European Joint Programme on Radioactive Waste Management

7.3.3 Scenario development and FEP analysis, Domain Insight

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Overview

Based on the state-of-the-art, IAEA (2012) and NEA (2014, 2016) provided guidance and gave recommendations for preparing a safety case for radioactive waste repositories. For safety demonstration, it is necessary to predict the expected evolution of the overall system, which consists of the repository and the surrounding geosphere and biosphere. Due to limited knowledge on the system and the suitability of the modelling tools applied, a significant amount of uncertainties is related to the prediction of the complex system's evolution. Therefore, a basic requirement for safety case methodology is to reduce and handle these uncertainties. A FEP list (compiled in a FEP catalogue) and the scenario development are two measures to meet this objective. The NEA FEP catalogue compiles the FEP lists of many international repository projects and provides a comprehensive generic description of the repository system (features) and identifies processes and events that will occur in the future (NEA 2019). Based on the information in the FEP catalogue, scenarios will describe possible future evolutions of the system, which correspond to a combination of events and processes together with their characteristics and their chronological sequence. The occurrence of FEP as well as their properties (for features) or their intensities (for processes/events) may significantly vary, depending on location and time. Based on the extrapolation of geosphere/biosphere evolutions in the past on future evolution (actualism principle) as well as expert knowledge on the repository's impact on system evolution, possible (or expected) properties/intensities of processes/events can be identified and combined in probable/expected scenarios (also called: normal evolution scenarios, reference scenarios). Probabilities/intensities with lower probabilities will be described in alternative scenarios. The set of all analysed scenarios is supposed to cover the significant uncertainties regarding the future repository evolution (NEA 2016).

Keywords

Features, Events and Processes, FEP, Scenario development, Long-term Safety Assessment

Key Acronyms

Features, Events and Processes (FEP)

1. Typical overall goals and activities in the domain of Scenario development and FEP analysis

A comprehensive description of the repository system with its features and the identification of relevant processes and events as well as a prognosis of the future system evolution are prerequisites for a long-term safety assessment of the repository system and development of a safety case. FEP and scenarios are also important to design adequately the EBS and to conduct the performance assessment. Furthermore, those tools contribute to uncertainty handling in the prognosis of the future system evolution. They become international standards for preparing a safety case (IAEA 2012, NEA 2014) and have been implemented in most national radioactive waste management programmes. The corresponding methodology is a stepwise and iterative procedure and is supplemented by typical activities, according to the phase of implementation. In most national geological disposal programmes, the suitable activities are still generic. Usually, differences in methodology are attributed to the national regulations.

This section provides the overall goal for this domain, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to the phase of implementation, needed to achieve the domain goal. Activities are generic and are common to most geological disposal programmes.

<table>
<tr><th colspan="2">Domain Goal</th></tr>
<tr><td colspan="2">7.3.3 Evaluate post-closure features, events and processes relevant to safety to create plausible scenarios of disposal system behaviour (Scenario development and FEP analysis)</td></tr>
<tr><th colspan="2">Domain Activities</th></tr>
<tr><td>Phase 1: Programme Initiation</td><td>Starting points for the site selection process are the development of safety and safety demonstration strategies for different kinds of host rocks and waste types, the implementation of the safety strategy in selected disposal concepts, the description of generic geologic sites for different types of host rock (based on existing data from comparable sites), the development of generic FEP catalogues and deriving corresponding scenarios, process analyses for relevant phenomena and preliminary generic safety assessments.</td></tr>
<tr><td>Phase 2: DGR Site Identification</td><td>The site selection process is based on a comprehensive exploration programme to evaluate the geosphere’s properties and check the compliance with suitability criteria defined in regulations. Preliminary safety assessments (basing on FEP and scenarios) may also be measures required to evaluate rock suitability and thus contribute to site selection. Therefore, FEP catalogue and scenario development have to be substantiated continuously, based on the results of data acquisition by the exploration programme.</td></tr>
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Phase 3: DGR Site Characterisation	After site selection, comprehensive and detailed site exploration will be started. Furthermore, the compliance of the repository design and disposal strategy with the host rock's properties have to be demonstrated. Additionally, the technical feasibility and functionality of repository components, including the engineered barrier system (EBS), have to be demonstrated. At this phase, the generic FEP catalogue, the scenario development and the safety assessment will be transformed to site-specific ones.
Phase 4: DGR Construction	During DGR construction, further information will be acquired on the geosphere. The "as the built state" of the repository components will be verified and their properties will be specified. Based on this additional information, the FEP catalogue and the scenarios will be updated (iteration). During this phase, both tools are necessary to verify assumptions for repository design and functionality by performance assessments.
Phase 5: DGR Operation and Closure	During DGR operation and (simultaneous) construction, the information in the FEP catalogue and the scenarios will be updated continuously and confirmed corresponding to the status of the repository project (iteration). The boundary conditions and potential loads for the EBS can be identified by FEP and scenarios. During this phase, the geotechnical barrier system will be constructed (as-built-state) and therefore, the specific barrier properties have to be confirmed by performance assessments. The final status of the EBS is the starting point for long-term safety assessment.

2. Contribution to safety assessment and implementation goals

2.1 The roles of FEP and Scenarios in the Safety Case

2.1.1 Goal: Identification of all relevant future evolutions of the repository system

The prognosis of the evolution of the future repository system is a prerequisite for a long-term safety assessment in the context of a safety case. FEP catalogue and scenario development are common tools to describe the repository system and its future evolution. In this context, the limited knowledge about the system and the suitability of the modelling tools applied result in a significant number of uncertainties related to the prognosis of the system's evolution. The complexity of the investigated system (consisting of an engineered barrier system – EBS, and natural barriers/features (geosphere, biosphere)) over long periods of time demand an adequate management and communication of these uncertainties.

It is not possible to predict the future evolution of the repository system exactly. Therefore, it is a common international procedure to cover these uncertainties by means of a FEP catalogue and the scenario development. The FEP catalogue helps to reduce the system's complexity by analysing its components and the evolution of the key processes. A scenario describes one possible future evolution of the system by combining the system's components with events and processes, taking into account their characteristics and their chronological sequence (NEA 2014). A set of probable and less probable scenarios is supposed to cover the significant uncertainties regarding the safety of the repository (IAEA 2006).

In the development of safety cases, scenarios are not only important tools for managing uncertainties regarding the repository system's evolution but they are also used to describe and document the syntheses of the scientific and technical basis of the safety case. This includes the transfer of scenarios to numerical cases. The scenarios provide an overall framework in which the calculated consequences can be discussed, including biases or deficiencies due to omissions or limited knowledge (NEA 2001). Furthermore, they provide a tool to analyse the comprehensiveness of the analysis and a basis for communication and explanation of the safety case to different audiences.

Given a potentially large number of scenarios, scenario development is a systematic process for producing a realistic assessment that still spans the range of possible system evolutions and does not neglect any scenario that could make a significant contribution to the overall risk associated with a repository.

Because of their high relevance for the safety case, many national regulations demand the use of scenarios. Mostly, scenarios with a certain probability have been considered as basis. Scenario categories include expected scenarios (probable) and variant, alternative or disturbant scenarios (less probable). In some methodologies, the corresponding conditional annual risk is considered as a criterion for scenario classification. In addition to these scenarios, hypothetical scenarios (="what-if-scenarios") are often used in safety assessments to check the robustness of the system (IAEA, 2012). Due to the speculative nature of these scenarios, there are no corresponding regulatory criteria. Another special category of scenarios includes human intrusion scenarios. Because human evolution as well as the corresponding living conditions and technologies are unpredictable and thus theoretical in the long term, the corresponding scenarios are stylised and often defined in regulations (IAEA 2012). The safety assessment has to be structured according to these classes.

Alternative approaches for comprehensive system description and scenario development are also available. For example, ANDRA's methodology for scenario development relies on a Phenomenological Analysis of Repository Situations (PARS) (ANDRA 2005). This means a description of the evolution of relevant processes that affect natural and engineering components for post-closure safety assessment. In this methodology, the NEA FEP catalogue has been used as a verification tool to ensure completeness of its safety understanding.

Sometimes, scenarios that have to be considered in safety assessment are defined in the regulations (e.g. for the Yucca Mountain Project, Freeze et al. 2001). In this case, a FEP catalogue can be used to check the completeness of the safety assessment.

2.1.2 Goal: Completeness of the safety assessment

With regard to the reliability of the long-term safety assessment for a repository for radioactive waste, the "completeness" of the FEP catalogue is an important objective. Therefore, the comprehensive description of all features of the repository system and the identification of relevant processes and events for the future system evolution in the FEP catalogue reduces the complexity of the system. Furthermore, the description of the relationships between natural site characteristics and evolutions on the one hand and environmental conditions and processes that are changed by the repository mine and the disposal of radioactive waste one the other hand, are suitable measures to provide a proper basis for the description of the future system evolution.

The underlying idea of FEP is that the engineered and natural features making up the repository system as well as the events and processes that determine its performance can be described by a set of discrete and interrelated units of information or phenomenon descriptions. In principle, a completeness check of the features is possible by comparison with the site description and the repository concept. An adequate check for the comprehensive consideration of processes and events is more complicated due to missing criteria. The processes and events in past and at the time of consideration give indications for expected processes to be considered for future system evolution. However, these processes and events do not cover impacts of the construction and operation of the repository on the geosphere and biosphere. Corresponding processes and events can be estimated by considering the interactions between different FEP in a predicted environment due to natural laws. This means that the combination of specific boundary conditions (e.g. liquids with specific hydrochemistry) and components (e.g. metal components) will result in corrosion processes and gas generation in the future.

Another tool for a completeness check is the NEA FEP database, which provides a useful international benchmark against national safety assessment studies (NEA 2019). The evaluation of the resulting FEP list is based on the overall assessment strategy, taking into account the limits of the scientific knowledge and of the analysis tools that are available. The FEP approach encourages consideration of the aspects and implications on a detailed level. The properties of the components as well as the occurrence, characteristics, intensities of processes and events depend on the boundary conditions that are described in the scenarios. Therefore, iterations between scenario development and FEP characteristics are necessary.

The discretisation of the repository system into FEP may be the basis for completeness check and the scenario development process. In most countries, this process consists of the steps FEP identification (incl. FEP screening + future evolution of the FEP), the combination of FEP into a set of scenarios (scenario development) and synthesis of a final set of scenarios (by combination of similar scenarios to representative scenarios). In some methodologies, modifications or supplementary steps are included in this general procedure to come to a more systematic and stringent approach. E.g. the German methodology considers important barriers from the safety strategy as "initial barriers", processes/events impacting the barrier function as "initial FEP", and FEP related to radionuclide mobilisation and transport, and takes them as starting points for the scenario development (Lommerzheim et al. 2019).

Taking the comprehensive data compilation of a FEP catalogue as a basis, the scenario development can be performed systematically and checked for completeness. Finally, it can be argued that the set of scenarios will be "complete" as well.

2.1.3 Goal: Basic tools for the design and performance assessment of geotechnical barriers

In addition to the total system performance analysis, FEP and scenarios can also be used as basic tools for specific investigations to design geotechnical barriers and to analyse their functionality (performance assessment).

The engineered barrier system (EBS) is a key element to restore the barrier function of the geosphere after excavation of the mine openings of the repository and to contain the radionuclides at the disposal site. Depending on the safety strategy, the EBS may consist of shaft, drift, and borehole seals as well as of a suitable backfill material. The EBS will seal the mine openings for the demonstration period. FEP and scenarios describe the potential future evolution of the repository system and are thus important tools to identify possible actions that may impair the barriers during in the future.

In Europe, there are standard codes for technical engineering called EUROCODE, that are also implemented in national regulations. But in principle, these regulations are defined for constructions with a significantly shorter functional time than the geotechnical barriers. Nevertheless, the criteria as well as the procedure for engineering demonstration of functionality can be extrapolated to longer functional times and are thus applicable to geotechnical barriers (Müller-Hoeppe et al. 2017). The methodology of EUROCODE is based on two fundamental issues - the 'ultimate limit states', which define the stability of the construction, and the 'partial safety factors', which have to be added to impacts/loads on EBS to reduce the load resistance of EBS. Thus, uncertainties in engineering design can be handled.

For the application of the EUROCODE methodology in the context of a safety assessment for a repository, an approach to obtain the required data for performance assessment of the barriers from the FEP catalogue and the scenarios has been developed (Müller-Hoeppe et al. 2014, Simo et al. 2021). Thus, the key elements of the EUROCODE methodology can be derived from the FEP catalogue and scenarios in the following way: "actions" = processes and events, "construction resistances" = feature properties, "design situations" = scenarios and "load cases" = impacts on EBS by combination of processes and events. To evaluate the boundary conditions of the barriers, an overall description of the repository system evolution (base scenario, farfield) as well as detailed descriptions of the barriers' close surroundings can be used (base scenario, nearfield). Processes and events that may impair the function of the barriers can be identified from the FEP catalogue and the intensity and properties of these processes can be derived from the interactions with other FEP. The "resistances of the barriers" are specified in the properties of the corresponding component FEP. The "design situations" can be derived from the expected base (probable) scenario as well as from the alternative scenarios with lower probability. For the numerical performance demonstration of the EBS, different "load cases" that cover the most relevant impacts, have to be defined. In this context, hydraulic (fluid pressure in combination with chemical actions) and hydro-mechanical (in combination with thermal) load cases are the most relevant ones. The design of the barriers has to be robust for the boundary conditions defined by the (expected) base scenario. Other load cases will analyse the consequences of the failure of a barrier (shaft or drift seal), the water inflow from reservoirs in the host rock, high gas generation rates etc. on the repository system's evolution (alternative scenarios).

In Germany, the methodology to demonstrate the functionality of the EBS by means of FEP catalogue and scenarios is applied in the closure projects for the Morsleben Repository and the Asse Mine.

2.1.4 Goal: Building confidence in the safety case

Transparency and traceability of basic information in the FEP catalogue and scenario development are important measures to explain the fundamentals of the safety case to different stakeholders. Furthermore, the complexity of the system can be reduced by the structured FEP description. So, the FEP catalogue gives an overview of the respective current understanding of the repository system and its expected future evolution. Furthermore, the methodology, the justification of scientific decisions, and deficiencies in information are explained.

The elements of the FEP catalogue provide the following information (Lommerzheim et al. 2019): the "features" describe all relevant components of the repository system, including the geosphere and the biosphere comprehensively in a transparent manner. The prognosis of the "events and processes" during the expected system evolution is based on an analysis of slow and long-ranging processes and events in the past and at the time of consideration (e.g. geological or climatic processes) and their extrapolation to the future (actualism principle) on the one hand. On the other hand, new processes and events will be initiated by the excavation and operation of the mine openings and the impact of the disposal of radioactive waste on the geosphere and biosphere. These processes can be identified by expert judgement by referring to natural laws and causal chains (especially in early phases of repository project), site investigations including exploration and in-situ tests in underground research laboratories or by surface laboratory tests and the analysis of technical and natural analogues. All expert decisions will be documented, explained, and justified in the FEP catalogue in a transparent matter. Thus, the assumptions for the safety assessment can be checked for consistency and reviewed by independent experts. Supplementary to the comprehensive data set, any lack of data or poor data, and the handling of these deficiencies will be documented in the FEP catalogue.

During the repository system evolution, the features, events and processes interact in a different manner depending on the specific boundary conditions reflected in the scenarios. These interactions determine the properties of the components as well as the occurrence, characteristics, intensities of processes and events. Therefore, iterations between scenario development and FEP characteristics are necessary. Due to the systematic development of scenarios from the "complete" FEP catalogue, the development of a comprehensive set of scenarios that cover all relevant future evolutions is plausible and traceable as well.

3. International examples of FEP and scenarios

The NEA International FEP (IFEP) List provides a compilation of FEP from different host rock types and repository concepts of advanced international Radioactive Waste Management (RWM) programmes (NEA 2019). This is a comprehensive and structured list of generic FEP, that is relevant to the assessments of the post-closure safety of any DGR in the international framework of the NEA. The comprehensive NEA IFEP list has been accepted internationally as a tool to support national programmes in the generation of the respective FEP catalogues that is used as a basis for a safety case and as benchmark to check for "completeness" of just implemented FEP catalogues. Additionally, RWM organisations have provided NEA with so-called "Project-specific" FEP (PFEP) Lists referring to specific waste types, geologic environments, and disposal concepts. They can be seen as examples on how to adapt generic FEP lists to project specific ones. NEA also presents the FEP lists in the form of electronic FEP databases, which are in an easily navigable and searchable format.

Boundary conditions are different for near surface disposal facilities for LILW resulting in adapted FEP lists (higher relevance of biosphere impacts esp. human intrusion). In IAEA (2004a, b) safety assessment methodologies for near surface disposal facilities have been addressed and examples have been discussed (ISAM project).

The development of scenarios is one of the key elements of a safety case (IAEA 2012) and has been discussed at two workshops of OECD-NEA concerning scenario development methods and practice (NEA 2014, 2016). During these workshops, a variety of methods were presented and discussed. Most of these methods are based on characterising future evolutions of a repository system by means of FEP catalogues. In addition to geology, waste inventory, and repository design data, the fundamentals of the safety case include international and national safety standards and requirements that are fixed in the respective national legal framework. Based on these safety standards, a specific safety concept has to be developed, taking into account the host rock as well as the repository concept. Here, relevant barriers and their safety functions are defined and explained. Relying on the FEP catalogue, the safety functions can be used as starting points for scenario development.

Some national programmes divide their scenarios into different categories, based on relevant FEP, their probability, and their potential effect on the evolution of the repository. Often, these classifications are determined by national regulations. Due to its speculative nature, there are no specific requirements for what-if-scenarios in the national regulations but they are widely used in demonstrating system robustness and in illustrating the function of specific barriers. Future human intrusion is treated as a separate scenario category, which requires a handling using stylised approaches.

The integration of top-down and bottom-up elements is a feature of all practical approaches to scenario development. So, the bottom-up approach gives a comprehensive description of the repository system evolution ("phenomenology" and "technology"), taking into account impacts on the safety functions of the barrier system (base (expected) scenario). The top-down approach considers alternative (deviant) evolutions caused by different intensities of relevant processes and events (perturbing FEP) and hence gives rise to alternative scenarios. FEP lists and other tools are used to confirm that key FEP and uncertainties are covered adequately in one or more of the identified scenarios and associated calculation cases.

Examples for mature national project-specific FEP lists and/or scenario development for different host rocks and repository concepts include

- for salt formations: Germany (Mönig et al. 2013) and USA (Sandia National Laboratories 2008)
- for clay formations: Belgium (Mallants et al. 2008), France (ANDRA 2005), Germany (Lommerzheim et al. 2019) and Switzerland (NAGRA 2002)
- for crystalline rock: Sweden (SKB 2019) and Finland (Posiva 2012)
- for other host rocks: USA (Yucca Mountain) (Freece et al. 2001)

4. Critical background information

The section highlights specific components, key information, processes, mechanisms, data or challenges that have a high impact or are considered most critical for the above-mentioned impacts on disposal safety and implementation goals for both the pre-disposal phase, the repository layout, and the post-closure phase.

4.1 Pre-disposal

The focus of predisposal investigations relies on data acquisition for completion of the FEP catalogue in combination with an update of the scenario development. Furthermore, assumptions for repository design and geoscientific long-term prognosis have to be specified and verified.

Geosphere investigations and evaluations: Starting with site exploration and continuing during the construction and operation phase, a comprehensive exploration and monitoring programme will be implemented to verify the safety-relevant properties of the host rock. These properties include lithological, hydrogeological, and tectonic characteristics of the rock that enable an evaluation of the mechanical, hydraulic and thermal properties. In-situ tests provide further information on mechanical and hydraulic processes. Compliance with the requirements for host rock properties has to be demonstrated. The new geological data and results of investigations will be recorded continuously in the FEP catalogue to convert the initial generic FEP catalogue into a site-specific one.

Natural analogues: Many processes in the repository system evolution occurred in the past but will also continue in the future. Some of these processes are extremely slow and run over long periods of time (e.g. diffusion processes or mineral transformation). Therefore, these processes cannot be analysed by in-situ tests or laboratory experiments. If these processes were initiated in past and documented in the rock characteristics, they would provide important information for the future system evolution. For example, age determination of pore water or stagnant ground water gives indications of the containment function of the host rock. Host rock that has been heated by plutonic or hydrothermal intrusions, shows mineralogical alterations and the consequences of the thermal impact on the host rock properties.

Geoscientific long-term prognosis: During site exploration, additional site-specific data will be acquired for the geoscientific long-term prognosis. These investigations analyse the site evolution in the past and at present and extrapolate it to the future. The corresponding information will be included in the FEP catalogue as well as in the scenario development.

4.2 Repository layout

Verification of repository design: Initially, the repository design is just a generic design that has to be verified and adapted to the specific site. Fundamentals are the exploration data, acquired by drilling and geophysical measurements during the site exploration and the construction phase of the repository mine. Important data for repository design characterise the thermo-hydro-mechanical properties of the geosphere. Data of fractures and faults as well as the occurrence and characteristics of fluid reservoirs are of special relevance. For all mine excavations, compliance with the requirements of Mining Law and Nuclear Regulations for operational safety as well as for long-term safety has to be demonstrated. The most restrictive demands will be defined for the disposal areas that are of highest importance for the safe containment of the radionuclides. The site-specific optimisation of the repository design will be included in the FEP catalogue and also reflected in the scenario development.

Technical feasibility and functionality studies: When the host rock characteristics have been specified to a suitable level of detail, the technical feasibility and functionality of the provided technical equipment and installations for mining (e.g. lining), disposal (e.g. verify required rock properties for waste disposal) and closure (e.g. compatibility of construction material and barrier design with impacts from geosphere) has to be analysed and evaluated. For repository operation, for instance, the stabilisation of the mine openings by means of suitable lining and the reduction or prevention of water inflow by means of effective injection measures are important issues. For the disposal areas, compliance of the host rock with the specific requirements has to be verified (e.g. homogeneous rock texture, no fractures/faults with a high hydraulic conductivity, no fluid reservoirs, mechanical properties must enable the drilling of vertical/horizontal emplacement boreholes or excavation of disposal drifts with the required geometry). Important issues for the closure of the repository include the compatibility of the construction materials with the geosphere properties, a suitable design of the barriers to resist litho- und hydrostatic pressure as well as no undue impairments by thermomechanical stresses resulting from the disposal of heat generating waste. Furthermore, it has to be shown that the barrier construction will be appropriately fixed in the mine excavation. The contact zone between the barrier and the adjacent rock as well as the excavation damaged zone (EDZ) will be sealed by convergence or by technical measures (swelling construction material or sealing by injection measures). The resulting information will also be included in the FEP catalogue and the scenario development.

4.3 Post-closure

FEP analysis and scenario development are linked to the post-closure phase of the repository. They give a compilation of possible future evolutions of the repository system. All uncertainties that consider the occurrence, the characteristics, and the intensities of future processes and events have to be reflected. The uncertainties will be handled by the bandwidth of FEP characteristics and by a spectrum of probable and less probable scenarios. Some examples include:

Corrosion of waste matrix and of waste container: Depending on the host rock type and the corresponding safety concept, waste matrix and waste containers are primary technical barriers that contribute to the safe containment of the radionuclide inventory in the repository for different periods of time (early post closure period in salt and clay formations, throughout the demonstration period in crystalline rock). Waste matrix corrosion will only occur after failure of waste container (i.e. after functional lifetime of the container or due to design exceeding impacts). Depending on humidity and hydrochemistry waste container and matrix will be altered by corrosion processes. The corresponding boundary conditions are compiled in the FEP and the expected evolutions are deduced in the scenarios. An important consequence of the corrosion of the waste matrix and of the waste container is the radionuclide mobilisation and the start of radionuclide transport, which is part of scenario description. Due to the uncertainties with regard to the future repository evolution (e.g. evolution of hydrochemistry over time), generation of pathways by repository processes (e.g. thermomechanical stresses, alteration of rock/construction materials due to modified hydrochemistry), the timeframe and the intensity of corrosion are difficult to predict. With regard to the release of radionuclides, the sorption capacity of the corrosion products may have to be analysed if the sorption capacity of the host rock itself is low (e.g. salt formations). In contrast, for clay formations the sorption capacity of corrosion products is of low relevance.

Functionality of the engineered barrier system (EBS): For many engineered barriers, bentonite is considered as the favourite construction material, due to its swelling properties and its high sorption capacity for radionuclides (as characterized in the FEP). However, to ensure functionality, sufficient amounts of liquids have to be available for bentonite saturation. Therefore, a "dry" environment would be unfavourable for bentonite functionality but favourable for reducing radionuclide mobilisation (“conflictive” requirements). Furthermore, hydrochemistry will influence both the swelling and the sorption capacity of the bentonite. So concrete corrosion – originating from other barrier components (e.g. concrete abutments) – would influence hydrochemistry in an unfavourable way. In general, the long-term stability of the construction materials depends on the changes in hydrochemistry, which are difficult to predict. In the shafts, differences in hydrochemistry may result from climate changes. Thus, during glacial periods, the hydrochemistry of the groundwater will change due to a reduced groundwater recharge. The microbial degradation of asphalt sealing elements also depends on hydrochemistry. In the context of the diverse impacts the probable and less probable evolutions described in the scenarios are of highest relevance. In total, there are many uncertainties with regard to processes and events that could impair the EBS. FEP catalogue and scenario development contribute to the uncertainty management.

Transport processes for radionuclides: Radionuclide transport is a key issue of the safety case. This transport is induced by the complex interactions between multiple properties of solid matters and the fluids in the repository system. Key issues are the hydraulic (porosity, permeability) and mineralogical properties (sorption capacity, colloid generation) of the geosphere and the construction materials as well as the mechanical (fluid pressure) and hydrochemical properties (composition) of the liquids and gases. The main uncertainties for the description of the future system evolution comprise changes of the hydraulic and mineralogical properties of the solid matters by thermo-hydro-mechanical and chemical impacts in the long-term, fluid inflow from the geosphere or via the shaft/boreholes from overburden formations or the biosphere, and changes of hydrochemistry and fluid pressure. In addition to flow processes, the transport of constituents by colloids or complexation and the retardation by sorption have to be considered. The comprehensive description of the repository system components and processes/events by FEP in combination with the description of the future system evolution by scenarios helps to manage the complexity of the system and increases the understanding of future systems evolution.

Undetected properties of geosphere: All technologies for the exploration of the geosphere are characterised by inherent uncertainties. Therefore, the information value and the precision of geophysical measurements depend on the properties of the rock formations – if the rock diversity is high, the significance of geophysical results increases. So, the mineralogy and texture as well as the fluid saturation of the pore or fracture volume and the occurrence of layer boundaries, fractures and faults are important characteristics that are detectable by geophysical measurements. Other sources for uncertainties are the limited resolution and inaccuracy of geophysical sensors as well as the influence of the measuring conditions – the exactness of structure detection decreases with increasing distance between geological structure and the measuring site.

Exploration drillings offer very precise information on the lithological and hydrogeological characteristics of the geologic formations, but the possibilities to detect fractures and faults are limited. Furthermore, the information acquired by an exploration drilling only provides punctual information that must not be representative for the whole rock formation.

Therefore, undetected geologic characteristics cannot be excluded in the evaluation of the future repository evolution and have to be considered in the FEP catalogue and the scenario development.

Climate evolution: The prognosis of future climate evolution is based on the analysis of climate changes in the past (mostly restricted to the last 1 mio. years) that are documented in the characteristics of the geosphere. Climate cycles are usually interpreted to originate from astronomical cycles (Milankovitsch–cycles) that are constant for long periods of time and that will also persist in the future (actualism principle). However, analysing long periods of time, the timeframe of the astronomical and climate cycles also changed. Therefore, it is not possible to state exactly what type of cycle will occur in the future. Furthermore, the different phases of climate cycles show different characteristics, e.g. intensities of temperature changes, precipitations and glaciation (e.g. Elster, Saale, Weichsel-periods). In future, the climate cycles may be changed by human impact. The uncertainties with regard to future climate evolution can be reflected by suitable FEP and scenarios that cover the spectrum of possible future climate evolutions.

Biosphere characteristics: The characteristics of the biosphere will vary significantly, depending on the climate regime (warm or cold periods). Especially glacial periods will completely reconfigure the surface of the landscape and of the upper parts of the rock formations by erosion and deposition. The climate impacts by temperature, water cycles (including precipitation, evaporation, surface and groundwater) and soil properties will require corresponding adaptions of animals and plants as well as of the living conditions of the human population. Due to the long demonstration period of 1 mio. years for a HLW repository, 10 climate cycles have to be taken into account (assuming 100.000 years per cycle). The consequences for the biosphere and the human behaviour are unpredictable. Therefore, the biosphere will be described in a stylised manner in the FEP catalogue and in the scenario development.

4.4 Integrated information, data, or knowledge (from other domains) that impact the understanding of FEP and Scenarios

FEP and scenarios are fundamental elements of the safety case. They are to give a comprehensive description of the repository system and to identify all its relevant future evolutions. Therefore, there are numerous interfaces with themes and domains that describe parts of the repository. The most relevant issues include:

• Theme 3 Engineered barrier system: This is the key issue of the safety case. In this theme package, all relevant characteristics of waste forms (3.1), waste containers (3.2), geotechnical barriers (buffer, backfill, seal/plug materials) (3.3), and EBS systems integration (3.4) are described and evaluated with regard to their impact on the disposal environment.

• Theme 4 Geoscience: In this theme group, all relevant aspects of the geosphere are discussed. So the natural barrier system and its contributions to the safety objectives (4.1), the impact of repository construction and operation on the natural geologic barrier (4.2), and the expected evolution of the geosphere (including the repository) in response to natural processes and future human actions (4.3) are described. A compilation of relevant geoscientific key information regarding long-term safety (conceptual models) and repository is given in theme 4.4.

• Theme 5 Disposal Facility: From this theme, the as-built status at the end of the closure phase has to be included in the FEP catalogue and scenario development, which is important for the performance assessment.

Theme 7 Safety Case: In this theme, the different steps of methodology for developing a safety case are described. The steps 7.1 Safety strategy and 7.2 Integration of safety-related information define objectives for the safety assessment that are also reflected in the FEP catalogue and scenario development. FEP catalogue and scenario development are combined in the domain 7.3.3 of subtheme 7.3 Safety assessment. Due to iterations in the safety assessment procedure, the domain is closely linked to domain 7.3.1 Performance assessment and models. FEP and scenarios also contribute to the domain 7.3.2 uncertainty management.

5. Maturity of knowledge and technology

Processes and events as well as a prognosis of the future system evolution are prerequisites for a long-term safety assessment of the repository system (safety case). Scenario development and FEP analysis are approaches for uncertainty handling regarding the future system evolution. They have become international standards for preparing a safety case (IAEA, NEA) and have been implemented in most national radioactive waste management programmes. The corresponding methodology is a stepwise and iterative procedure and is supplemented by typical activities, according to the phase of implementation. In most national geological disposal programmes, suitable activities are still generic. Usually, differences in methodology are due to the respective national regulations.

5.1 Advancement of safety case

There is a common international understanding of the objective, the structure and the contents of a safety case (IAEA, NEA). This consensus also includes screening of FEP and scenario developments as fundamentals of the methodological approach. For the methodology, the FEP catalogue may be used as starting point for scenario development or for completeness check of scenarios that have been derived from phenomenological or technological descriptions. Sometimes, national regulations demand modifications of the methodology, e.g. by defining special scenarios that have to be taken into account. For countries that start to implement the safety case for projects and for countries with advanced programmes, the NEA FEP database provides a useful international benchmark to check for completeness of their national FEP catalogue (NEA 2019).

5.2 Optimisation challenges and innovations

In national radioactive waste programmes, the methodological approach for the safety case has to be adapted to the regulations, which sometimes also include specific requirements for the safety concepts and safety demonstration methodologies.

With regard to the FEP, an optimisation of the approach to evaluate the comprehensive and complex information provided by the FEP catalogue would be useful. The information about components (and their properties), processes and events should be included completely in scenario descriptions in an effective and transparent manner. Dependence trees have often been generated to illustrate the interactions between the FEP. However, the number of levels has to be restricted in order to limit complexity and to ensure manageability and transparency. The FEP screening (non-relevant FEP) and the cutting of the causal chains have to be justified in a plausible manner.

Numerical models are important and efficient tools to increase future repository system evolution. Comprehensive descriptions of thermal, hydraulic, mechanical and chemical processes are possible. Uncertainties and restrictions of numerical models result from the data reduction and the abstraction of the repository system. In an iterative process the numerical results can be also included in the FEP catalogue. The FEP catalogue is important to check whether all FEP couplings were really included in the phenomenological description assessed by numerical modelling.

For scenario development, different methodologies have been implemented – some relying on the FEP catalogue and others on numerical models (PARS methodology) (compare chapter “The roles of FEP and Scenarios in the Safety Case”). A benchmarking of the results of those different methodologies would be of high value.

Another challenge in the safety assessment methodology is the procedure to proceed from scenarios to numerical models. At this point, an approach to check for completeness of the numerical model on the one hand and for the consequences of the simplification and abstraction in models on the results of the safety assessment on the other hand is necessary.

5.3 Past EC Projects and ongoing RD&D in EURAD

Past EC Projects:

Ongoing EURAD Work Package (2019-2024): In the EURAD programme, the safety case and related issues (safety strategy, integration of safety related information, safety assessment and tools) are covered in work package 7 HITEC. This also includes FEP catalogue and scenario development as tools to integrate safety related information and to define potential future evolutions of repository system as starting points for safety assessment.

6. Uncertainties

With regard to methodology, there are fundamental uncertainties regarding the procedure to coming to the most effective and transparent evaluation of FEP data for scenario development:

- The procedure to reflect the complex interactions between features, processes and events in a comprehensive and transparent manner. The features are characterized by a significant number of THMC properties, that are differently affected by events and processes (e.g. stress changes mainly effect mechanical properties). Due to the complexity the system description cannot reflect all FEP interactions, but they have to focus on the most relevant issues. The resulting consequences have to be addressed.

- To limit complexity and to ensure manageability, non-relevant FEP have to be screened out in the dependence trees by expert judgement. Even if the screening process has been done in a systematic approach and supported by arguments and plausibilities, uncertainties will persist.

- In many aspects, the definition of basic scenarios with the highest probabilities of occurrence and the definition of comprehensive descriptions of future evolutions (representative scenarios), that cover all relevant aspects, rely on expert judgement. Despite logical arguments and plausibilities, it is not possible to demonstrate the completeness of the provided system evolutions and their probabilities of occurrence.

- Some assumptions for future evolution of the repository system are also based on plausibilities (e.g. actualism principle) and expert judgement (e.g. climate development). Those uncertainties will persist in future and cannot be verified. They have to be discussed basing on their bandwidth of characteristics and their possible consequences in a balanced and equivalent manner.

Additional uncertainties occur with regard to the next step which is the transition from scenarios to numerical models:

- The scenarios are to give a realistic description of future repository system evolution. Due to restrictions of hardware and software, the entire repository system evolution cannot be included in a numerical model. Simplifications and abstractions are necessary to make the numerical model manageable. A systematic approach is necessary to demonstrate the transition from the realistic description to the numerical model. It has to be ensured that the scenario is completely represented by the model.

- The consequences of simplifications and abstractions in the numerical model on the results of the safety assessment must be evaluated.

7. Guidance, training, and communities of practice

The main goal of European Joint Programme on Radioactive Waste Management (EURAD) Work Package (WP) 13 is to establish the ‘School of Radioactive Waste Management (RWM)’. In this context a “training course on safety case development and review” is provided in November 2022.

OECD-NEA published on one hand a paper on the “Nature and Purposes of the Safety Cases for Geological Repositories” (NEA 2013) and on the other hand provides several papers on the FEP catalogue and Scenario Development as key issues for the safety cases (NEA 1992, 2001, 2013, 2014, 2016, 2019). Furthermore, OECD-NEA implemented the “Integration Group for the Safety Case (IGSC)” as a main technical advisory body to the “Radioactive Waste Management Committee (RWMC)” on the deep geological disposal of long-lived and high-level radioactive waste to foster full integration of all aspects of the safety case. The task of the IGSC is to assist member countries to develop effective safety cases supported by a robust scientific-technical basis. Furthermore, the group provides a platform for international dialogues between safety experts to address strategic and policy aspects of repository development. The IGSC is supported by four subgroups carrying out tasks on specific topics, e.g. Clay Club, Salt Club, Crystalline Club and the Expert Group on Operational Safety (EGOS). Work of IGSC is closely linked to IAEA and EC groups.

IAEA is another international guiding authority that publishes several Safety Guides and TECDOC dealing with issues of safety cases, e.g. IAEA 2011, 2012, 2016.

With regard to education and on-the-job training of students and young colleagues many waste management organisations have implemented adequate programs, which are often linked with lectures at universities. Furthermore, training courses are often offered at underground research laboratories (e.g. Grimsel URL, Mont Terri URL, Bure URL, ÄSPÖ URL).

Guidance
- Radioactive Waste Management Committee - RWMC - The Safety Case and Safety Assessment for the Disposal of Radioactive Waste - IAEA - Geological Disposal - Generic Post-closure Safety Assessment (December 2016) – RWM - Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste, An International Database – OECD NEA - Scenario Development Methods and Practice: An Evaluation Based on NEA Workshop on Scenario Development - Scenario Development Workshop Synopsis - Integration Group for the Safety Case – OECD NEA - International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste – OECD NEA - Safety concept, FEP catalogue and scenario development as fundamentals of a long-term safety demonstration for high-level waste repositories in German clay formations
Training
- Training offered in EURAD - ENEN2plus project, the largest and most integrative nuclear Education and Training (E&T) effort
Active communities of practice and networks
Links to CoPs/networks will be added in updated versions.

8. Key References

ANDRA (2005): Dossier Argile 2005. Tome Phenomological evolution of a geological repository.- Agence national pour la gestion des déchèts radioactifs , Paris.

Freeze, G.A.; Brodsky, N.S.; and Swift, P.N. 2001. The Development of Information Catalogued in REV00 of the YMP FEP Database. TDR-WIS-MD-000003 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company.

Freeze, G.A., Kirkes, Ross, and Leigh, Christi. 2015. Scenario Development in the U.S. NEA IGSC Scenario Development Workshop. Paris, France. June 1-3, 2015.

IAEA, 2004a: Safety Assessment Methodologies for Near Surface Disposal Facilities. Volume 1 Review and enhancement of safety assessment approaches and tools.- International Atomic Energy Agency, Vienna, ISBN 92–0–104004–0

IAEA, 2004b: Safety Assessment Methodologies for Near Surface Disposal Facilities. Volume 2 Test Cases.- International Atomic Energy Agency, Vienna, ISBN 92–0–104004–0

IAEA, 2006. *Fundamental Safety Principles*. Safety Fundamentals No. SF-1.

IAEA (2011): Disposal of Radioactive Waste. IAEA Safety Standards, Specific Safety Requirements No. SSR-5, International Atomic Energy Agency (IAEA), Vienna, 2011.

IAEA (2012): The Safety Case and Safety Assessment for the Disposal of Radioactive Waste. IAEA Safety Standards, Specific Safety Guide No. SSG-23. ISBN 978-92-0-128310-8, International Atomic Energy Agency (IAEA), Vienna.

IAEA (2016): Managing integration of post-closure safety and pre-closure activities in the Safety Case for Geological Disposal. Draft TECDOC, International Atomic Energy Agency (IAEA), Vienna.

Lommerzheim, A., Jobmann, M., Meleshyn, A., Mrugalla, S., Rübel, A. & Stark, L. (2019): Safety concept, FEP catalogue and scenario development as fundamentals of a long-term safety demonstration for high-level waste repositories in German clay formations.- In: Norris,S., Neft, E.A.C. & Van Geet, M.: Multiple Roles Clays in Radioactive Waste Confinement, Geol. Soc. London, Vol. SP 482, London.

Mallants, D., Vermariën, E., Wilmot, R. & Cool, W. (2008): Selection and description of scenarios for longterm radiological safety assessment. Project near surface disposal of category A waste at Dessel. NIRAS-MP4-02 Version 1, NIROND-TR 2007–09 E, Brussels

Mönig, J., Beuth, T. Wolf, J.,Lommerzheim, A. & Mrugalla, S. (2013): Preliminary Safety Analysis of the Gorleben Site: Safety Concept and Application to Scenario Development Based on a Site Specific Features, Events and Processes (FEP) Database – 13304.- WM2013 Conference, February 24 – 28, Phoenix, Arizona, USA

Müller-Hoeppe, N. (2014): FEPs and their Designation in the Technical Proof of a Geotechnical Barrier's Safety Function. Proc.Int.Conf.Perf.Eng.Barr., Feb. 6-7 2014, Hannover

Müller-Hoeppe, N., Krone, J. & Engelhardt, H.J. (2017): Applicability of the Partial Safety Factor Method on Long Time Periods.- ENTRIA Conference, September 26–30, 2017

NAGRA (2002): Project Opalinus Clay: FEP Management for Safety Assessment – Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis).- Technical Report 02-23, Nagra, Wettingen

NEA (1992): Systematic approaches to scenario development. Report of the NEA Working Group on the Identification and Selection of Scenarios for Performance Assessment. OECD Publications, Paris,

NEA (2001). Scenario Development Methods and Practice. An Evaluation Based on the NEA Workshop on Scenario Development, Madrid, May 1999, Spain. OECD/NEA, Paris, France.

NEA (2013): The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories. Report NEA/RWM/R(2013)1. OECD Nuclear Energy Agency, Paris, 2013.

NEA (2014): The Safety Case for deep Geological Disposal of Radioactive Waste. (2013): State of the Arte. Symposium Proc. 7-9, October 2013, Paris, France.- Rad. Waste Management, NEA/RWM/R(2013) 9, March 2014, Paris

NEA (2016): Scenario Development Workshop Synopsis. Integration Group for the Safety Case. Nuclear Energy Agency, NEA/RWM/R (2015)3, OECD/NEA, Paris, France.

NEA: (2019): International Features, Events and Processes (IFEP) - List for disposal of Deep Geological Disposal of Radioactive Waste. Version 3.0.- Radioactive Waste Management and Decommissioning, NEA/RWM/R.1, Juli 2019, Paris

POSIVA (2012): Safety case for the disposal of spent nuclear fuel at Olkiluoto, Features, Events, and Processes. POSIVA report 2012-07, Eurajoki, Finland.

Sandia National Laboratories (SNL). 2008. Features, Events, and Processes for the Total System Performance Assessment: Methods. ANL-WIS-MD-000026 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080211.0010.

Simo, E.; Herold, P.; Keller, A.; Lommerzheim, A., Matteo, E.N.; Hadgu, T.; Jayne, R.S.; Mills, M.M. & Kuhlman, K.L. (2021): Methodology for Design and Performance Assessment of Engineered Barrier Systems in a Salt Repository for HLW/SNF.- Paper N°21132, WM2021 Conference, March 7 - 11, 2021, Phoenix, Arizona, USA.

SKB (2019): FEP report for the safety evaluation SE-SFL.- Svensk Kärnbränslehantering AB, SKB TR-19-02, Solna