THE ROLE OF STRUCTURAL RELIABILITY OF GEOTECHNICAL BARRIERS OF AN HLW/SF REPOSITORY IN SALT ROCK WITHIN THE SAFETY CASE

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SAFETY CASES FOR THE DEEP DISPOSAL OF RADIOACTIVE WASTE: WHERE DO WE STAND?
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Structural reliability according to technical standards

One geotechnical barrier

- Failure probability: \( p_f \leq 10^{-4} / \text{working life} \)

A system of two independent geotechnical barriers

- Failure probability: \( p_f \leq 10^{-8} / \text{working lives} \)

\[ \rightarrow 2 \quad \text{effective geotechnical barriers} – \text{undisturbed evolution} \\
\rightarrow 1 \quad \text{effective geotechnical barrier} – \text{disturbed evolution} \\
\rightarrow 0 \quad \text{effective geotechnical barrier} – \text{excluded, because of low probability} \]

Structural reliability of geotechnical barriers (combined with an intelligent repository design) is decisive for dry/wet repository evolution in salt rock
Geological structure of Gorleben exploration area 1

Stratigraphic series

- Overburden:
  - Z3AM
  - Z3BT
  - Z3BK/BKD
  - Z3OSO
  - Z3OSM
  - Z3OSU
  - Z3LS
  - Z3BS
  - Z3HA
- Leine-series:
  - Z3LS
  - Z3BS
  - Z3HA
- Staßfurt-series:
  - Z3LK
  - Z3GT
  - Z3DA
  - Z3DS
  - Z3SF
  - Z3UE
  - Z3HG
  - Z2HS3
  - Z2HS2
  - Z2HS1

- Salt rock:
  - Tight rock
  - Salt barrier

- Shaft 1
- Shaft 2

- Shaft seals
- 820 m-level
- 840 m-level
- Drift seal
- Exploration area 1
- Tight rock salt barrier
- Brine/water intrusion

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Scheme of proofs to demonstrate barrier integrity

- Radionuclide transport “long-term SA”
- Integrity of geotechnical barrier
  - Proof of flow resistance
    - Flow resistance sealing body
    - Flow resistance contact zone
    - Flow resistance EDZ
  - Proof of structural resistivity
    - Durability / long-term stability
    - Limited crack evolution
    - Mechanical stability
- Combination of actions
  - Chemical actions
  - (Geotechnical) Actions - direct and indirect
  - Actions - persistent / transient design situation
  - Actions - accidental / seismic design situations
Methods to prove structural reliability

Two options to prove structural reliability

- By calculation
  → Safety criteria, modelling tools, validated models, and a method to manage uncertainty are required
- Design assisted by testing
  → E.g., if modelling tools resp. validated models are not available

ERAM drift seals:
- Structural resistivity is proved by calculation
- Flow resistance is proved by testing

Salzdetfurth Shaft II seal:
- Structural resistivity is proved by testing
- Flow resistance is proved by testing
  → Validation of models as a by-product
Example: ERAM drift seals

Design requirements and constraints

**Design requirements from long-term safety:** \( k \leq 10^{-18} \, \text{m}^2 \text{ initially} \)

\[ 5,000 - 30,000 \text{ years working life} \]

**Site-specific constraints:**
- Limited length of seals
- Difficult / limited access of seal locations
- Compatibility of seal material with salt concrete backfill
- Low convergence rates of rock salt at seal locations

Source: BfS / DBE
Position of drift seals – 3rd level

Source: BfS / DBE
Schematic overview – drift seal segment

- Schematic overview – drift seal segment
- plastic joints
  - crushed salt
  - salt briquettes
- re-ripping of drift contour
  (0.3 to 0.5 m)
- contact zone
- short-term EDZ
- joint
- sealing body
- EDZ

Segment of drift seal
salt concrete

0.5 – 1.0 m
15 – 30 m
0.5 – 1.0 m

retreat working direction

Source: BfS / DBE

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ERAM drift seals – proof of structural resistivity

- Safety criteria, modelling tools, validated models, and a method to manage uncertainty were applied according to state-of-the-art
  - Adequate level of structural reliability was shown
  - Cooling of salt concrete to avoid temperature-induced cracking

- New question: Cooling of salt concrete avoidable?
  - Applying a more sophisticated salt concrete constitutive model
  - Using cracking index to rate crack evolution

- New question: Autogenous shrinking of salt concrete
  - Presently, further investigations

Source: BfS / DBE
Flow resistance

Assessing flow resistance of contact zone

Data basis to prove adequate hydraulic resistance of contact zone must be obtained by testing from comparable, existing structures

- Comparable structure: Asse seal
- Investigation:
  - Permeability test in situ
  - Hydraulic fracturing in situ
  - Ultrasonic fault analysis in situ
  - Lab tests using core samples from Asse seal

Source: GSF / BfS / DBE
Asse seal – rating investigation results

- The construction process must be improved resp. the structure modified construction-compatible
- The salt concrete sealing body shows a sufficiently low permeability
- Basically, the contact zone being a weak spot is avoidable
- The EDZ shows a permeability equivalent to intact rock salt
- Healing of EDZ is uncertain
  - High pore pressure may increase permeability
  - Meeting the fluid pressure criterion is important

Source: BfS / DBE
Example: Experimental shaft Salzdetfurth

Schematic test arrangement

- upper concrete abutment
- upper filter layer
  - grain size 0-3 mm
- upper bentonite seal
  - grain size 1-3 mm
  - pressure chamber
  - grain size 1-3 mm
- lower bentonite seal
  - grain size 0-3 mm
- lower filter layer
- lower gravel abutment

Design requirements from long-term dry closure:

\[ k_f \leq 5 \cdot 10^{-10} \text{ m/s} \]

\[ p_{q0} \geq 1 \text{ MPa (NaCl-brine)} \]

Long-term durability

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Experimental shaft – saturation of bentonite seal

dismantled seal

Results:  
\[ k_f = 4.4 \times 10^{-11} \text{ m/s} < 5 \times 10^{-10} \text{ m/s} \]

\[ p_{qo} = 1-1.2 \text{ MPa} \geq 1 \text{ MPa} \]

Long-term durability: natural analogue
Summary and conclusion

ERAM drift seals:

→ Advanced state of proof of structural reliability
→ Main uncertainty: Assessing state of EDZ

Salzdetfurth Shaft II seal:

→ Advanced state of proof of structural reliability
→ Validity is restricted due to initial, boundary, and loading conditions of testing
→ Initial, boundary, and loading conditions might be comparable to Gorleben shaft seals

In the case of an HLW/SF repository in salt rock, proving structural reliability of two independent geotechnical barriers is a realistic option → dry repository evolution