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

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ABSTRACT

Based upon the German safety criteria, released in 2010 by the Federal Ministry of the Environment (BMU), a safety concept and a safety assessment concept for the disposal of heat-generating high-level waste have both been developed in the framework of the preliminary safety case for the Gorleben site (Project VSG). The main objective of the disposal is to contain the radioactive waste inside a defined rock zone, which is called containment-providing rock zone. The radionuclides shall remain essentially at the emplacement site, and at the most, a small defined quantity of material shall be able to leave this rock zone. This shall be accomplished by the geological barrier and a technical barrier system, which is required to seal the inevitable penetration of the geological barrier by the construction of the mine. The safe containment has to be demonstrated for probable and less probable evolutions of the site, while evolutions with very low probability (less than 1 % over the demonstration period of 1 million years) need not to be considered.

Owing to the uncertainty in predicting the real evolution of the site, plausible scenarios have been derived in a systematic manner. Therefore, a comprehensive site-specific features, events and processes (FEP) data base for the Gorleben site has been developed. The safety concept was directly taken into account, e.g. by identification of FEP with direct influence on the barriers that provide the containment. No effort was spared to identify the interactions of the FEP, their probabilities of occurrence, and their characteristics (values). The information stored in the data base provided the basis for the development of scenarios.

The scenario development methodology is based on FEP related to an impairment of the functionality of a subset of barriers, called initial barriers. By taking these FEP into account in their probable characteristics the reference scenario is derived. Thus, the reference scenario describes a comprehensive set of probable future evolutions of the repository site. By stepwise consideration of less probable FEP or less probable characteristics of FEP within this process, alternative scenarios are also developed, which are characterized by a lower probability of occurrence. An important methodological aspect is that some assumptions had to be made for the scenario development. They allow, on the one hand, to deal systematically with incomplete knowledge regarding the geological situation below ground owing to restricted site investigations, and, on the other hand, to structure the scenario development process. The consideration of alternative assumptions may result in additional alternative scenarios.

INTRODUCTION

The Gorleben site, which is located in Northern Germany, has been investigated for decades as a candidate site for the disposal of high-level radioactive waste in Germany. Site investigations were ceased between 2000 and 2010 based on an agreement between the German Government and the utilities. In 2010 site investigations were resumed and the preliminary safety assessment for the Gorleben site (German project name "Vorläufige Sicherheitsanalyse für den Standort Gorleben – VSG") was started. A project overview is given in [1]. The Project VSG is performed by seven German research institutions, led by Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS). Its main objective is to answer, based on a safety assessment, the questions whether the Gorleben site or another geologically comparable site is suitable for hosting high-level radioactive waste, i.e. spent fuel, vitrified waste from reprocessing of spent fuel, and technological waste from reprocessing such as hulls and end-pieces, and whether knowledge exists, that argues against a suitability of the salt dome Gorleben. In addition, open issues concerning research and technological development as well as future site investigations shall be identified.

Initially, a safety concept and a concept for demonstrating long-term safety were developed, that provided the basis for the design of the repository and the safety assessments performed in the Project VSG. Based on the safety concept specific requirements were derived concerning the site, the repository concept, the design of the mine buildings and the assessments to be performed within the Project VSG. The requirements concerning the site have to be fulfilled by the characteristic properties of the host rock and the overall geological situation. In contrast, the repository concept and design offer some degree of freedom in fulfilling the requirements. In combination with the concept for demonstrating long-term safety, the safety concept defines the framework for the Project VSG and they both establish the programmatic focus of the work.

THE SAFETY CONCEPT

A safety concept describes which circumstances and measures contribute to accomplish and maintain the required level for the long-term safety of a repository at the given site. The safety requirements for the disposal of high-level radioactive waste of the German Ministry of Environment, Nature Conservation and Reactor Safety [2] provide some stipulations with respect to the safety concept. For example, the radioactive waste must be contained in a defined rock zone surrounding the mine openings, called the containment-providing rock zone (CPRZ). The safety requirements [2] are enunciated independent of the type of host rock. They must be explicated and specified for the considered site with its geological situation.

In due consideration of the German safety requirements [2] the safety concept for the Project VSG is based on the following guiding principles:

- the radioactive waste must be contained as widely as possible in the containment-providing rock zone (CPRZ),
- the containment shall be effective immediately post-closure and it must be provided by the repository system permanently and maintenance-free, and
- the immediate and permanent containment shall be accomplished by preventing or limiting intrusion of brine to the waste forms.

These guiding principles have been derived based on existing knowledge concerning both the processes that could possibly impair the safety of the repository and the site properties. This knowledge stems from partly generic research work and site investigations, respectively. The geological barrier shall provide the permanent containment of the radioactive waste. The salt rock within the CPRZ is essential for the containment, i.e. its practical impermeability for solutions. Thereto the integrity of the salt rock within the CPRZ must be ensured, which is governed by the rock properties.

Perforations of the geological barrier are inevitable upon mine construction and result in a hydraulic bypass of the geological barrier. Creep processes promoted by visco-plastic-elastic properties of the salt rock will lead eventually to the closure of such mine openings, thus restoring the original properties of the geological barrier. Since this process requires some time, engineered high-performance shaft seals and drift seals will be built, that exhibit dedicated sealing properties immediately upon construction. These engineered barriers may be affected by thermal and mechanical impacts and by chemical alteration processes, and, therefore, their long-term performance may not be proven irrefutably. It is foreseen to backfill all mine openings in the emplacement areas with crushed salt as a long-term stable material. Owing to the compaction of the crushed salt that is driven by the salt creep a very low permeability of the crushed salt will develop with time. As a result, brine intrusion to the waste via the shaft and the drifts cannot occur or becomes negligible. Evidence must be provided that the sealing by the compacted backfill material is fully developed at the times, when the performance of the engineered barriers can no longer be demonstrated. The evolution of the seal effect with time is schematically shown in Fig. 1 for various barriers in the repository system. The colour intensity represents the degree of the respective seal effect. According to the German safety requirements [2], it must be possible to retrieve spent fuel canisters during the repository's operational phase. Also it must be shown for all probable evolutions of the repository system, that the spent fuel canisters can be handled up to 500 years post closure, with adhering to the prevention of release of aerosols from the waste canister.

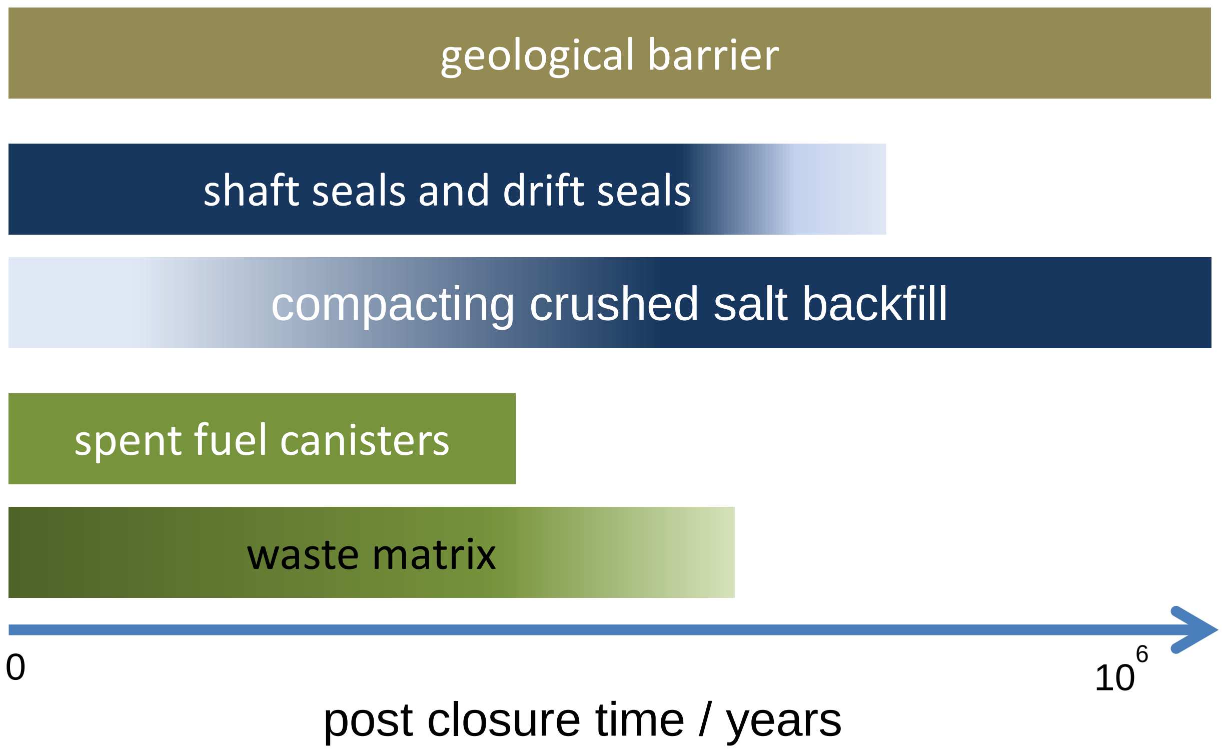

Fig. 1. Evolution with time of the seal effects of various barriers in the repository system (the colour intensity represents the degree of the respective seal effect)

In the event that brine intrusion to the waste cannot be completely cut off, these barriers in combination with other barriers contribute to the enclosure of the radionuclides in the CPRZ via different processes. This is achieved, either by restricting the movement of contaminated solutions along the former drifts or, as in the case of the waste matrix, by retarding the mobilization of the radionuclides.

Three design requirements were defined based on the general regulatory stipulations [2] and the guiding principles:

- The emplaced waste canisters shall be enclosed quickly and as tightly as possible by the salt.
- During the demonstration period of one million years the CPRZ shall remain intact and its barrier function shall neither be impaired by internal nor by external processes and effects.

- Criticality must be excluded in all phases of the repository development.

These design requirements were then used, both to derive specific objectives and to determine strategic measures, which embrace design specifications, e.g. with respect to the mine position in the salt dome, and technical provisions. Typically, each strategic measure serves several specific objectives. The strategic measures in their entirety contribute to meet the objectives of the safety concept. The principle types of correlations between design requirements, specific objectives and measures are schematically shown in Fig. 2. This approach allows mapping of the general stipulations of the German safety requirements [2] to objectives and measures for the safety concept of a given site in a transparent way. For the safety concept for the Project VSG, altogether 14 specific targets were derived and 16 strategic measures were identified, each of which is usually serving several specific targets.

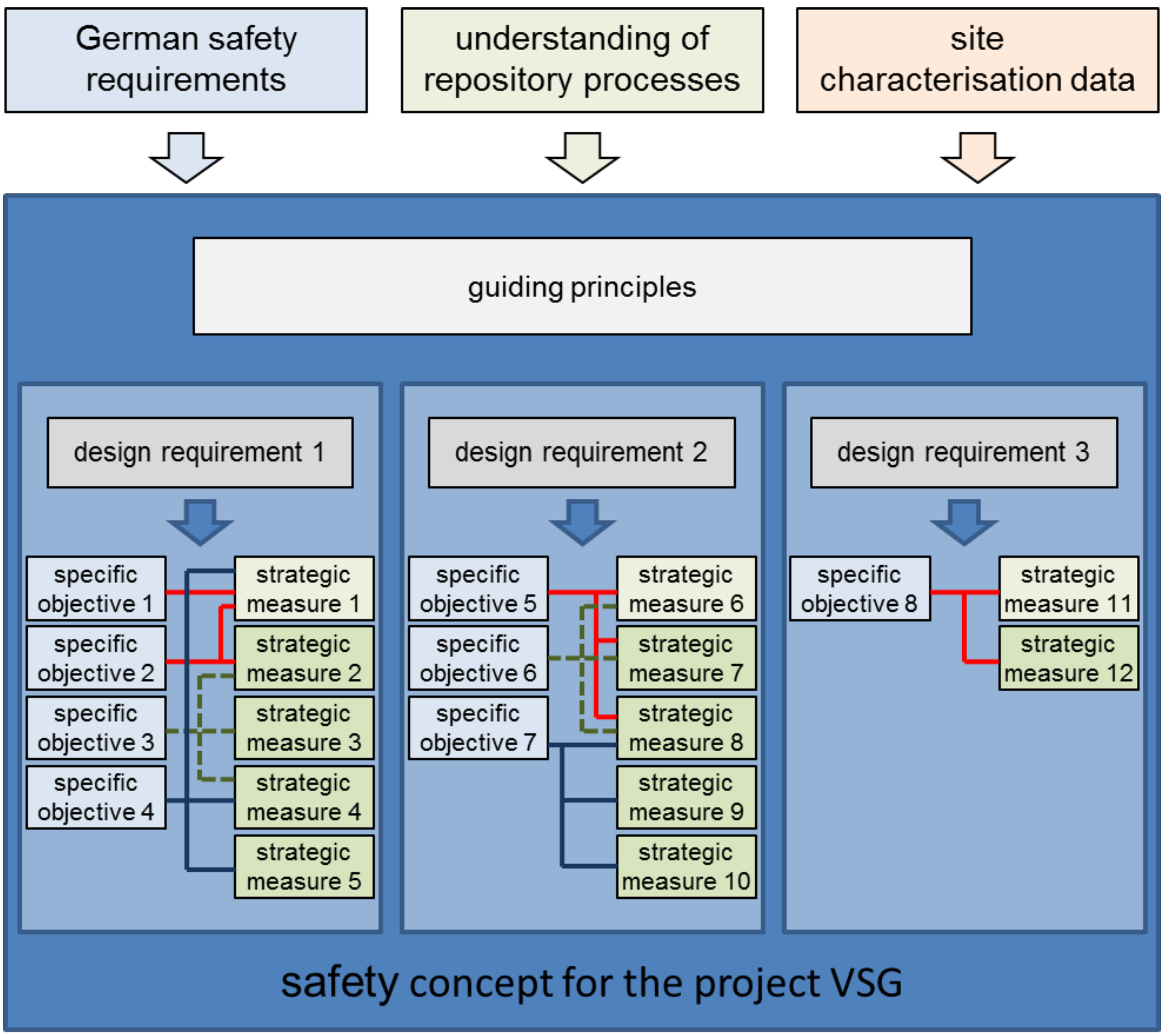

Fig. 2. Principle approach to derive specific objectives and strategic measures for the safety concept

This approach is exemplified for the first design requirement, i.e. to enclose the waste as quickly as possible by the salt. Eight specific objectives are derived:

O1 No solution or at best very minute amounts of solution shall get into contact with the waste canisters emplaced in all probable evolutions of the repository system.

O2. Only limited amounts of solution shall get into contact with the waste canisters in less probable evolutions of the repository system.

O3. In the event of radionuclides being mobilized from the waste, transport of these pollutants shall be retarded by chemical and physical processes.

O4. The properties of both the salt rock and the engineered barriers that are responsible for the containment of the radionuclides, shall be well predictable.

O5. The repository shall be designed such that no intervention is necessary from the outside during the post-closure period.

O6. The engineered barriers shall be designed robustly, in order to ensure their functional efficiency taking into account different load cases and possible degradation processes.

O7. The immediate and long-term containment of the radioactive waste in the CPRZ shall be ensured by a staggered barrier system. Its individual elements shall act redundantly or on diverse processes and they shall complement each other in their temporal effectiveness.

O8. At any time the number of mine areas that are accessible simultaneously shall be kept to an absolute minimum. The emplacement fields shall be separated into individual segments, which can as quickly as possible be sequentially emplaced, backfilled, and sealed. The interactions between the various radioactive waste types via physical and/or chemical processes, that could impair the containment capacity of the CPRZ, shall be minimized to the greatest possible extent.

The strategic measures to meet these objectives are as follows:

M1. The excavation volume of the repository will be as small as possible. The excavation will be performed using gentle methods in order to limit the impact on the geological barrier. (→ O1, O2, O3)

M2. The mine openings of the emplacement areas will be excavated in salt regions with homogeneous structure and properties, e.g. in the main salt of the Staßfurt series (z2HS). (→ O4)

M3. The mine openings of the emplacement areas will be excavated in salt regions that are free of brine pockets with significant volume and that provide favorable creep properties. These emplacement areas will be excavated in the main salt of the Staßfurt series (z2HS). (→ O1, O2)

M4. The mine openings of the emplacement areas will be excavated with sufficient safety pillars to the shafts, to rock strata with potentially larger brine pockets, and to potential transport paths for solutions. Based on the existing experience in salt mining, a minimum safety pillar of 50 m was determined. It is necessary to demonstrate, that this safety pillar is sufficient to maintain the integrity of the geological barrier in the CPRZ. (→ O1, O2)

M5. Engineered barriers with defined hydraulic properties will be erected in the shafts and in the access drifts between infrastructure area and the emplacement areas. Their design is based on load cases which should cover the potential range of future impacts during the required duration of effectiveness. The engineered barriers must be adequately tight until the hydraulic resistance of the compacted crushed salt hinders effectively the brine intrusion to the waste. (→ O1, O2, O3, O5, O6, O7)

M6. The mine openings of the emplacement areas will be backfilled with crushed salt. The convergence process will result in a compaction of the crushed salt with a reduction in its porosity and permeability. Owing to the higher temperatures, this process is faster in the vicinity of the heat-generating high-level radioactive waste then elsewhere in the mine. The volume of crushed salt limits the extent of the convergence process and, thus, minimizes the rock stresses induced. In addition, this measure reduces the void volume in the emplacement areas that can be filled with solution. (→ O1, O2, O5, O6, O7)

M7. Small amounts of moisture will be added to the crushed salt, that is used to backfill the access drifts, at least in the vicinity of the emplacement areas, in order to reduce the resistance against the compaction process and to a accelerate compaction of the crushed salt. (→ O1, O2, O5, O6, O7)

M8. The amount of humidity in the repository will be minimized in order to constrain the corrosion of waste canisters with its associated gas formation. Crushed salt having only the small natural aqueous content of the main rock salt of the Staßfurt series, z2HS, will be used as backfill material in the emplacement drifts. To this end operational provisions will be taken for handling the crushed salt upon excavation. If necessary, the crushed salt will be dryed before backfilling. (→ O1, O2, O5, O6, O7)
M9. The shaft seals are designed such that their seal efficiency relies on several different seal elements that are independent from each other and that have diverse functionality owing to their configuration. (→ O6, O7)
M10. All emplacement fields will be subdivided into individual sectors, each having a volume as small as possible. The individual sectors are sequentially filled with waste canisters, backfilled with crushed salt, and sealed against the remaining mine. Waste types with different physical and chemical properties will be disposed of in separate sectors, thus minimizing interactions between them that could impair the containment capacity of the CPRZ. If feasible from the operational point of view, waste disposal will start at sectors that are furthest away from the shaft. This enables crushed salt compaction to proceed widely in these sectors already during mine operation. (→ O8)

The second design requirement states, that the CPRZ remains intact and its barrier function is neither impaired by internal nor by external processes and effects, results in 5 specific objectives and 5 strategic measures, while the third design requirement led to one objective and one strategic measure. The strategic measures at large provide the basis for the site-specific design and layout of the repository [3].

SCENARIO DEVELOPMENT

The site and the repository system will undergo exactly one evolution, which will be governed both by climatic and geological processes at the site and processes induced by the repository construction and the emplacement of heat-generating waste. Despite a detailed understanding of the various influencing factors, this real evolution cannot be predicted unequivocally in all details. The points in times and the characteristics of future events at the Gorleben site cannot be determined in all details. The resulting uncertainty with regard to the future evolution of the repository system can be reduced only marginally by additional research and site investigations. For example, it can be safely assumed that several glacial periods will occur with permafrost formation at the Gorleben site within the next one million years, which may be associated with glaciation of the site. An exact prediction, when these glacial periods will occur and which areas are affected by glaciers advancing from the north is not possible.

Conceptions concerning the future evolution of the repository system are prerequisites for numerical long-term safety assessments. Therefore, a limited number of reasonable possible evolutions were derived within the Project VSG based on a systematic assessment of relevant influencing factors with the objective to identify and describe in detail relevant scenarios, which allow to assess post-closure repository safety. Special emphasis was put to include evolutions which lead to an intrusion of solutions to the waste canisters or which result in a mobilization of radionuclides from the waste, both in the liquid phase and the gas phase.

A novel scenario development methodology was developed in the Project VSG. It aims at deriving one reference scenario and a number of alternative scenarios. At large, the scenarios shall represent comprehensively the reasonable range of repository system evolutions. The methodology allows straightforwardly the assignment of probability classes to the scenarios pursuant to the regulatory framework [2]. The individual scenarios are characterized by features, events, and processes (in short FEP) that may influence the future evolution of the final repository system at Gorleben, and their associated characteristics. The relevant information is given in a site-specific FEP data base. The scenario development methodology is depicted schematically in Fig. 3.

A number of basic assumptions were made in the Project VSG in order to deal with uncertainties resulting from incomplete site investigations below ground. So far, only a fairly small region of the salt dome has been investigated in situ. The basic assumptions pertain to the lateral size and geological structure of the Gorleben salt dome in the emplacement depths, the properties of the salt rocks in the CPRZ, and the available dimension of the main salt of the Staßfurt Series, z2HS.

Scenario development commences at two starting points that ensue directly from the guiding principles for deriving the safety concept:

- A number of so-called initial barriers are identified that constitute a subset of all barriers acting in the repository system via diverse mode of operations and, partly, in different time frames. The initial barriers embrace the salt rock, the shaft seals, the drift seals, and the spent fuel canisters. Their collective characteristic is that these barriers prevent the contact of solutions with the emplaced waste immediately upon closure of the repository system. FEP that could impair the functionality of the initial barriers provide the first starting point for scenario development.
- In addition all possible system evolutions need to be considered which involve a release of radionuclides from the waste form even without any contact of solutions with the waste forms. Those FEP which are related to the mobilization of radionuclides and their transport constitute the second starting point for scenario development.

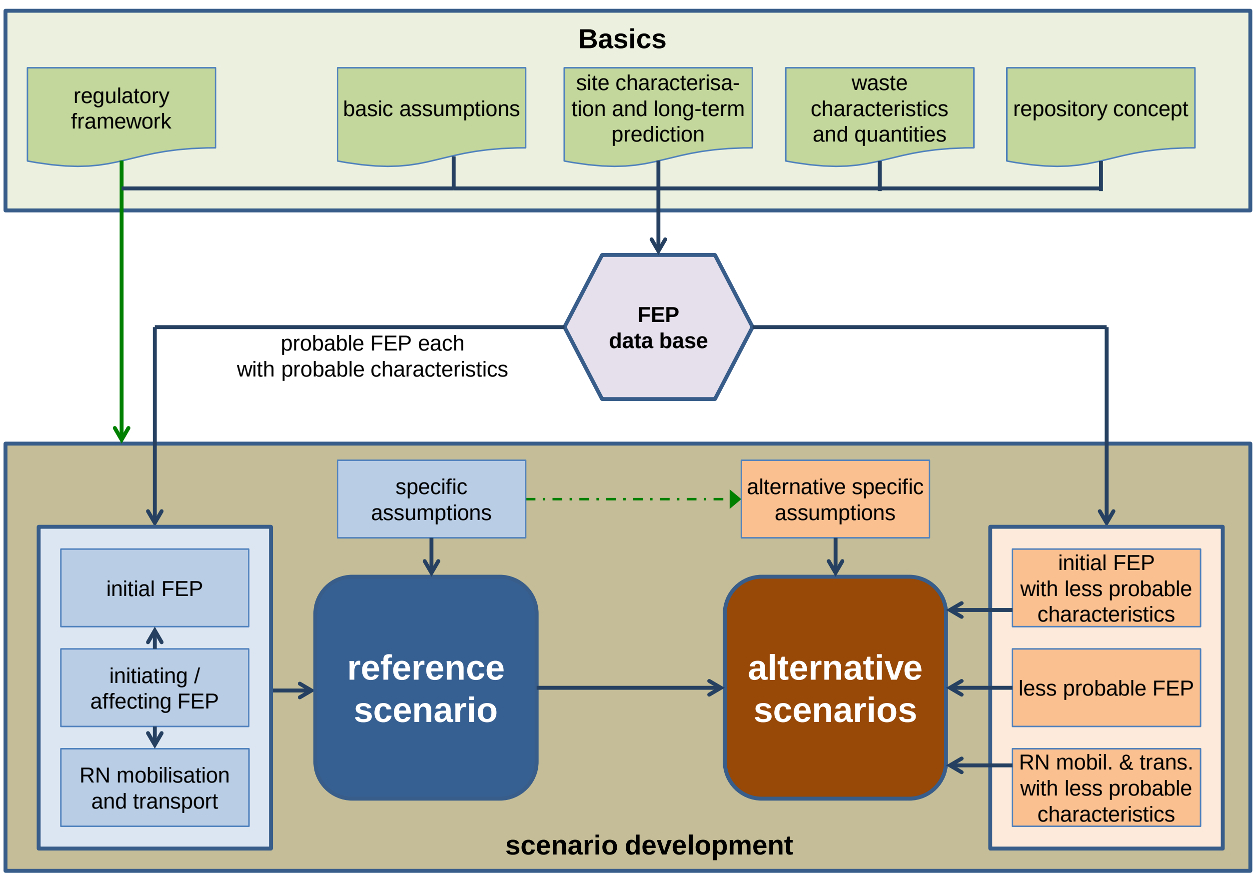

Fig. 3. Scenario development methodology applied in Project VSG

FEP Data Base

Based on the geological situation at the site, the repository concept developed with VSG [3] and the different types of waste, a site-specific FEP data base was systematically compiled. Structure and content of the FEP data base reflect the scenario development methodology. For each FEP detailed information is provided that allows selecting directly all FEP which are relevant for the reference scenario and the alternative scenarios.

Each FEP entry in the data base comprises general information, a description of the circumstances at the site and site-specific impacts, a classification of the conditional probability of occurrence, details on the impairment of the initial barriers' functionality, and information regarding the time frame of action. The direct interdependence with other FEP are specified and explained, thereby distinguishing between initiating FEP, resulting FEP, affecting FEP, and affected FEP, respectively. Where possible, probable and less probable characteristics of the FEP are indicated. Sometimes it is only possible to describe a characteristic but no probabilities can be attributed to it. This may be due to scarce data or information, or to a situation, where only bounding values are of interest with respect to the scenario analyses. In those cases representative characteristics are described.

Complementary approaches to identify potentially relevant FEP were pursued and finally consolidated in order to contribute towards the completeness of the FEP data base. One approach had the goal of identifying all FEP that, principally, may have an impact on the geological evolution of the site or on the repository system. Another approach focused on the issue of if and how brines potentially could come into contact with the waste bearing in mind, that rock salt is tight. Conceivable evolutions were identified that could lead to the failure of one or more geotechnical barriers. As a consequence of such sequence of events, radionuclides might be released from the waste and even be transported across repository barriers into the biosphere. All FEP that could play a role in these evolutions were identified. In order to check whether any relevant aspect has been overlooked the consolidated FEP list was checked using the generic NEA FEP list. The FEP catalogue for the Gorleben site contains 115 FEP entries, 98 of which are categorized as probable, and 4 as less probable. Thirteen FEP need not to be considered for the Gorleben site and, thus, are excluded from the scenario development process.

Derivation of the Reference Scenario

Taking specific assumptions into account, the reference scenario results by considering all probable FEP

- that may impair the functionality of the initial barriers (initial FEP), and
- that determine the mobilization of radionuclides from the waste and their subsequent transport, both in the gas phase and in the liquid phase.

If appropriate information is available in the FEP catalogue, the probable characteristics of these FEP or their representative characteristics are taken as a basis. Otherwise, the characteristics result from the interaction with FEP that affect directly these FEP (first level). In this case, always the probable or representative characteristics of the controlling FEP of the first level are assumed. If these FEP themselves are controlled directly by other FEP (second level), their characteristics are used. More levels are only included, if the aspects are not yet covered by FEP in the first level or second level, respectively. Owing to the method applied, the reference scenario is probable. The procedure to identify the characteristics of FEP for the reference scenario is depicted in Fig. 4.

Specific assumptions concerning the reference scenario are an important element for the scenario development. They provide a means to deal in a transparent and traceable way with particular uncertainties, some of which may be minimized in the future while others may never be reduced at all. In particular, the latter pertains to the future climatic evolution. Therefore, a certain climatic evolution at the Gorleben site with a series of different types of glacial periods (Weichsel-type, Saale-type, and Elster-type) was defined for the reference scenario. Other specific assumptions deal with situations, where no proof has been furnished yet with regard to producibility and functionality of engineered barriers or other technical components. Another specific assumption regards the excavation of the whole mine working, especially that the required safety pillars are observed to strata outside the main rock salt of the Staßfurt Series, z2HS, which may contain larger content of fluids or which provide a possible transport path. Alternative specific assumptions constitute inter alia a starting point for deriving alternative scenarios.

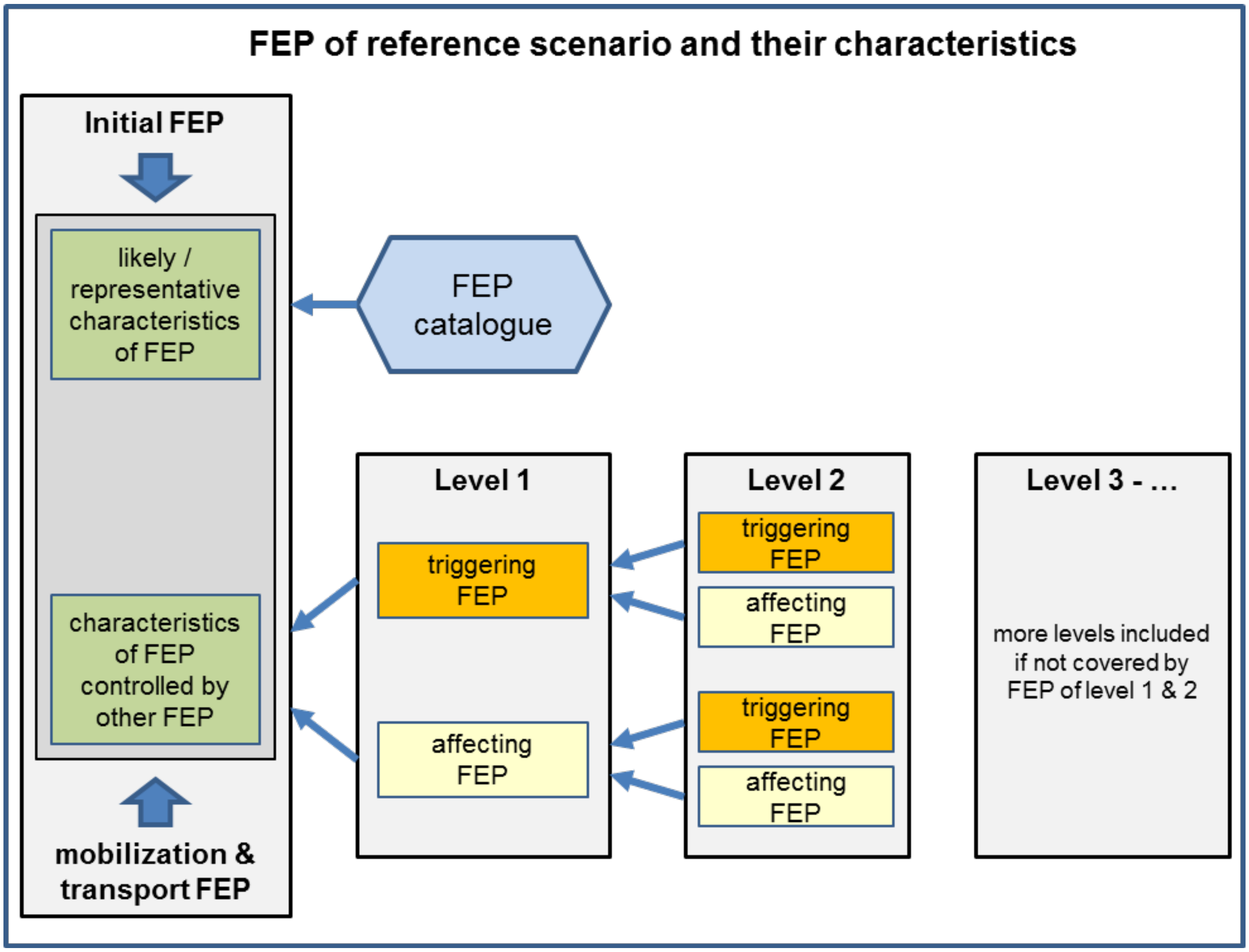

Fig. 4. Approach to derive characteristics of FEP describing the reference scenario

Alternative Scenarios

The reference scenario embraces a set of probable evolutions of the repository system that is as comprehensive as possible. Alternative scenarios are evolutions which differ in exactly one aspect from the reference scenario. Alternative scenarios are developed from the following starting points:

- evolutions resulting from alternatives concerning the specific assumptions for the reference scenario,
- evolutions resulting from less probable characteristics of the FEP that may impair the functionality of the initial barriers (initial FEP),
- evolutions resulting from less probable characteristics of the FEP describing mobilization and transport of radionuclides, and
- evolutions resulting from less probable FEP.

If possible, information is directly taken from the FEP catalogue concerning less probable characteristics of FEP that may impair the functionality of the initial barriers or that describe mobilization and transport of radionuclides, respectively, and less probable FEP. Otherwise, the characteristics are directly controlled by other FEP in a similar way as shown in Fig. 4.

It is feasible that similar alternative evolutions result from the different starting points. In this case, various evolutions may be abstracted into one representative alternative scenario that covers the characteristics of the various evolutions. In the Project VSG 17 alternative scenarios have been developed and described in detail for the drift emplacement disposal concept.

CONCLUSIONS

Starting from the general German regulatory requirements for the disposal of high-level waste, for the first time a methodological approach was developed that allows the systematic derivation of a safety concept for a repository for heat-generating high-level waste in a salt dome such as in Gorleben. On the basis of a few guiding principles, specific objectives were devised, which were used to identify strategic measures. These measures provide the basis for the detailed design and layout of the repository.

A novel scenario development methodology was developed and successfully employed in the Project VSG. Taking into account the principle features of the repository system to provide long-term safety, a reference scenario and a number of alternative scenarios were derived. The reference scenario embraces a set of probable evolutions of the repository system that is as comprehensive as possible. Alternative scenarios are evolutions which differ in exactly one aspect from the reference scenario (additional FEP, different specific assumption or different characteristic of one FEP). Since the methodological approach covers systematically all aspects, it is concluded that the scenarios in their entirety cover comprehensively the uncertainty regarding the future evolution of the repository system at Gorleben. Each scenario is described in detail by FEP and their characteristics. The respective information stems from the site-specific FEP catalogue which has been assembled also in the Project VSG.

The methodological approaches for establishing a safety concept and for scenario development are applicable to other sites with a salt dome. It is expected that this methodologies can be transferred with small adjustments to other geological situations with bedded salt as host rock.

REFERENCES

1. G. BRACKE and K. FISCHER-APPELT. “Overview on the Preliminary Safety Analysis of the Gorleben Site”, WM2013 Conference, Phoenix, Arizona, USA, Feb. 24 -28, 2013, paper no.13298
2. BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT, „Sicherheitsanforderungen an die Endlagerung wärmeentwickelnder radioaktiver Abfälle. Stand 30. Oktober 2010”.
3. W. BOLLINGERFEHR, W. FILBERT, C. LERCH, P. HEROLD, N. MÜLLER-HOEPPE; F. CHARLIER and R. KILGER. “Technical Design and Optimization of a HLW-Repository in the Gorleben Salt Dome including Detailed Design of the Sealing System”, WM2013 Conference, Phoenix, Arizona, USA, Feb. 24 -28, 2013, paper no.13305

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