FEPs and their Designation in the Technical Proof of a Geotechnical Barrier´s Safety Function

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1 Introduction

When planning a final repository for radioactive waste, the following fundamentals are available:

- The (legal) demands resulting from the (national) safety requirements for final disposal of radioactive waste
- Waste specification and amount of waste
- Site-specific conditions of a potential disposal site and a prognosis of its long-term evolution

In the present context, the safety requirements of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [1] that stipulate the safe containment of the radioactive waste in a so-called CRZ (containing rock zone), the fact that the waste mainly consists of high-level radioactive waste and spent fuel e.g. [2], and the geological site characterization of a potential site that for example shows the characteristics of the Gorleben site [2] serve as the design basis. As the Gorleben site is not yet completely explored, several assumptions are made with regard to its spatial extent and its internal geologic structure.

Based on this information, the repository as well as the backfill and sealing measures for its closure are planned.

2 Assessment of the final repository system

After the repository has been planned and adequate backfill and sealing measures have been selected, the repository system is analyzed to prove the long-term safety of the repository system for selected potential evolutions (scenarios). The CRZ is supported by sealing measures that close the access routes into the repository mine that are necessary for repository operation. Shaft and drift seals are parts of the sealing measures. Integrity of the geological and the geotechnical barriers – so-called initial-barriers – complementing each other are essential to prove safe containment of radioactive waste.

The demonstration of the integrity of the geological and the geotechnical barriers is based on scenarios that have been developed for the repository system and that in turn are based on features, events, and processes (FEPs). Because of the FEP collection´s relevance when building the safety case for a site, the Nuclear Energy Agency (NEA) compiled an international FEP data base and derived a general scheme for arranging the FEPs in a catalogue. This scheme is based on the experience of several repository projects as well as on different waste specifications and types of host rocks. It serves as a basis for compiling site-specific FEP catalogues. Deriving the site-specific FEP catalogue from the NEA database is equivalent to an empirical proof of completeness. Additionally, the FEPs are categorized as probable FEPs and FEPs with a low probability of occurrence. In a further step, FEPs are selected that potentially affect the integrity of the initial barriers. The FEPs identified as potentially impairing the initial barriers shaft and drift seals, which were identified as initial barriers within the VSG project (Preliminary Safety Analysis of the Gorleben Site) are given in Table 1 (probable FEPs) and Table 2 (less likely FEPs). Based on site-specific conditions, the functional working life of the geotechnical barriers was determined to be 50,000 years [2].

Tab. 1: Initial FEPs [2]

FEP-No.	FEP-Name	Affected geotechnical barrier
1.2.03.01	Earthquake	Shaft seal, drift seal
1.2.09.01	Diapirism	Shaft seal, drift
1.2.09.02	Subrosion	Shaft seal
1.3.05.03	Formation of glacial channels	Shaft seal
2.1.05.04	Alteration of drift and shaft seals	Shaft seal, drift seal
2.1.07.01	Convergence	Shaft seal, drift seal
2.1.07.02	Fluid pressure	Shaft seal, drift seal
2.1.07.04	Volume changes in materials – not thermally induced	Shaft seal, drift seal
2.1.07.07	Displacement of shaft seal	Shaft seal
2.1.08.08	Swelling of bentonite	Shaft seal
2.1.09.02	Solution and precipitation	Shaft seal, drift seal
2.1.09.06	Corrosion of materials with cement or magnesium oxychloride phases	Shaft seal, drift seal
2.2.01.01	Excavtion damaged zone	Shaft seal, drift seal
2.2.06.01	Change of stresses	Shaft seal, drift seal

Tab 2: Less likely FEPs [2]

FEP-No.	FEP-Name	Affected geotechnical barrier
2.1.07.05	Early failure of a shaft seal*	Shaft seal
2.1.07.06	Early failure of a drift seal*	Drift seal
2.1.08.05	Piping in seals	Shaft seal, drift seal

*incl. malfunction caused by insufficient construction process

Geotechnical barriers are structures of civil engineering. They comprise the sealing body, the contact zone to the surrounding rock and the excavation damaged zone. They are dimensioned according to the technical regulations although their functional working life (= performance period) exceeds the usual functional working life of conventional structures in civil engineering, which is 50 – 100 years.

3 Dimensioning geotechnical barriers

The adequate design of the geotechnical barriers is verified by a technical functional proof in accordance with the technical regulations, e.g. DIN-EN-1997-1, DIN-EN-1990 (=implementation of the EUROCODE), with the aim to verify the required level of reliability of barrier constructions. In constructional design practice, the concept of ultimate limit states is used in combination with the partial safety factor method. Within the concept of ultimate limit states, the quantitative value of the actions that may impair a structure´s safety function is compared with the quantitative value of the resistances that the structure offers against the actions. With respect to an ultimate limit state, it is required that the resistances are higher than the actions (= impacts). If the ultimate limit state is exceeded, the structure does not function as required.

For geotechnical barriers, ultimate limit states of integrity, e.g. cracking or decompaction, can be described by

- Stress limits (e.g. defined by material-specific fracture strength and dilatancy)
- Deformation limits (e.g. volume and shear deformations)

When the partial safety factor method is applied the actions and resistances are additionally multiplied by safety factors that cover uncertainties, e.g. variations of representative values and imprecisions in modeling. Resistances are material and design specific and therefore depend on the outline design of the sealing structures. The resistance and the ultimate limit state functions must be determined for the selected design.

Regarding the sealing system in the VSG project, the structure of the technical functional proof, which consists of several individual proofs, is given in Fig. 1.

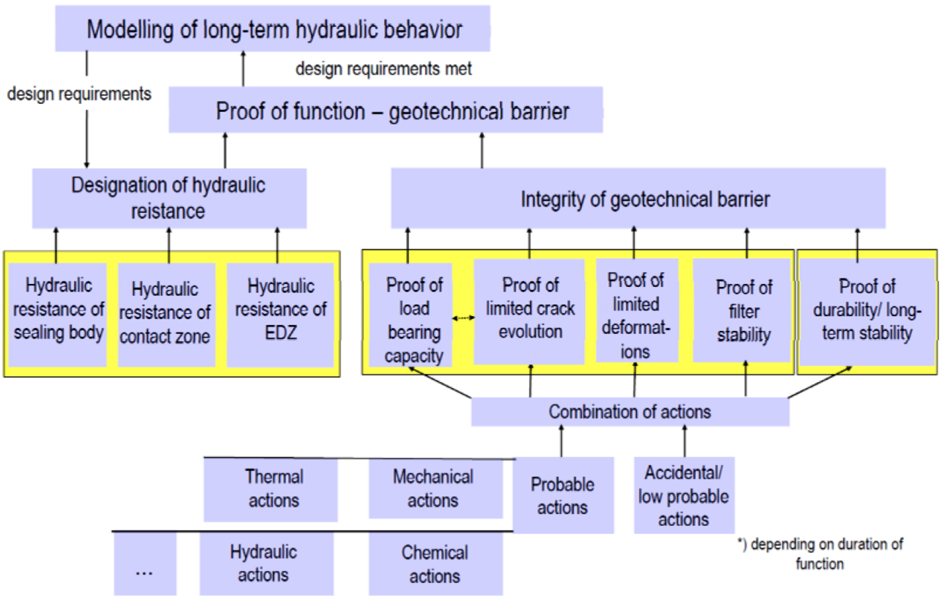

Fig. 1: The structure of the technical functional proof, hydraulic actions = hydro-mechanical actions, thermal actions = thermochemical and thermo-mechanical actions

In accordance with technical regulations, the following actions were identified to be treated within the technical functional proof:

- Chemical actions:
  - Chemical attack by solutions and gases, the compositions of which have to be specified in detail
  - Chemical attack induced by temperature changes, e.g. change of solubility
- Mechanical actions:
  - Actions induced by forces and stresses:
  - Dead load, rock pressure, fluid pressure, flow forces, restraint stresses (e.g. induced by stiffness differences)
- Actions induced by deformations and strains:

- Temperature changes/-differences inducing thermal expansion and contraction, swelling and shrinking, creep and relaxation, restraint strains due to barrier rock interaction (e.g. settling)
- Biological actions (e.g. bacteria, fungi) are not taken into account because no organic material was selected for geotechnical barriers in the VSG project. Thermal and hydraulic actions are covered by chemical actions and mechanical actions, indirectly.

Ultimate limit state analysis is performed taking design situations into account. In [3] four typical design situations are distinguished (Table 3) which are identified by characteristic conditions that influence the reliability level required. In this context, it has to be noted that where a barrier failure implies a danger to life and health, a reliability level is required that is typically applied to load-bearing structures. This issue is taken into account when stating the design situations according to Table 3.

Tab. 3: Design situations and their characteristic conditions

Design situation	Characteristic conditions
Transient situations*	Temporary, normal situations, e.g. construction process
Persistent situations*	Normal situations according to normal function and use
Abnormal (accidental) situations**	Rare, mostly extraordinary situations, e.g. accidental situations as impacts or explosions
Seismic situations (earthquakes)***	Short, limited in time, design-defining earthquakes rare

* will occur ** will probably not occur ***regional differences in occurrence

The assignment of design situations defines the combinations of actions to be considered, i.e. which actions can act at the same time within a design situation and which partial safety factors have to be applied. For example actions of two independent accidental situations are not combined. Thus, the probability of occurrence is considered in terms of guaranteeing the same standard level of reliability.

4 Classification of the initial FEPs within the technical functional proof

Where possible actions, resistances, and design situations are assigned to the FEPs for consideration during the technical functional proof (Table 4). This step allows the FEPs and scenarios to be considered in the technical function proof, and a sizing of the components of the geotechnical barriers can be carried out using the partial safety factors method.

Tab. 4: Classification of the initial FEPs within the technical functional proof (DS = Design situation, A = Action, R = Resistance)

FEP-No.	FEP-Name	Classification within the functional proof*
1.2.03.01	Earthquake	DS, A, must be added
1.2.09.01	Diapirism	A, restraint strains
1.2.09.02	Subrosion	Excluded, because significance starts with next glaciation (after selected performance period)
1.3.05.03	Formation of glacial channels	Excluded, because significance starts with next glaciation (after selected performance period)
2.1.05.04	Alteration of drift and shaft seals	A, consequence of chemical action incl. temperature
2.1.07.01	Convergence	A, equivalent to rock pressure due to constitutive equation
2.1.07.02	Fluid pressure	A, fluid pressure
2.1.07.04	Volume changes in materials – not thermally induced	A, swelling/shrinking
2.1.07.07	Displacement of shaft seal	A, restraint strains or a consequence of forces/stresses
2.1.08.08	Swelling of bentonite	A, swelling
2.1.09.02	Solution and precipitation	A, consequence of chemical action incl. temperature
2.1.09.06	Corrosion of materials with cement or magnesium oxychloride phases	A, consequence of chemical action incl. temperature
2.2.01.01	Excavation damaged zone	Neither DS, A nor R but component of the seal
2.2.06.01	Change of stresses	A, dead load, rock pressure, fluid pressure, flow forces, restraint stresses

* If classification is impossible or meaningless, a comment is given

Tab. 5: Classification of less likely FEPs within the technical functional proof (DS = Design situation, A = Action, R = Resistance)

FEP-No.	FEP-Name	Classification within the functional proof
2.1.07.05	Early failure of a shaft seal	DS
2.1.07.06	Early failure of a drift seal	DS
2.1.08.05	Piping in seals	A, consequence of chemical actions or flow forces

Table 4 shows that the relevant FEPs that potentially affect the sealing system are widely covered by the actions and design situations mentioned before. Solely mass forces resulting from earthquakes in case of seismic design situations have to be added.

Table 4 and Table 5 specify several FEPs that are categorized as design situations within the technical functional proof. These are the seismic design situations (earthquake) (FEP 1.2.03.01) and abnormal (accidental) design situations (FEP 2.1.07.05 and 2.1.07.06) which comprise the early failure of a shaft seal and early failure of a drift seal. The persistent design situations comprise all remaining, probable FEPs within their probable occurrence, which were not previously excluded. Scenarios evolving from the less probable characteristics of probable FEPs also form abnormal design situations, see [2]. The FEP "piping in seals" (2.1.08.05) is covered by the failure of a shaft seal and a drift seal both forming abnormal design situations.

5 Conclusion

As the technical functionality can be demonstrated taking into account actions (impacts) that reflect the FEPs that can impair the function of the sealing structures (Figure 1), it has been demonstrated that – in the case of geotechnical barriers – a breakdown of the FEPs down to the technical level is possible which assists in completing the safety case.

References

[1] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (2010): Sicherheitsanforderungen an die Endlagerung wärmeentwickelnder, radioaktiver Abfälle, Stand 30. September

[2] http://www.grs.de/endlagersicherheit/gorleben/ergebnisse

[3] DIN EN 1990 Eurocode: Basis of structural design (English version of DIN EN 1990), October 2002