 600 m are the most relevant glacial impacts on the geosphere. They are the only impacts from the surface that can perforate the protective layer of the overburden formations incl. the cap rock and remove part of the host rock.

4.2 Surrounding geosphere

The uppermost geological formations are Quaternary and Tertiary sediments, which have a thickness of 340 m on top of the salt dome. Furthermore, the top of the salt dome is covered by a caprock with a medium thickness of 60 m. In the adjacent rim basins, thick Triassic, Jurassic, Cretaceous, and Tertiary sediments have deposited. These sediments influence the radionuclide transport from the host rock towards the biosphere by their hydraulic properties. Aquifers occur in the Quaternary (fresh water) and Triassic formations (mineralised water), other sediments in Tertiary and Cretaceous formations have a lower hydraulic conductivity. Fractures and faults occur in all consolidated rocks. The rock properties incl. fractures and faults can be modified significantly by thermo-/mechanical stress changes (resulting from *Thermal expansion or contraction* (climate induced)*, seismicity, salt diapirism, loads from glaciation, glacial channelling, isostatic movements*) or chemical impacts like mineral alteration (*solution, transformation, and regeneration of minerals, microbial processes*) resulting from changes of hydrochemistry (e.g. during glacial periods). Especially the chemical processes may have a significant impact on the hydrochemistry of the liquids in the overburden and adjacent formations. As a consequence, flow paths can be reactivated/newly formed or closed. Furthermore, the solubility of radionuclides and thus radionuclide transport may be influenced.

The *heat flow* in the surrounding geosphere will be dominated by *geothermal heat flow* but with decreasing depth climate, the impact of *climate-induced heat flow* will continuously increase. Thermal calculations have shown that temperature decrease during glacial periods may proceed up to a depth of several hundred meters. All chemical processes are temperature-dependent. Furthermore, temperature change may induce thermomechanical stresses in the rock and barriers (*thermal expansion or contraction*).

The current properties of the unconsolidated Quaternary sediments are only representative up to the next glacial period. In future times, those sediments will be completely eroded and re-deposited (with unknown properties) during the glacial cycles.

The hydraulic properties of the cap rock may be variable. The residual deposits of the salt dome are dominated by anhydrite or, if altered, by gypsum. These formations are intensively fractured and show leaching cavities, but the fractures and void volumes may be sealed by recrystallised salt minerals or gypsum.

4.3 Host rock

The geological model describes a hypothetical salt dome with a simplified internal structure (chapter 2.2). In the central part of the salt dome, homogeneous rock salt (halite) of the “Staßfurt-Hauptsalz” is accumulated with a large thickness. Due to the favourite properties of the rock salt, this part of the salt dome will mainly ensure the barrier function (containment-providing rock zone (CRZ)). The petrographic and stratigraphic sequence towards the flanks of the salt dome is heterogeneous and includes a potash seam, salt clay, main anhydrite, and rock formations from the Leine series to the Fulda series. Some of these salt formations have less favourable properties, e.g. the fractured anhydrite includes fluid reservoirs and the potash seam (carnallitite) is characterised by a reduced thermal stability and may release crystal water.

The halite may have a humidity below 0.1 vol %. The minimum thickness of the salt barrier from the upper disposal level (750 m below sea level) to the salt table is 340 m. The competent layers of the Main Anhydrite with fluid reservoirs are fragmented by salt movements and arching. There is a safety pillar of at least 300 m between the anhydrite and the repository excavations.

For several hundreds to thousands of years, the disposal of heat-generating waste will result in thermomechanical stresses in the surrounding rock and in deformation of the pillar between the -750 and -850 m levels (*thermal extension or contraction*). Furthermore, *fractures in the host rock* and an expansion of the *EDZ* will be induced. Even though *permafrost* will not affect the host rock directly, the climate-induced cooling of the geosphere will proceed to greater depths and induce thermomechanical stresses. They may generate *cryogenic joints* at the salt table.

In the surroundings of the heat-generating HLW, *thermomigration* is a thermally-induced process, which influences the distribution of brine in the host rock.

The main triggers for *mechanical stress changes* in the host rock will be *salt diapirism* and *seismicity* on one hand, and different loads resulting from climate evolution, e.g. *glaciation, glacial channelling* and *cryogenic joints*, on the other hand. The *mechanical stress changes* may reactivate fractures and faults esp. at the boundaries between different types of rocks, or generate new fractures in the host rock.

Chemical impacts will also significantly influence the barrier function of the host rock. So, in sum, *subrosion* may reduce the thickness of the salt barrier by 100 m/1 mio. years. The subrosion rates will be accelerated during glacial periods (by low mineralised groundwater) and if rock formations with a high solubility (e.g. potash salt) are exposed at the salt table. Low mineralised groundwater may also intrude into deeper parts of the host rock via fracture zones and alter different salt minerals (*dissolution of salt minerals, transformation of anhydrite to gypsum*). Brine pockets may occur in the salt rock but exploration will ensure that a safety distance will be kept between the reservoirs and the mine excavations. The autochthonal brines are in equilibrium with the surrounding host rock. But brines with deviant hydrochemistry may intrude from the mine excavations or from the salt table and initiate alterations.

Although rock salt has a low humidity of <0.1 vol. %, brine reservoirs may occur in salt formations and in anhydrite. Groundwater can also intrude via the shafts and liquids will be bounded in backfill and construction materials. Therefore, the metal components of the repository will be corroded in the long-term and large volumes of hydrogen gas might be generated. If the fluid pressure exceeds the minimum principal stress, *pressure-induced permeation of fluids into the salt formations* will occur. Due to this process, the hydraulic conductivity of the halite will be increased temporarily.

Natural gas may intrude into the salt dome structure from gas reservoirs in the surrounding geosphere or from permanent gas generation in mature source rock. This gas may penetrate the salt structure via fractures and faults. If it intrudes into the mine openings, it will increase the fluid pressure (*fluid pressure change*), and provide a transport medium for volatile radionuclides (*radionuclide transport*).

4.4 Other underground excavations

This compartment includes all underground excavations except the disposal areas – i.e. the 3 shafts, the ramp between levels -750 m and -850 m, the infrastructure area, and the different kinds of chambers and galleries/drifts (chapter 2.4). The EBS comprises shaft seals (redundant, divers materials depending on geology), ramp and drift/chamber seals (Mg-oxychloride concrete), crushed salt as backfill for the drifts and chambers, gravel as backfill for infrastructure rooms as well as borehole seals for the exploration drillings (different construction materials depending on geology: bentonite, Portland cement, salt concrete, and Mg-oxychloride concrete).

Due to the uncertainties for the prognosis of the hydrochemical conditions during future glacial periods, the safety concept only takes credit from a functional period of the EBS of 50,000 years, which is the well-predictable period up to the next glacial period. The subsequent long-term sealing of the underground excavations will be ensured by the compacted crushed salt, which will eventually have similar properties as the surrounding salt rock. For the underground barriers, the 50,000-year-period conservatively covers the uncertainties with regard to the prognosis of the compaction process.

The infrastructure areas and salt bunker will be backfilled with gravel and will function as a fluid reservoir. This reservoir will significantly influence the hydraulic conditions in the underground facilities. The corresponding fluids will comprise groundwater from surface or overburden formations by percolating through the shaft seals and the EDZ, on the one hand, and limited brine volumes from brine pockets in the rock salt, on the other hand (*liquid flow processes*). Therefore, the hydrochemistry of the liquids in the infrastructure area may be quite inhomogeneous. Additionally, mine air and gas from *metal corrosion* (mainly originating from the disposal areas) or *microbial processes* may significantly contribute to the fluid pressure in the mine excavations (*gas flow processes*). Liquids can intrude via the EDZ of the shafts (bypassing the seals) or intrude from reservoirs in salt formations. The objective of the fluid reservoir is to avoid high hydraulic loads on the shaft and drift seals (*fluid pressure change*) prior to their fixation in the excavation contour.

After EBS construction, their tight fixation in the contour of the mine excavation and thereby their functionality will be accomplished by the swelling of the construction material (*swelling and shrinking of bentonite, swelling, shrinking and creeping of concrete*) as well as by the *convergence* of the surrounding rock. Volume changes of construction materials will result in stress changes in the surroundings and may result in displacements. The EDZ will be re-cut before installation of the engineered barriers. Remaining fractures will be sealed by concrete injections. It has been estimated from experience in old salt mines and from results of in-situ-tests in the Asse Mine and the Morsleben repository, that the contact zone as well as fissures in die EDZ will be closed by convergence in several 100 years at the latest. *Convergence* is a very important mechanical process that ensures the fixation and functionality of the barriers. Reference values for convergence can be taken from experience in other salt mines.

When the host rock overrides the barrier, lithostatic pressure will load the EBS (*mechanical stress change*). Other mechanical loads will result from *seismic activity* and *salt diapirism.* Mining experience shows that the impact of seismic waves on the restrained geosphere decreases with increasing depth (Minkley et al. 2010). But at early time, open parts of the mine excavations (e.g. roof crevasse above the backfill), the rigid concrete, and the loose EDZ may be affected. Furthermore, fissures may be induced in concrete, and the gravel columns in the shafts and infrastructure area may be compacted. *Diapirism* will induce stress and strains in large barriers because the uplift proceeds asymmetrically in the different parts of the salt dome.

Glacial channelling can erode large parts of the shaft seals and *permafrost* can impair the sealing function of the upper bentonite seal. Furthermore, the climate-induced heat flow can result in thermomechanical stresses in the shafts (*Thermal expansion and contraction*), and glaciation (*continental ice sheet close to or near the site*) will be an additional mechanical load on geosphere and the repository excavations. All these climate-induced impairments will occur beyond the functional lifetime of these barriers (50,000 years).

The long-term sealing function of backfill depends on the reduction of permeability by compaction (*settlement and compaction of backfill*). Due to the settlement of the loose backfill, there will initially be a roof crevasse (*channelling of backfill*). But this crevasse will be closed by *convergence* in several decades. In contrast to this development, high porosity of the gravel backfill in the infrastructure area and salt bunker should be preserved to keep an adequate reservoir volume.

The estimated intensities of the THMC-processes/events have to be considered in the design of the barrier.

The shaft seals and surface exploration drillings cut through the whole geological sequence. Therefore, the mechanical, hydraulic, and chemical properties of all formations from the surface to the host rock have to be considered for the barrier design. Thus, a broad spectrum of hydraulic impacts is possible – from the overburden, from anhydrite reservoirs and from brine pockets in the salt formations as well as (at late times) from fluids that are squeezed out from the underground excavations via the infrastructure area to the shafts. Hence, a broad spectrum of liquids with different hydrochemical properties has to be considered, e.g. unsaturated groundwater from the surface and the overburden formations and different kinds of brine (Na, K, Mg / Cl, SO_4 concentrations) from diverse salt formations. Although different reference liquids are considered in barrier design by adequate construction materials, corrosion and alteration processes (e.g. *concrete corrosion, alteration of bentonite, microbial processes*) hydrochemical evolution are important aspects for the future site evolution. This is caused by uncertainties in the hydrochemical prognosis. At early times, the corrosion of the shaft liner determines the time of water inflow from adjacent aquifers and for the corresponding hydraulic loads at the shaft seal. Liquid inflow will modify hydrochemistry and therefore induce alteration processes at the contour of the mine excavations and in the EDZ (*dissolution and precipitation of* *salt minerals, transformation of anhydrite to gypsum*) and of mine constructions and barriers (*alteration of concrete, alteration of bentonite*).

The thermal boundary conditions in the shafts are dominated by the (constant) *geothermal heat flow* as well as by *climate-induced heat flow* (most relevant during glacial periods). The heat flow from the disposal of high level radioactive waste is of lower relevance due to the large distance between the disposal areas and the shafts and the long interim storage period in the Netherlands. Nevertheless, the heat input in the HLW disposal fields will induce thermo-mechanical stresses (compressive strength) at the shafts (*thermal expansion and contraction*). The climate-induced cooling may result in tensile stresses and the generation of fractures at the top of the salt structure (*cryogenic joints at the salt tables*). Due to the high uncertainties in the hydrochemical evolution, the glacial impacts are of lower relevance for the performance assessment of the EBS. The numerical models only consider the full functionality of the barriers during the pre-glacial period.

In the repository system, a two-phase flow of liquid and gas is often expected (*liquid flow processes, gas flow processes, dissolution and degassing*). The most important hydraulic process is the *fluid pressure change*, which is mostly linked to fluid flow processes that are important for *radionuclide transport*. Fluid squeezing by convergence and gas generation are the most important processes to initiate *fluid pressure change* and resulting *liquid flow processes* (incl. advection) and *gas flow processes*. *Advection*, *dispersion*, and *diffusion* are important processes for *radionuclide transport in the liquid and gas phase*.

The repository layout provides two disposal levels, both connected via a ramp and the shafts. Each drift will be sealed by a drift seal to avoid water inflow from the infrastructure area / shafts to the disposal areas or a release of possibly contaminated fluids from the disposal areas. All mine excavations that have to be operated for a long period (e.g. shaft landings, infrastructure, transport/service drifts) will be stabilised by lining (steel anchors and steel meshes) for operational safety. The corrosion of steel anchors may loosen the EDZ and the adjacent host rock.
The system evolution of the disposal areas will influence the hydraulic boundary conditions in the other underground excavations, especially due to the high gas generation rate originating from *metal corrosion* and *microbial degradation* of organic matters in the LILW. This may result in asymmetrical hydraulic loads on the drift seals – with high pressure at the disposal area side and lower pressure at the infrastructure side. This is a special challenge for barrier design. At later periods, fluid pressure will be increased by *convergence*. If the leakage rate of the drift seal is smaller than the gas generation rate, the fluid pressure will exceed the minimum stress in the host rock, and fluid percolation in salt formations will start (*pressure-induced permeation of fluids into salt formations*).

The thermal impact from the disposal of high-level radioactive waste on the other underground excavations is closely linked to the distance from the heat sources (heat flow from HLW disposal). Therefore, this impact is highest at the drift seals separating the disposal areas from the other underground excavations and lower at the ramp seal, which is far away. *Geothermal heat flow* (which is constant) as well as *climate-induced heat flow* (only a temperature impact of 3 - 4°C is expected at the -750 m level) are of low relevance. For the drift seals, significant thermomechanical stresses (compressive strength) have to be considered for the thermal phase (*thermal expansion or contraction*), and tensile stresses after temperature decrease.

These stresses may result in fissures in the concrete constructions as well as in loosening of the EDZ. The temperature will also influence chemical processes (e.g. *corrosion of concrete*) and the solubility of compounds in brine. Therefore, it is an important aspect for *radionuclide transport in liquid phase.*

4.5 Disposal areas

The disposal areas are situated in the Staßfurt Main Halite Formation. For the halite, a humidity (fluid inclusions) of 0.1 vol. % has been assumed. Due to careful exploration in the disposal areas, larger brine pockets are excluded. As soon as disposal operations are completed, the corresponding drifts will be backfilled with dry crushed salt and closed by a drift seal. Exploration boreholes are carefully sealed as well. Earthquakes (*Seismicity*) and *salt diapirism* may induce stresses and affect the functionality of the drift seals and borehole seals. If the mine excavations are not yet stabilised by compacted backfill, mechanical loads may also impair the EDZ. Other important mechanical processes are c*onvergence* and *mechanical stress changes.* They are relevant for the fixation of the barriers in the drift contour and/or for the compaction and functionality of the backfill.

The temperature maximum of the HLW packages will be limited to 100°C by package loading and cooling period during interim storage (*heat flow from HLW disposal*). After disposal, temperature will rapidly decline. The thermal and thermomechanical loads have been considered in repository design by appropriate distances between the disposal boreholes/containers, disposal drifts, disposal levels, and carnallite formations (potash seam) to avoid undue interactions between these components (*thermal expansion or contraction*). The heat-generating HLW will be disposed in the furthest disposal drifts from the infrastructure and shafts to minimise thermomechanical stresses in distant repository areas and at a sufficient distance to the potash seam to avoid a thermal degradation of the carnallitite (starting >80°C) and a resulting crystal water release.

The heat generation will significantly increase *convergence* rates in the nearfield and therefore force compaction of the backfill (*settlement and compaction of backfill*). This process is important for the enclosure of the waste packages. If the void volume in the disposal drifts is stabilised by compacted backfill, lithostatic pressure will load the waste packages (*mechanical stress changes*). Furthermore, the heating will result in thermomechanical stresses (*Thermal expansion or contraction*) in the containers, the backfill, the EDZ and the surrounding host rock. The waste containers will be designed to resist these stresses. The corresponding thermomechanical fracturing may enlarge the EDZ, impair the drift seals, and generate fractures in the adjacent host rock.

Brine inflow into the HLW disposal drifts will be intensified by *thermomigration* and thus intensify *metal corrosion* and resulting gas generation. As a consequence, fluid pressure will be enlarged (*fluid pressure change*). A high pore pressure will retard the compaction of the backfill. Furthermore, salt minerals in the backfill may be altered (*dissolution and precipitation of salt minerals*). The impact of brine on the drift seals depends on the hydrochemistry and resulting processes (*alteration of concrete*, and *swelling, shrinking, and creeping of concrete)*. The volume changes of concrete will influence the hydraulic properties of the barrier and induce stresses in the surroundings (*mechanical stress changes*). Metal corrosion products are also characterised by an increased volume and will therefore induce stresses in the surroundings.

For the thermal phase, *thermochemical sulphate reduction* (at temperatures >80°C) may modify hydrochemistry (sulphide/H_2S), increase stresses by a volume increase of 10 % and contribute to gas generation. An increase in metal corrosion rate is possible.

All processes that are closely linked to high temperatures will not occur or are of low relevance for the areas with non-heat-generating waste at the -850 m and -750 m levels. The *Convergence* rate will be lower compared with the HLW area and, as a consequence, the compaction of the backfill will be decelerated and takes longer (*settlement and compaction of backfill*).

Mixed LILW often comprises a higher portion of organic matters (e.g. synthetics, cellulose) and water (fixed water, pore water, crystal water, free water) from waste and waste matrices. Therefore, different chemical/microbial processes will occur, which will modify the hydrochemical environment and intensify the alteration of the waste, waste matrices, and waste containers (*metal corrosion, concrete corrosion, microbial processes*). These processes are very important for *radionuclide mobilisation and transport*, e.g. through increase of radionuclide solubilities through the release of complexing agents (EDTA, NTA, organic acids, fluoride, detergents etc.). The high gas generation rate resulting from *microbial processes* and *metal corrosion* is very important for the evolution of the LILW areas. Fluid pressure will be a significant hydraulic load on the disposal drift seals (*fluid pressure change*), influences backfill compaction or can initiate *backfill channelling,* and will retard the closing of the contact zone and EDZ. If the fluid pressure exceeds the minimum principal stress of the host rock, the *pressure-induced permeation of fluids into salt formations* will start.

4.6 Radionuclide mobilisation and transport

A key issue of the safety assessment and a supplementary approach for developing the normal evolution scenario addresses processes that are linked to radionuclide mobilisation and radionuclide transport.

The LILW/(TE) NORM containers consist of steel and concrete. The waste is fixed in a Portland concrete matrix. Therefore, *alteration of concrete* is an important impact on the containers and on the waste matrix for the LILW/(TE) NORM packages. The integrity requirements for the LILW/(TE) containers are restricted to the operational period. Portland concrete will rapidly corrode in the saline environment (Glasser et al. 2008). Therefore, these containers will fail shortly after repository closure due to mechanical, hydraulic, and chemical impacts (*alteration of concrete, metal corrosion, mechanical stress change, fluid pressure change)*. Due to the early container failure, the backfill and the EBS components will not yet have their full containment function. Because LILW containers will contain volatile radionuclides that will have been released from the waste matrices by *microbial processes* and *metal corrosion* already during the operating period, *radionuclide mobilisation* und *radionuclide transport* will start immediately after repository closure. Additionally, liquids and gases from geosphere will intrude into the disposal area and contaminated fluids may extrude. The corrosion of the waste matrices (*metal corrosion, alteration of concrete, chemical alteration of organic matters,* and *microbial processes*) will be intensified by brine influx. *Metal corrosion* and *microbial processes* will result in the generation of large volumes of gas. As a consequence of waste matrix alteration, radionuclides will be mobilised in gaseous phase or dissolved in brine. The fluid-induced radionuclide transport and release by *advection, dispersion,* and *diffusion* are influenced by the hydraulic properties of the mine excavations (including closure measures (EBS)), geosphere, and biosphere (see chapters 4.1 to 4.5) Furthermore, chemical processes like *sorption, desorption, complexation,* and *colloid generation* will affect radionuclide transport.

In the HLW disposal area, radionuclide mobilisation and radionuclide transport will start at later times. The minimum functional lifetime of the HLW carbon steel containers is 1,000 years. While the spent fuel is not fixed by a matrix in the container, the waste from reprocessing is fixed in borosilicate glass. After the functional period of the containers, a container failure may result from mechanical (*seismic activity, mechanical stress change, thermal expansion or contraction, convergence, settlement and compaction of backfill*), hydraulic (*fluid pressure change*), and chemical impacts (*metal corrosion*). Chemical and hydraulic processes are retarded by the low humidity in the HLW area (minimised liquid volume in the waste, fluid inclusions (< 0.1 vol. %) in the host rock. As a consequence, only limited gas generation is expected for the HLW disposal area. After container failure, the volatile radionuclides released from the fuel matrix will be released first. The release of further radionuclides from the HLW will be retarded by the low corrosion rates of the fuel matrix and the borosilicate matrix. Mobilised radionuclides will be transported in gaseous phase or dissolved in brine. The fluid-induced radionuclide transport and release by *advection, dispersion,* and *diffusion* is influenced by the hydraulic properties of the mine excavations (including closure measures (EBS)), geosphere, and biosphere (see chapters 4.1 to 4.5) as well as by chemical processes like *sorption, desorption, complexation,* and *colloid generation*.

5 Alternative evolution scenarios

Alternative evolution scenarios are evolutions that differ in exactly one aspect from the normal evolution scenario (Top-down-approach). The alternative evolution scenarios describe the modification of the normal evolution scenario by different boundary conditions. The starting points for the development of alternative evolution scenarios are described in chapter 3.4.2. They are discussed in detail in Beuth et al. (2012).

Several alternative evolution scenarios derived from different starting points may have similar consequences on repository system evolutions. For the procedure of performance assessment calculations, it is necessary to define representative scenarios that bundle and cover these similar alternative evolution scenarios.

5.1 Deviations concerning the specific assumptions

The specific assumptions for the normal evolution scenario are described in chapter 3.4.1. For the alternative evolution scenarios the following deviations have been assumed:

5.1.1 Climate development

The reference climate development includes assumptions for climate cycles (approx.100,000 years based on astronomic Milankovic cycles)) as well as for the intensities of glacials (Elster, Saale and Weichsel glacials) and warm interglacial periods. These assumptions are based on analyses of the climate development in the past and corresponding interpolations to future developments (actualism principle). These prognoses have a high inherent uncertainty.

So, the 100,000-year.climate cycles were characteristic for the last 800,000 years, but in former times, there were also cycles of 19,000 years - 23,000 years and 42,000 years. Short climate cycles would result in in a new glaciation in the next 20,000 to 40,000 years. But investigations have shown that shorter climate cycle durations correspond to lower temperature amplitudes between glacials and interglacials (Beuth et al. 2012a). Therefore, glacier thicknesses are reduced, permafrost will only penetrate to lower depths, and glacial channels will only cut into the uppermost part of the overburden formations. It is not expected that these short glacials will have any significant impact on the host rock. Therefore, the climate model defined for the normal evolution scenario covers the consequences of deviating potential glacial evolutions.

Another reference climate development assumes a longer period of temperate, warm, humid climate initiated by the human-induced increase in CO_2 content in the atmosphere. A qualitative evaluation of the impact of this climate and the related delay of the next glacial period on the repository system evolution has shown that the consequences are covered by the reference climate evolution. Therefore, no alternative referring to climate evolution is necessary.

Other prognostic uncertainties rely on the characteristics of the glacial periods. They are discussed in the corresponding initial FEP (see below).

So, the site-specific maximum thickness of the glaciers or the depth penetration of permafrost cannot be predicted. Therefore, conservative assumptions (e.g. taking the upper limits of the plausible bandwidth of the characteristics of the reference glacial period), or combinations of glacial impacts (e.g. overlying glacial channels) have already been considered in the normal evolution scenario. Therefore, an alternative evolution scenario for climate evolution has not been considered.

5.1.2 Functionality of geotechnical barriers

A fundamental assumption for the normal evolution scenario is that all technical barriers will work as required. While the host rock and the backfill will ensure the waste containment in the long-term, the functional lifetime of the engineered barriers is restricted to the initial time of the post-closure period. The HLW containers have the shortest functional lifetime (min. 1,000 years), while for all other geotechnical barriers (shaft, ramp, drift and borehole seals), a functional lifetime of 50,000 years (period before next glacial period) is considered. The failure of the EBS components after their functional lifetime is already included in the normal evolution scenario. “Failure” means, that the EBS components (incl. the contact zone and the EDZ) can no longer fulfil their safety functions.

Therefore, in the alternative evolution scenarios, only the early failure of EBS components during their functional lifetime is analysed. A short overview of the corresponding scenarios for the different kinds of technical/geotechnical barriers and the consequences of their failure on the repository system evolution is given below. Requirements for the operational period and for the post-closure period have been defined for HLW and LILW containers (referring to the legal constraints of retrievability / recoverability of the waste packages). However, the latter will fail shortly after repository closure and are thus no initial barriers.

The scenarios described in the following chapter do not analyse the reasons for the barrier failures. These potential impacts are addressed by the short description of the initial FEP with less probable characteristics (chapter 5.2). Additionally, undetected construction failures resulting from human errors have to be considered. In a conservative manner, the EBS failure scenarios assume a malfunction of the whole barrier and take no credit from the redundancy of the different barrier elements (abutments, sealing elements).

The barrier failure scenarios suppose a higher hydraulic conductivity (sealing element), a reduced mechanical stability (abutment), or a delay of functionality for the entire barrier construction (e.g. by a reduced *convergence* or saturation of a bentonite seal). The failures may arise from construction deficiencies and/or a higher hydraulic conductivity of the contact zone and/or the EDZ, or unexpected environmental impacts.

Beuth et al (2012) proposed to take the permeability of the EDZ, fissures or porous media with high porosity as reference scales for the increased hydraulic conductivity of the failed barriers. This would correspond to a hydraulic conductivity that is 3 or 4 times higher than that of the intact barrier. At the same time, not casually linked failures of several barriers can be excluded (a combination of two events with a low probability is improbable).

To evaluate the most severe consequences for repository system evolution, an early point in time is assumed for the barrier failure scenarios. A relevant boundary condition at this time is that the compaction of the backfill is not yet finished.

5.1.2.1 Failure of a HLW overpack container

The functional lifetime of the HLW containers will be >1000 years. An early failure of a container may be caused by human mistakes (construction and detection failures) or by environmental impacts (chemical, mechanical loads) exceeding the loads that have been assumed for container design. The latter ones have been addressed by the initial FEP described below. If a container fails at a very early time, the backfill and the other components of the EBS will not have yet reached their full containment capacity. Therefore, liquids and gases may intrude into the disposal areas and contaminated fluids may be squeezed out of the disposal areas. Even before waste matrix degradation (*corrosion of fuel matrix, corrosion of glass*), the waste containers will contain volatile radionuclides that will have been released from the spent fuel matrices and originated from *radionuclide decay*. Therefore, the failure of a HLW container is an important initiating event for *radionuclide mobilisation* and *radionuclide transport*.

5.1.2.2 Failure of a shaft seal

A broad spectrum of processes as well as human mistakes or construction failures may affect the functionality of the shaft seals (see initial FEP in Table 3.1). As a consequence, a groundwater flow from the surface, overburden formations, and/or reservoirs in the salt formations via the shafts can be initiated towards the underground infrastructure area. Therefore, all processes in the repository mine that are influenced by water and hydrochemistry will be triggered and intensified. The most relevant consequences on repository system evolution would be:

Unsaturated groundwater entering via the shaft will start leaching the surrounding salt formations. This process will continue up to the saturation of the groundwater. As a consequence, void volumes at the shaft and in the adjacent underground mine excavations will be generated and fractures and fissures in the surrounding host rock may be leached (*dissolution of salt minerals, transformation of anhydrite to gypsum*). This may impair the stability of the host rock in this area. As a consequence, flow paths to brine reservoirs in the host rock may be generated, and the drift seal may be bypassed in parts. On the other hand, the high humidity would increase the creep rate of the salt (*convergence*) and so contribute to the closure of void volumes.

Furthermore, hydrochemistry will be modified and different alteration processes of the host rock and construction materials of EBS (e.g. *concrete corrosion*) may be initiated.

Due to the groundwater inflow, the fluid pressure will increase significantly (*fluid pressure change*), and fluid flow will intensify (*liquid flow processes).* This brine will percolate through the drift seal/EDZ and flood the disposal areas. Here, *metal corrosion* of the disposal overpacks will be initiated. This is also relevant for *radionuclide mobilisation*. Fluid inflow as well as gas generation due to *metal corrosion* are important for flow processes in the mine excavations (*liquid flow, gas flow processes*) and therefore for *radionuclide transport*.

5.1.2.3 Failure of a drift seal

Due to a drift seal failure (and the not yet compacted backfill with a higher hydraulic conductivity), there is a flow path from the infrastructure area to the disposal fields and vice versa. Relevant consequences of this scenario on repository system evolution would be:

The fluids in the infrastructure area have a diverse hydrochemistry. Therefore, leaching of the salt formations (dissolution of salt minerals) and *alteration of concrete* at the barriers will be induced. Both processes may result in bypassing / malfunctioning of the drift seal. The fluids at the side of the disposal fields are saturated with the salts in the surroundings. The disposal areas are located in rock salt formations with a low humidity. Brine pockets in the salt formations with a fluid volume of several hundred m^3 are rare. Therefore, the hydraulic loads at both sides of the drift seal will be different, which is a challenge for the drift seal design.

The brine passing the drift seal will initiate intensive *metal corrosion* at the waste containers in the disposal fields, and intensive gas generation will be initiated. This causes an additional fluid pressure at the drift seal (*fluid pressure change*) and may impair the functionality of the barrier *(channelling of a sealing element)*. Due to the gas generation, a *liquid/gas flow* back to the infrastructure area will be initiated. The high gas-induced fluid pressure in the infrastructure area may impair the shaft seal by channelling (*channelling of a sealing element*). If the gas flow rate through the drift seal is lower than the gas generation rate, the gas pressure will exceed the minimum principle stress in the host rock and permeation into the geosphere will start (*pressure induced permeation of fluids into salt formations*).

Waste packages will fail due to *metal / concrete corrosion*. Subsequently, the waste matrices will be corroded, and radionuclides will be mobilised and transported through the underground excavations via the shaft.

5.1.2.4 Failure of the ramp seal

The ramp connects the two disposal levels at -750 m and -850 m. Therefore, it is a potential pathway between disposal areas with different hydrochemical environments that has been closed by a ramp seal. The construction material and the design of the ramp seal are quite similar to the drift seals. Therefore, the affecting initial FEP and the resulting hydraulic and mechanical impacts on repository system evolution will be similar (see above). Important differences will result from the hydraulic and hydrochemical interactions between the disposal areas. The high gas generation rate in the LILW area, resulting *fluid pressure* gradients as well as chemical and thermal gradients will intensify the *liquid and gas flow* processes and the resulting mass transport (*advection, dispersion, diffusion*). The modification of the hydrochemical environment may influence the mobilisation and solubility of actinides in the HLW area (*radionuclide mobilisation*). So, e.g. the occurrence of complexing agents in the LILW *(complexation*), *colloid formation* and *microbial processes* will reinforce actinides transport (*radionuclide transport*).

5.1.2.5 Failure of a borehole seal

For surface exploration drillings, there will be a safety pillar between the boreholes and the underground mine excavations. Therefore, if the host rock pillar keeps its integrity, there is no connection to the underground excavations if a borehole seal fails. Thus, no impact on the mine has to be considered. Only if a combination of impacts on the host rock (e.g. fracture generation by *tectonic movements, seismicity, thermal expansion or contraction,* or *salt diapirism*) and the borehole seal (mechanical impacts mentioned before, *alteration of concrete, alteration of bentonite*) occurs, a pathway from the underground facilities to the biosphere would be generated.

This is different for underground exploration boreholes that are drilled from the mine excavations. A failure of the borehole seals of these drillings would have different consequences depending on their locations and the geological boundary conditions. The most relevant types are:

<u>Underground drillings connecting reservoirs in the host rock</u>: Depending on the fluid volume and the hydrochemistry of the fluids, different chemical, hydraulic, and mechanical processes can be initiated in the mine openings in the case of drift seal failure.

<u>Underground drillings connecting different mine openings</u>: These drillings may form new flow paths in the mine excavations and even bypass the drift or ramp seals if the sealing material corrodes (*alteration of concrete*) and a leakage occurs. Thus, a fluid flow from the infrastructure area to the disposal areas may be facilitated and intensified or a release of possibly contaminated fluids from the disposal fields towards the infrastructure area and the shafts will be enabled.

The consequences of both system evolutions can be included in the alternative evolution scenarios "Failure of a Drift Seal" and “Failure of a ramp seal”, which are described above.

5.1.3 Unknown geological characteristics

Due to limitations of measuring precision, malfunctions, or human errors in analysing or interpreting measuring results, various unfavourable geological properties may not be recognised. Due to mechanical, thermomechanical, and chemical (leaching) processes, flow paths can be generated between the unknown reservoirs and the mine openings. So, for the corresponding alternative evolution scenarios, the occurrence of brine pockets in salts, fractures, and faults with a high hydraulic conductivity are important. If they are not identified, safety distances may not be kept and connections to the mine openings may be generated during repository system evolution. Furthermore, the humidity of the rock salt due to fluid inclusions may be higher than expected. With regard to the consequences, the locations and volumes of the reservoirs and fractures/faults in the repository mine are crucial. Fluid inclusions are of special relevance for the disposal areas.

Summarising potential consequences on repository system evolution, a flow path between a large brine pocket and the mine openings (HLW disposal area) will be supposed. The resulting brine inflow will initiate / intensify multiple corrosion processes of the waste packages and the drift seals (*metal corrosion, alteration of concrete, corrosion of fuel matrix, corrosion of glass*). Therefore, deviant from the normal evolution scenario, an early *radionuclide mobilisation* and *radionuclide transport* will arise. At the same time, an impairment of the drift seal function will be assumed (*alteration of concrete*).

5.2 Less probable characteristics of the initial FEP

As summarised in chapter 3.4 and Figure 3.1 processes that may directly affect the function of the geological and geotechnical barriers have been identified. Therefore, all these processes can result in a failure of an EBS component if they occur with a design-exceeding intensity. The consequences of deviant process intensities may be ambivalent for different issues. E.g. a slow *convergence* rate will retard the restraint of the barriers in the contour of the excavations and are therefore unfavourable. But looking at flow processes in the repository mine and the linked radionuclide transport, a slow *convergence* rate would retard the squeezing of contaminated fluids from the disposal levels and are therefore favourable.

5.2.1 Impact on the host rock barrier function

The corresponding potential impairing processes are compiled in Table 3.1.

Seismicity: The design earthquake considered in the normal evolution scenario is the maximum seismic activity that may occur because of the geological boundary conditions. Therefore, no higher seismicity has to be considered in an alternative evolution scenario.

Subrosion: Subrosion is closely linked to the hydrochemical development depending on the future climate evolution. Because of the high uncertainties with regard to the future climate evolution, a prognosis of future subrosion rates is uncertain as well. Therefore, a doubling of the subrosion rate in the normal evolution scenario has been assumed conservatively, even though it is well-known that subrosion rate will decrease with increasing depth (due to density layering in hydrogeology). A subrosion rate of 0.2 mm/year would result in a maximum erosion of 200 m in 1 million years. The salt barrier between the uppermost disposal level (-750 m) and the salt table is ca. 150 m. Therefore, even for a very high subrosion rate, a salt barrier with a sufficient thickness will be preserved. An alternative evolution scenario has not to be considered.

Glacial channelling: The maximum depth of 600 m of glacial channels has already been considered in the normal evolution scenario. After their formation, the channels will rapidly be backfilled with sediments. Thus, a superposition of several channels during the following glacial periods would not result in a deeper incision into the geosphere. Therefore, an alternative evolution scenario has not to be considered.

Salt diapirism: During salt diapirism, the uplift rate of the salt formations in the central part of the salt dome in higher than on the flanks of the structure. Due to this heterogeneous salt movement, large structures that are oriented perpendicular to these structures (e.g. large drift seals) may be displaced and disrupted. But this impairment of the EBS will be covered by the failure scenarios described in chapter 5.1.2. Therefore, an alternative evolution scenario has not to be considered.

Cryogenic joints and *thermal expansion or contraction:* At the salt table, cryogenic joints may be generated by thermomechanical stresses during glacial periods. In the normal evolution scenario, the maximum penetration depth of these joints is 30 m. For less probable evolutions, a maximum depth of 100 m has been considered. Because of the thickness of the salt barrier, the containment function of the host rock would not be significantly impaired by such joints.

Pressure-induced permeation of fluids in salt formations: If a longer permeation path will be assumed for an alternative evolution, it has to be analysed whether the 150-m-thick salt barrier will be passed. Therefore, an alternative evolution scenario has to be considered.

Mechanical stress changes: Mechanical stress changes may result from different loads by *glaciation, sedimentation, erosion, earthquakes* etc. In compact, restrained rock formations, no significant consequences are expected. Fracture zones may be reactivated or new fractures generated, but – on the one hand – a fracture network that bypasses the salt barrier is not to be expected, and – on the other hand – fractures will soon be sealed by precipitation of salt minerals from brine. Therefore, an alternative evolution scenario has not to be considered.

Dissolution of salt minerals and *transformation of anhydrite to gypsum:* Both chemical processes will result in local alterations of the salt barrier. But even if these processes occur with a less probable high intensity, the barrier function of the 500-m-thick host rock will not be significantly impaired. Therefore, an alternative evolution scenario has not to be considered.

Natural gas intrusion: The gases from the surrounding geosphere will intrude into the salt dome through fractures and faults and will generate temporary flow paths and modify the hydrochemistry. Finally, the gases may also intrude into the mine openings. The potential consequences will be covered by the alternative evolution scenario for radionuclide transport.

5.2.2 Impact on the functionality of the Engineered Barrier System

The geotechnical barriers will be designed to resist the loads from the initial FEP in expected intensity (normal evolution scenario). Initial FEP can result in a failure of an EBS component if they occur with a design-exceeding intensity. Table 5.1 gives a short compilation of the initial FEP, their probable intensity, potential consequences, affected barriers, and an evaluation whether the consequences are already covered by another alternative evolution scenario or if a new alternative evolution scenario has to be described (scenario screening). Failure scenarios for the different engineered barriers are described in chapter 5.1.2.

Table 5.1: Initial-FEP, their characterisation and scenario screening, and FEP with a low probility of occurence

Initial FEP	**Less probable Intensity**	**Potential Consequences**	**Affected barriers**	**Alternative evolution scenario**
Seismicity	MSK 8	Fractures in concrete components of EBS, extension of EDZ	All barriers	No, covered by failure scenarios
Salt diapirism	0.2 mm/year corresponds to 200 m / 1 mio. years	Heterogeneous salt flow results in displacement and disrupture of EBS	EBS	No, covered by failure scenarios
Permafrost	200 m	Freezing of the upper bentonite seal (after functional lifetime)	Shaft seal	No, covered by failure scenarios
Glacial channelling	600 m	Destruction of shaft seal (after functional lifetime)	Shaft seal	No, covered by failure scenarios
Mechanical stress changes	20 % increase of lithostatic pressure by glaciation	Fracture generation in EBS (after functional lifetime)	EBS	No, covered by failure scenarios
Convergence	Low convergence rate	Retardation of fixation of EBS components in contour of excavations, late compaction of backfill	EBS	No, covered by failure scenarios
Pressure-induced permeation of fluids in salt formations	Increased permeation distance	If the salt table will be reached, radionuclides will be released	Host rock	Yes
Thermal expansion or contraction	Design-exceeding loads	Induced by heat flow from waste disposal and climate > fracture generation in EBS	All barriers	No, covered by failure scenarios
Swelling, shrinking and creeping of concrete	Different hydrochemistry > lower / higher swelling pressure	The swelling pressure of MgO concrete is important for sealing function	All geotechnical barriers	No, covered by failure scenarios
Swelling and shrinking of bentonite	Different hydrochemistry > lower / higher swelling pressure	The swelling pressure of bentonite is important for sealing function	Shaft seal, borehole seal	No, covered by failure scenarios
Settlement and compaction of backfill	Retardation of backfill compaction, high residual porosity (5 %)	Delay of long-term sealing, increased hydraulic conductivity > long-term flow paths via excavat.	Backfill	No, covered by backfill channelling

Initial FEP	**Less probable Intensity**	**Potential Consequences**	**Affected barriers**	**Alternative evolution scenario**
Fluid pressure changes	Design exceeding loads	Channelling in EBS and permeation in host rock	All barriers	No, covered by failure scenarios
Dissolution and precipitation of salt minerals	Inflow of unsaturated liquids and resulting leaching	Enlargement of fractures and EDZ < impairment of sealing of EBS; leaching of salt backfill > increased hydraulic conductivity	EBS, backfill	No, covered by failure scenarios, backfill channelling
Transformation of anhydrite to gypsum	Significant increase of volume > high swelling press.	Enlargement of fractures and EDZ, increased hydraulic conductivity	Shaft seal	No, covered by failure scenarios
Metal corrosion	Corrosion rate one magnitude higher than normal evolution scenario	High gas generation rate > fluid pressure, failure of container, transport of volatile RN. Initiation of pressure induced permeation in salt rock	HLW container, indirect by gas generation: EBS, host rock	No, covered by failure scenarios and by less probable characteristics of RN transport
Alteration of concrete	Corrosion rate one magnitude higher than base	Increased hydraulic conductivity, decreased mechanical stability	EBS	No, covered by failure scenarios
Alteration of bentonite	Alteration rate one magnitude higher than base	Increased hydraulic conductivity, decreased mechanical stability	Shaft seal, borehole seal	No, covered by failure scenarios
Microbial processes	Intensifies metal corrosion and gas generation	Early failure of the HLW disposal overpacks and high fluid pressure.	HLW disposal overpack	No, covered by failure scenarios
Channelling of sealing element	Final hydraulic conductivity 10^{-7} m/s	Failure of EBS	EBS	No, covered by failure scenarios
Channelling of a borehole seal	Final hydraulic conductivity 10^{-7} m/s	Failure of borehole seal	Borehole seal	No, covered by failure scenarios
Channelling of backfilling	Final hydraulic conductivity 10^{-6} m/s	Delay of long-term sealing, increased hydraulic conductivity > long-term flow paths via excavat.	Backfill	Yes

5.3 Less probable characteristics of the initial FEP mobilisation and transport of radionuclides

For the evaluation of the radiological consequences of repository system evolution, the FEP radionuclide mobilisation as well as radionuclide transport in the liquid phase and radionuclide transport in the gas phase are of highest relevance. Alternative characteristics for these processes can be justified to several uncertainties with regard to future evolution of the repository system and with the properties of the waste inventory.

With regard to radionuclide inventory, uncertainties may occur in terms of their chemical form (e.g. gaseous or easily mobilised). Considering radionuclide mobilisation, hydrochemistry is very important, first, for the corrosion of the waste container and second, for the alteration of the waste matrices (corrosion of fuel matrix, corrosion of glass, corrosion of metal, alteration of concrete). For hydrochemistry, a band width has been defined resulting from uncertainties with regard to concentrations, composition, and distribution of the constituents. Therefore, if hydrochemistry deviates significantly from the boundary conditions assumed for design and closure planning, an early failure of the waste container may occur and corrosion of the waste matrices may be intensified as well. Corrosion of waste matrices is combined with radionuclide mobilisation. The hydrochemistry and the amount of free water also influence the intensity of gas generation induced by the corrosion process. Gas – from *metal corrosion, microbial processes*, or from the geosphere (*gases in host rock, natural gas intrusion* (from surrounding geosphere)) is an important transport medium for volatile radionuclides.

Radionuclide transport relies on fluid flow (*liquid flow processes* and *gas flow processes*) and transport (*advection, dispersion, diffusion*) processes. The intensity of these processes depends on the hydraulic (porosity, permeability) and chemical (sorption, desorption, complexation, colloid generation and filtration) properties of the media flowed through (barriers, backfill, EDZ, host rock). Therefore, the alternative evolution scenario for radionuclide mobilisation and transport is closely linked to the alternative evolution scenarios for the failure of barriers (see chapter 5.1.2).

The alternative evolution scenario for radionuclide mobilisation and transport should address the uncertainties and the parameter band width of waste characteristics and boundary conditions.

5.4 Less likely FEP

These FEP describe undue modifications of technical barriers that have a lower probability of occurrence due to the comprehensive quality assurance measures for the preparation of construction materials and the performance of construction. Three FEP have been attributed to this FEP category (compare Table 5.1):

- *Channelling of a sealing element*: the consequences are covered by the failure scenario described in chapter 5.1.2.
- *Channelling of a borehole seal*: the consequences are covered by the failure scenario described in chapter 5.1.2.
- *Channelling of backfill:* if referring to the hydraulic long-term properties of the backfill, a new alternative evolution scenario has to be described. At early times, a roof crevasse will be generated by backfill compaction, but this crevasse should be closed by convergence in several thousands of years.

5.5 Reduced long-term sealing by crushed salt

There are still uncertainties with regard to the long-term compaction of crushed salt. Compaction is significantly linked with the humidity of the backfill – very slow compaction for dry backfill (disposal areas of COVRA concept), increased compaction rate for moistened backfill (transport and ventilation drifts of COVRA concept). But in any case, the compaction rate continuously decreases with reduced porosity and finally becomes a very slow and long-lasting process (running several 1,000s to 10,000s of years), which cannot be analysed by in-situ experiments. For the normal evolution scenario, the final porosity has been estimated as 1 %, but e.g. enclosed fluids in the pores can stop the compaction process. Therefore, a final residual porosity of 5 % has been assumed for the alternative evolution scenario. In this scenario, the backfilled mine excavation remains a potential fluid pathway in the long term. As a consequence, liquid flow and gas flow and linked compound (radionuclide) transport will continue. Furthermore, chemical alteration processes can persist.

5.6 Representative alternative evolution scenarios

Basing on the methodology described in chapter 3.4.2, the categories "Deviations concerning specific assumptions (with subcategories climate development, functionality of geotechnical barriers, and unknown geological characteristics)", "Less probable characteristics of initial barriers", and "Less probable characteristics of radionuclide mobilisation and radionuclide transport" have been analysed. As a result of the scenario screening, the following representative alternative evolution scenarios have been identified:

- Failure of a HLW waste container
- Failure of a shaft seal
- Failure of a drift seal
- Failure of a ramp seal
- Flow path between brine pocket and mine excavations
- Less probable characteristics of radionuclide mobilisation and transport
- Reduced long-term sealing by backfill
- Pressure-induced permeation of fluids in salt formations

6 Inadvertent human intrusion scenarios

Neither the future evolution of the biosphere nor future human actions are predictable. Therefore, the description of the biosphere in the FEP catalogue is rudimentary and vague.

“Inadvertent human intrusion” comprises all human activities after repository closure that will directly impair the geological and engineered barriers of the repository system (Beuth et al. 2012b). Therefore, such potential impacts have to be considered in long-term safety assessments. Because the future evolution of human beings and the human society are not predictable for long time frames, a systematic and comprehensive development of scenarios from the FEP catalogue is not possible. Therefore, stylised scenarios have to be used, referring to human actions that are plausible from a current point of view. In many national regulations, the procedures and the boundary conditions for handling these evolutions are defined.

Human intrusion activities may occur if all knowledge about the existence of the repository has been lost, which means in several centuries years after repository closure (IAEA 2017). There are many reasons for future exploration of the salt formations. Halite is an important constituent of the human diet, and potash salt is important for fertilizer production and other chemical processes. Furthermore, hydrocarbon reservoirs are often arranged at the flanks of salt dome structures, and salt dome structures may be used for hydrocarbon storage in caverns. Therefore, inadvertent human intrusion is seen as an possible future impact. The consequences of impairments of the repository system by human actions depend on the location of intrusion (disposal areas, other areas) and the status of the repository system (full or partial functionality of EBS, mine excavations flooded or dry).

In the FEP catalogue, four potential human actions that will be important for the long-term safety assessment of the repository are identified. “Human influences on climate” are reflected in the FEP Climate change. The other FEP define human actions that have to be considered in stylised scenarios.

6.1 Drilling activities

This FEP covers a broad spectrum of different scenarios, depending on the location of the drillings (salt dome flanks (HC exploration) or salt dome centre, disposal area with or without damage of a disposal overpack (different inventories), other underground excavations) and status of repository system evolution (functionality of EBS, status of backfill compaction, liquids/gas in mine excavations). If intrusion occurs at later times, fluids in all repository excavations will be contaminated. In general, drillings will disturb the geosphere around the repository and the performance of the engineered barrier system. While exploration drillings at the salt dome flanks are of low relevance due to their distance from the repository, any direct intrusion into the repository excavations may induce a liquid inflow or, if the repository is already flooded and the fluid pressure is high in the excavations, contaminated fluids can be squeezed out and contaminate near surface aquifers.

6.2 Mining and other underground activities

This FEP describes the construction and operation of a salt and potash mine or of leaching caverns in the vicinity of or within the repository. As for the drilling activities, this FEP will include a spectrum of scenarios differing in the location of the salt mine / caverns and the time of intrusion. In general, both activity groups will disturb the geosphere around the repository and the performance of the engineered barrier system. The relevance of consequences will increase with the reduction of distance to repository excavations. Because monitoring is part of construction work, it is expected that only a short inflow of contaminated fluids will occur during construction prior to the detection of the contamination. Therefore, the contamination will most probably be restricted to the mine openings or the cavern, with minor release into the biosphere.

6.3 Water management

Water management will take place in the overburden and adjacent formations. It includes water wells for water procurement, pumping, infiltration, underground storage, groundwater reservoirs, dams, sewage water treatment, and river management. These human actions may become relevant at late stages of the repository system evolution, if contaminated fluids from the repository have been transported through the shafts or the host rock into the aquifers of the overburden formations. Water management will affect groundwater flow, hydrochemistry, erosion, and sedimentation, and provide pathways from deep overburden formations to the biosphere. Therefore, water management may accelerate and intensify the spreading of contaminated fluids in aquifers and surface water bodies (seas, rivers, etc.).

7 Conclusions

The Dutch programme for analysing options for the disposal of radioactive waste in a deep geological repository in salt formations is at an early stage. For developing suitable disposal options and evaluate their long-term safety, generic studies will be carried out. In this context, the waste inventory has been compiled, the geological boundary conditions have been summarised, and the draft outlines for a disposal concept have been identified. To prepare a generic performance assessment, a FEP catalogue and scenario development are necessary. BGE TECHNOLOLGY GmbH has been commissioned by COVRA with the preparation of the corresponding documents.

For preparing the required FEP catalogue, FEP catalogues from different German salt projects as well as the NEA IFEP list have been referred to and adapted to the Dutch inventory, geology, and repository design. The FEP catalogue includes FEP descriptions, gives indications for relevance to performance and safety, identifies FEP that are directly affected by the property of a feature or the intensity of a process, and FEP that may change properties of a feature or intensity of a process, as well as results from a FEP screening (plausibility check). To increase the transparency of the repository system description, the FEP catalogue is structured into 5 compartments. The FEP catalogue includes all information necessary for scenario development. The present study considers the following categories of scenarios:

- Normal evolution scenario (= expected system evolution)
- Alternative evolution scenarios (=deviant system evolution)
- Inadvertent human intrusion scenarios

As agreed by COVRA, the methodology for scenario development corresponds to the German approach developed in several R&D projects and applied in the licensing procedure for the closure of the Morsleben repository.

The development of the normal evolution scenario is a “bottom-up approach” aiming for a comprehensive description of the expected evolution of the repository system. Starting points for description of the normal evolution scenario are the “initial-barriers” (= important barriers due to the safety concept) and the “initial-FEP” (= processes that directly affect the function of barriers). Furthermore, FEP that are related to radionuclide mobilisation and radionuclide migration have been addressed initially. All FEP considered in the normal evolution scenario have expected properties (features) and intensities (events/processes). Additionally, specific assumptions have to be defined to handle uncertainties that cannot be clarified at present (functionality of barriers, undetected geological properties) or will never be resolved (future climate evolution).

Alternative evolution scenarios are evolutions that differ in exactly one aspect from the normal evolution scenario (top-down-approach). They were developed from the following starting points:

- Deviations concerning specific assumptions (i.e. undetected geological properties, functionality of barriers, future climate evolutions)
- Less probable characteristics of initial FEP

- Less probable characteristics of the FEP mobilisation of radionuclides and transport of radionuclides
- Less likely FEP (describing modifications of barriers with a lower probability)

Finally, eight representative scenarios were identified for further consideration in the performance assessment:

- Failure of a HLW waste container
- Failure of a shaft seal
- Failure of a drift seal
- Failure of a ramp seal
- Flow path between brine pocket and mine excavations
- Less probable characteristics of radionuclide mobilisation and transport
- Reduced long-term sealing by backfill
- Pressure-induced permeation of fluids in salt formations

The future development of the biosphere as well as future human evolution cannot be predicted. Therefore, a systematic and comprehensive development of “Inadvertent human action scenarios” is not possible. Therefore, plausible stylised scenarios have to be addressed that refer to current human behaviour. Three potential activities that may have an impact on future repository evolution have been identified:

- Drilling activities
- Mining and other underground activities (incl. cavern leaching)
- Water management

The present study gives an overview of the well-tried and proven German methodology for FEP catalogue and scenario development. The document reflects the initial status of the Dutch programme for developing a DGR in salt formations. Therefore, the present characterisation of the FEP and the scenario description only give broad outlines of the future system evolution and have to be specified and verified at later stages of the Dutch programme.

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9 Annexes

Annex 1: FEP-Catalogue and Scenario Development for a HLW repository in a salt dome. Annex 1: FEP-Catalogue.- BGE TECHNOLOGY GmbH, BGE TEC 2023-10, Peine.

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