RANGERS:
Methodology and Numerical Applications

11th US/German Workshop on Salt Repository Research, Design, and Operation

Eric Simo, Philipp Herold, Andreas Keller, Andree Lommerzheim, Paola Léon-Vargas
BGE TECHNOLOGY GmbH

Edward Matteo, Kristopher Kuhlman, Teklu Hadgu, Richard Jayne, Melissa Mills
SANDIA National Laboratories

The research work that is the basis of this report was funded by the German Federal Ministry for Economic Affairs and Energy (BMiW) represented by the Project Management Agency Karlsruhe (Karlsruhe Institute of Technology, KIT) under contract number FKZ 02 E 1830. The authors alone, however, are responsible for the contents of this study.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. SAND2021-10982 C. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.
What is RANGERS?

- RANGERS stands for:
  - (german) Entwicklung eines methodischen Ansatzes zur Auslegung und zum Nachweis von geo-technischen Barriern für ein HAW Endlager in Salzformationen Design
  - (english) Methodology for design and performance assessment of geotechnical barriers in a HLW repository in salt formations
- Joint-Project between BGE TECHNOLOGY and SANDIA National Lab
- Project duration: 2020 - 2022
Project Goals

- **Main goals:**
  - Compilation of existing knowledge and experience for the design of geotechnical barriers and compilation of new concepts and technologies on the subject of geotechnical barriers.
  - Development of a methodology based on the state of the art in science and technology for the design and verification of geotechnical barriers.
  - Preliminary design and verification of the geotechnical barrier system for the selected repository system based on the developed methodology.
  - Comparison of design results according to the new methodology with results of previous design and assessment.
Secondary goals:

- Estimation of the optimization potential of EBS in salt repositories
- Analysis of the impact of gases on EBS in salt
- Exploiting synergy effects between BGE TEC and SANDIA in the numerical treatment of EBS in the course of the overall safety assessment of salt repositories:
  - The expertise of BGE TEC on numerical based design of EBS will be used for the dimensioning of the components of the EBS.
  - The expertise of SNL in the performance assessment of large repository systems will serve to analyze the geochemical evolution and radionuclide transport through the EBS
RANGERS Methodology

Regulatory Framework + Safety Concept

**Generic salt pillow model from KOSINA**

- Selected Geological Site
- Repository Concept
- Sealing Concept
- FEP Analysis
- Total System Evolution (Scenario)

- Load Combinations derived from FEPs

**BGE TEC**

- Integrity Assessment of the Engineered Barrier System
  - Based on insights from safety assessments in Germany (VSG, Morsleben, ELSA)

- Design of the Engineered Barrier System

**SANDIA**

- Integrated Performance Assessment of the Repository System
  - Based on insights from performance assessments in the USA

- Assessment of Radiological Impact to the Biosphere and Humans

**Reference shaft seal concept for salt from ELSA**

- Drift seal concept from KOSINA

Based on insights from performance assessments in the USA

Assessment of Human Intrusion

(1): Treatment of uncertainties for PA & Determination of time-dependent parameter
(2): Design adjustment according to PA results
Repository in the selected geological site

LEGEND
- Q - Quaternary
- T - Tertiary
- S - Bunter Sandstone
- NA4 - Aller rock salt
- AM3 - Anhydritmittelsalz
- K3 - Ronnenberg potash seam
- NA3 - Leine rock salt
- A3 - Main Anhydrite
- K2 - Staßfurt potash seam
- NA2 - Staßfurt rock salt
- A2/C2 - Anhydrite/Carbonate
- R - Underlying Red

with courtesy of BGR
Sealing concept: Shaft seals

- Water tight liner with gravel column
- Bitumen filled gravel column
- Crushed salt and clay mixture
- Bentonite
- Gravel column filled with Mg-salts
- MgO-concrete

Legend:
- Q
- T
- S
- NA4
- AM3
- K3
- NA3
- A3
- K2
- A2/C2
- NA2
- R

Layers:
- Quaternary
- Tertiary
- Red Sandstone
- Salt clay
- Anhydrite
- Potash seam
- Potash seam
- Salt pillow
Sealing concept: Drift seals

Long-term sealing made of crushed salt-clay mixture

Sealing elements and abutments made of MgO-concrete
## Preliminary FEPs for EBS in salt formation

<table>
<thead>
<tr>
<th>Sub-system: Drift</th>
<th>Process Group</th>
<th>FEP</th>
<th>Description</th>
<th>Impact on EBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>1: Drift seal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3: Drift Backfill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10: Concrete injection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7: EDZ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>XX: ...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processes/Events</td>
<td>Mechanical</td>
<td>Example: Earth quake</td>
<td>The release of accumulated geologic stress via rapid relative movements within the earth’s crust usually along existing faults or geological interfaces.</td>
<td>tectonic movements resulting from an earthquake may yield in fractures in the drift seal. The drift lining may collapse.</td>
</tr>
<tr>
<td></td>
<td>Hydraulic</td>
<td>Example: Gas flow processes</td>
<td>Describes the gas flow due to potential gradients. Gas flow is responsible for transport of volatile compounds.</td>
<td>Gas flow transport is important for chemical processes and radio-nuclide spreading.</td>
</tr>
<tr>
<td></td>
<td>Thermal</td>
<td>Example: Heat flow</td>
<td>Means the energy transport as a result of temperature differences. There are 3 main sources for heat flow: climate, geothermic and radionuclide decay of the waste</td>
<td>The impact of waste produced heat on geotechnical barriers depends on the distance between barrier and emplacement field.</td>
</tr>
<tr>
<td></td>
<td>Chemical</td>
<td>Example: Concrete corrosion</td>
<td>Describes the chemical degradation of concrete</td>
<td>The corrosion processes will impair the function of all concrete components in the drifts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Components affected by process</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scenario relevant for EBS

- **Reference Scenario**: The EBS retains its function over 50,000 years
  - Case 1: Water flow from overburden through the shaft to the disposal zones
  - Case 2: Gas production inside the repository from corrosion of the casks
  - Case 3: Water source inside the repository from inter-/intragranular salt solutions

- **Alternative Scenario 1**: Shaft seal loses its function and drift seals retain their function
  - Same cases

- **Alternative Scenario 2**: Shaft seal retains its function and drift seals lose their function
  - Same cases
Modelling Concept

- Integrity assessment:

```
FEPs -> Scenarios -> Loads -> Modelling Concept
```

```
Verification Concept

Safety evaluation by long-term calculation of radionuclide transport
```

```
Requirement met
Safety demonstration of geotechnical barrier
```

```
Specification of hydraulic resistance
Demonstration of structural integrity
```

```
Hydraulic resistance
sealing element
```

```
Structural stability
Crack limitation
Deformation limitation
Erosion stability
Long-term stability
```

```
Individual assessments
Combination of impacts
```

```
Mechanical impact
Hydraulic impact
Thermal Impact
Chemical Impact
Normal impacts
Specific impacts depend on functional intent
```

```
Combination of impacts
```

```
Requirement met
```

```
```

## Modelling Concept

- **Integrity assessment:**

| Case 1: Water flow from overburden through the shaft to the disposal zones | Hydraulic resistance-sealing element | Hydraulic resistance-contact zone | Hydraulic resistance-EDZ | Structural stability | Crack limitation | Deformation limitation | Filtration stability | Long-term stability |
|---|---|---|---|---|---|---|---|---|---|
| H: determination of flow rate and passing time. HM: including compaction of crushed salt, swelling of bentonite (shaft) and related kf-development | TM: structural analysis of components inside the shaft (gravel column, concrete elements) | No numerical modelling needed, design and assessment based on existing standards | Geochemical analysis: determination of geochemical stability of the sealing elements against water/brine, a) theoretically unlimited water reservoir b) limited reservoir or in combination with kf-development |
| THM: compaction and kf-development at drift seal |  |  |  |  |
| Case 2: Gas production inside the repository from corrosion of the casks | H: gas pressure development inside repository (backfill)/at the drift seal, permeation condition p=csig min | Not relevant | Not relevant | Not relevant |
| HM: Interaction between gas pressure evolution and compaction of crushed salt in the drifts |  |  |  |  |
| Case 3: Water source inside the repository from inter- / intragranular salt solutions | H: determination of flow rate and passing time. HM: including compaction of crushed salt, swelling of bentonite (shaft) and related kf-development | TM: structural analysis of components inside the drift (concrete abutments) | Not relevant | Geochemical analysis: determination of geochemical stability |
| THM: compaction and kf-development at drift seal |  |  |  |  |

**Reference Scenario:** The EBS retains its function over 50000 years.
Modelling Concept

- Performance assessment

\[ RGI = \sum_{i} S_i \cdot DKF_i \]

Verification Concept

Modelling Concept
# Modelling Concept

- **Performance assessment**

<table>
<thead>
<tr>
<th>Processes</th>
<th>Target Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclide decay</td>
<td>Advection</td>
</tr>
<tr>
<td></td>
<td>Diffusion</td>
</tr>
<tr>
<td></td>
<td>Convection/conduction</td>
</tr>
<tr>
<td></td>
<td>2-Phase-flow</td>
</tr>
<tr>
<td></td>
<td>Boiling</td>
</tr>
<tr>
<td></td>
<td>Recon-densation</td>
</tr>
<tr>
<td></td>
<td>Dose constraints</td>
</tr>
</tbody>
</table>

**Reference Scenario: The EBS retains its function over 50000 years**

<table>
<thead>
<tr>
<th>Case 1: Water flow from overburden through the shaft to the disposal zones</th>
<th>Nuclide decay</th>
<th>Advection</th>
<th>Diffusion</th>
<th>Convection/conduction</th>
<th>2-Phase-flow</th>
<th>Boiling</th>
<th>Recon-densation</th>
<th>Dose constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 2: Gas production inside the repository from corrosion of the casks</th>
<th>Nuclide decay</th>
<th>Advection</th>
<th>Diffusion</th>
<th>Convection/conduction</th>
<th>2-Phase-flow</th>
<th>Boiling</th>
<th>Recon-densation</th>
<th>Dose constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 3: Water source inside the repository from inter-/intragranular salt solutions</th>
<th>Nuclide decay</th>
<th>Advection</th>
<th>Diffusion</th>
<th>Convection/conduction</th>
<th>2-Phase-flow</th>
<th>Boiling</th>
<th>Recon-densation</th>
<th>Dose constraints</th>
</tr>
</thead>
</table>
Modelling Concept

- Interactions between integrity and performance assessment

**Interaction with performance assessment:** Determination of permeability/porosity-functions of EBS-components for the PA simulations

**Interaction with Integrity assessment:** Sensitivity analyses – Optimization of the EBS-parameters in the PA simulations
Numerical Model

- **BGE TEC:**
  - T: Analysis of the thermal evolution in the EBS components
  - H: 1-phase hydraulic evolution of the repository
  - TM-compaction of crushed salt in the repository – determination of permeability function

- **SANDIA:**
  - Performance Assessment Simulations
  - Gas transport simulations
Goal: Determination of the temperature increase in the EBS

**FLAC3D 5.01**
©2018 Itasca Consulting Group, Inc.

| Temperature, °C | 1.1000E+02 | 1.0500E+02 | 1.0000E+02 | 9.5000E+01 | 9.0000E+01 | 8.5000E+01 | 8.0000E+01 | 7.5000E+01 | 7.0000E+01 | 6.5000E+01 | 6.0000E+01 | 5.5000E+01 | 5.0000E+01 | 4.5000E+01 | 4.0000E+01 | 3.5000E+01 | 3.0000E+01 | 2.5000E+01 | 2.0000E+01 | 1.5000E+01 | 1.0000E+01 |
Thermal evolution in the repository (BGE TEC)

- Temperature evolution in the drift seal
Thermal evolution in the repository (BGE TEC)

- Temperature evolution in the shaft
Thermomechanical compaction of crushed salt in the repository (BGE TEC)

- Goal: Determination of porosity/permeability-function for PA
Demonstration PFLOTRAN Simulations (SANDIA)

- Goal: Test of the capacity of PFLOTRAN to simulate the relevant processes considered in the scenario evolution

- Assumption for the test case:
  - Two-phase flow of air and water
  - Drifts, seals, and shafts are initially air-filled
  - Host rock is initially water-filled
  - 20 years pressure equilibration, then heating
  - Small inventory: 765 Pollux-10 and 279 Pollux-9 canisters
  - Individual waste packages not resolved
  - Assumed fuel 100 years out-of-reactor

- Next step: more realistic scenarios
PFLOTRAN Simulations (200 yr)

- Seals re-saturating and gas pressure increasing
- Flow in hostrock confined to near repository
PFLOTRAN Simulations (2000 yr)

- Seals re-saturating and gas pressure increasing
- Flow in host rock confined to near repository
Conclusions

- A methodology for the design and performance assessment of EBS in a HLW repository in salt formations has been developed.
- The methodology has been applied for the preliminary design of the EBS of a generic repository system in Germany based on the generic salt pillow model developed in the KOSINA project.
- The methodology is now being used to assess the integrity of the EBS and the long term evolution of the repository system:
  - A unique numerical model used at BGE TEC and at SANDIA has been developed for this purpose.
  - First results show that the temperature evolution in the EBS remain transient in the first 2000 years.
  - The evolution of the compaction of crushed salt in the repository will be used to derive the time dependent permeability in the repository mine.
  - The capabilities of PFLOTRAN to analyze all relevant processes occurring in the near- and far-field of the repository system have been successfully shown.
Next steps

- Structural integrity of the drift seals
- Structural integrity of the shaft seals
- Performance Assessment Simulations of the whole repository using the realistic geological material parameters and the actual waste inventory available in Germany
- Model optimizations and several case studies
Questions?

Thank you for your attention!