Crystalline Host Rock: Disposal Concepts and Research & Development Activities

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Outline

• Host rock characteristics
• Disposal concepts
• Technical gaps and priorities
• Process model development and integration
• Future work
## Characteristics of host rocks

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Salt</th>
<th>Shale</th>
<th>Granite (crystalline rock)</th>
<th>Deep boreholes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Permeability</td>
<td>Low</td>
<td>Low</td>
<td>Low (unfractured) to permeable (fractured)</td>
<td>Low</td>
</tr>
<tr>
<td>Mechanical strength</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Deformation behavior</td>
<td>Visco-plastic</td>
<td>Plastic to brittle</td>
<td>Brittle</td>
<td>Brittle</td>
</tr>
<tr>
<td>Stability of cavity</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Dissolution behavior</td>
<td>High</td>
<td>Very low</td>
<td>Very low</td>
<td>Very low</td>
</tr>
<tr>
<td>Chemical condition</td>
<td>Reducing; high ionic strength; relatively simple chemical system</td>
<td>Reducing; complex chemical system</td>
<td>Reducing; relatively simple chemical system</td>
<td>Reducing; relatively simple chemical system; moderate to high ionic strength</td>
</tr>
<tr>
<td>Radionuclide retention</td>
<td>Very low</td>
<td>High</td>
<td>Medium to high</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Thermal limit</td>
<td>Relatively high</td>
<td>Relatively low (?)</td>
<td>No limit</td>
<td>No limit</td>
</tr>
<tr>
<td>Available geology</td>
<td>Wide</td>
<td>Wide</td>
<td>Wide</td>
<td>Wide</td>
</tr>
<tr>
<td>Geologic stability</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Engineered barrier system</td>
<td>Minimal; waste package damage by room closure</td>
<td>Minimal; waste package damage by room closure</td>
<td>Needed. Able to fully take credit for the engineered barrier system</td>
<td>Borehole seal needed</td>
</tr>
<tr>
<td>Human intrusion/resource exploration</td>
<td>Relatively high</td>
<td>Relatively high</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Retrievability of waste</td>
<td>Feasible</td>
<td>Feasible</td>
<td>Easily retrievable</td>
<td>Difficult</td>
</tr>
</tbody>
</table>

- High mechanical strength and thermal limit
- Suitable for disposal of large and hot waste canisters
- Fractured nature
- Engineered barrier system equally important as the nature barrier
Geochemical characteristics of groundwater

**Water type A:** Dilute 0.5-2 g/L TDS; δ¹⁸O = -11.7 to -9.5% SMOW; Na-HCO₃, mainly Meteoric
Main reactions: Weathering, ion exchange, dissolution of calcite, redox reactions, microbial reactions
Redox conditions: Oxidizing - reducing

**Water type B:** Brackish 5-18 g/L TDS; δ¹⁸O = -11.5 to -8.6% SMOW; Na(Ca,Mg)-Cl(SO₄) to Ca-Na(Mg)-Cl(SO₄); Marine (Strong Litorina Sea component); Glacial - Deeper Saline component.
Main reactions: Ion exchange, pCO₂, of calcite, redox and microbial reactions
Redox conditions: Reducing

**Water type C:** Saline 10-15 g/L TDS; δ¹⁸O = -11.5 to -13.6%; SMOW (only 3 samples); Na-Ca-CI to Ca-Na-CI; Glacial - Deeper Saline mixture
Main reactions: Ion exchange, microbial reactions
Redox conditions: Reducing

**Water type D:** Strongly saline > 20 g/L TDS; Ca-Na-Cl; Deep saline origin (Field observations)
Main reactions: Long term water rock interactions
Redox conditions: Reducing

Reducing conditions: Iron and sulfate reduction

**Forsmark & Laxemar Areas**

https://www.wsj.com/articles/a-100-000-year-tomb-for-finlands-nuclear-waste-1485253831
Crystalline rock post-closure safety strategy

- **Containment**
  - Waste package is isolated by depth, and protected by buffer/backfill and reducing conditions
  - Canister integrity is maintained for a significant portion of the regulatory time period.

- **Limited Release**
  - Slow fuel dissolution in anoxic repository
  - Low permeability of host rock (especially in rock matrix)
  - Retardation along fracture paths due to
    - Fracture-matrix diffusion
    - Adsorption in fractures and matrix

**R&D objective:** Advance understanding of long-term disposal of used fuel in crystalline rocks (granitic or metamorphic rocks) and develop experimental and computational capabilities to evaluate various disposal concepts in such media.
Waste form and engineered barrier in crystalline rock

- **Glass High-Level Waste**
  - 5 logs per waste package
  - In-drift axial emplacement
  - Bentonite buffer
- **Spent nuclear fuel (SNF) in 4-PWR waste package**
  - Vertical deposition holes in floor of drift (KBS-3V disposal concept)
  - Compacted blocks of bentonite buffer
  - To be implemented for DECOVALEX-2023 performance assessment comparison task
- **SNF in 12-PWR waste package**
  - In-drift axial emplacement
  - Bentonite buffer with or without additives

PWR = pressurized water reactor assembly
### 2019 Roadmap Update: High-Priority R&D Activities

<table>
<thead>
<tr>
<th>Activity Designator Legend:</th>
<th>A – Argillite</th>
</tr>
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<tbody>
<tr>
<td>C – Crystalline</td>
<td>S – Salt</td>
</tr>
<tr>
<td>D – Dual Purpose Canisters</td>
<td>E – Engineered Barrier System</td>
</tr>
<tr>
<td>I – International</td>
<td>O – Other</td>
</tr>
<tr>
<td>P – Performance Assessment</td>
<td></td>
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#### High Priority R&D Activities

<table>
<thead>
<tr>
<th>Activity Designator</th>
<th>Description</th>
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<tbody>
<tr>
<td>A-08</td>
<td>Evaluation of ordinary Portland cement (OPC)</td>
</tr>
<tr>
<td>C-15*</td>
<td>Design improved backfill and seal materials</td>
</tr>
<tr>
<td>C-16*</td>
<td>Development of new waste package concepts and models for evaluation of waste package performance for long-term disposal</td>
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</tbody>
</table>
| D-01                |Probabilistic post-closure DPC criticality consequence analyses  
Task 1 - Scoping Phase  
Task 2 - Preliminary Analysis Phase  
Task 3 - Development Phase |
| D-03                | DPC filler and neutron absorber degradation testing and analysis |
| D-04                | Coupled multi-physics simulation of DPC postclosure (chemical, mechanical, thermal-hydraulic) including processes external to the waste package. |
| D-05                | Source term development with and without criticality |
| E-09                | Cement plug/liner degradation |
| E-11                | EBS High Temp experimental data collection-To evaluate high temperature mineralogy /geochemistry changes. |
| E-14*               | In-Package Chemistry |
| E-17*               | Buffer Material by Design |
| I-04                | Experiment of bentonite EBS under high temperature, HotBENT |
| I-06                | Mont Terri FS Fault Slip Experiment |
| I-08                | DECOVALEX-2019 Task A: Advective gas flow in bentonite |
| I-12                | TH and THM Processes in Salt: German-US Collaborations (WEIMOS) |
| I-13                | TH and THM Processes in Salt: German-US Collaborations (BENVASIM) |
| I-16*               | New Activity: DECOVALEX Task on Salt Heater Test and Coupled Modeling |
| I-18*               | New Activity: Other potential DECOVALEX Tasks of Interest: Large-Scale Gas Transport |
| P-12                | WP Degradation Model Framework |
| S-01                | Salt Coupled THM processes, hydraulic properties from mechanical behavior (geomechanical) |
| S-03                | Coupled THC advection and diffusion processes in Salt, multi-phase flow processes and material properties in Salt |
| S-04                | Coupled THC processes in Salt, Dissolution and precipitation of salt near heat sources (heat pipes) |
| S-05                | Borehole-based Field Testing in Salt |
Current R&D activities and priorities mapped to R&D roadmap

- Fuel matrix degradation model (FMDM). (ANL). (H: D-05, E-14)
- Radionuclide interactions with corrosion products (LLNL). (H: D-05, E-14)
- Bentonite erosion and colloid generation and transport (LANL). (H: C-15, M-H: E-20)
- Fluid flow in low-permeability media (SNL, LBNL). (H: I-08, M-H: C-11)
- Multiple scale core experiments on radionuclide-bentonite interactions (SNL, LBNL). (H: C-15, M: C-08)
- New-generation buffer materials/waste package materials; understanding thermal limits of buffer materials (SNL). (H: C-15, C-16, E-11, E-17)
- Discrete fracture network (DFN) model; especially a reduced order model for GDSA (LANL). (M-H: C-01, P-02)
- Workflow for field data synthesis and flow modeling in fractured media (SNL). (M-H: C-01, M-H: C-13, P-02)
- Geophysical and well-testing techniques for site characterization (LBNL). (M-H: E-03)

Current focuses: (1) better characterization and understanding of fractured media and fluid flow and transport in such media, and (2) designing effective engineered barrier systems (EBS) for waste isolation.
Process model development and integration

- Regional flow (topography, climate changes)
  - EBS&DRZ thermal & hydrologic environments
  - Buffer & backfill material performance

- EBS chemistry
- EBS&DRZ thermal & hydrologic environments
  - Waste package degradation
  - RN release from WPs

- In-package chemistry
- Waste form degradation
- RN mobility & solubility

- RN transport through backfill
  - Flow & transport through access ramps/shafts
  - RN release to biosphere

- RN transport through DRZ
  - Flow & transport DRZ to major fracture zone
  - Flow & transport through soil

DRZ = Disturbed rock zone
RN = Radionuclide
THMC = Thermal-hydrologic-mechanical-chemical
WP = Waste package
Waste form and engineered barrier

Fuel matrix degradation model accounts for effects of radiolysis and waste package degradation (e.g. H₂ generation).

Wang et al. (2020)
Lead/lead-alloy as a corrosion-resistant outer layer packaging material

Lead/lead-alloy is much more stable than copper in the presence of H2S.
Development of next-generation buffer materials for harsh environments

Leverage materials science and engineering for engineered material development.

Saponite is more stable than Na-montmorillonite in alkaline and high temperature environments.
Coupled thermal-hydrological-mechanical-chemical (THMC) model buffer materials

- The full-scale in situ test is located in Grimsel, Switzerland, heating started in 1997 at 100 °C, as part of FEBEX (Full-scale Engineered Barrier Experiment).
- Extensive laboratory tests were carried out to characterize THMC properties of bentonite, concrete, steel liner and granite after two dismantling events (2002 and 2015).
- Coupled THMC models were developed to understand the processes in the bentonite and granite.

In 2015, Dismantling of Heater #2
Colloid-facilitated transport model and buffer material erosion

Multiple site sorption model

Multiple column experiments for interrogating radionuclide sorption parameters

Figure 2-11. Model matches to the extraction breakthrough curves of test 08-01.

The model is ready available to be incorporated into Generic Disposal Safety Analysis (GDSA)

Reimus et al. (2017)
Comparison of different modeling approaches: The results show that DFN and ECM are comparable in the prediction of fluid flow and transport.

DFN toolkit for meshing discrete fractures and simulating flow and transport in fracture networks.

Hadgu et al. (2017)
Discrete fracture model: Field data synthesis and validation

- It is important to condition fracture network generation on actual fracture distribution (location, size) in tunnel and borehole.
- Statistical stability of fracture networks?

Mizunami Underground Research Lab, Japan

Wang et al. (2020)
Technology for site characterization and monitoring: Disturbed rock zone (DRZ) characterization

Dual-sample triaxial rock testing system

Granite core samples from Grimsel, Switzerland

Rigid-body-spring network model for simulating fracture patterns

Measurements of flow rate of a rock sample as a function of stress
Fracture characterization and field monitoring

500 particles evenly distributed within the tunnel at time 0.

- Challenge: Design a monitoring system to capture sufficient number of particles.
- Key capabilities: High-resolution geophysical techniques for fracture characterization.

Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) system
Current status of process models and total system integration

- Significant level of understanding achieved
- Some level of understanding achieved
- Work initiated

THMC – Thermal-hydrologic-mechanical-chemical
DRZ = Disturbed rock zone
WN = Radionuclide
WF = Waste form
WP = Waste package

10^0 10^1 10^2 10^3 10^4 10^5 10^6 year

- Manufacturing defects of Waste package
- WF degradation; RN release & transport

- Failure of copper-shelled waste package
- WF degradation; RN release & transport

- Failure of overpack
- WF degradation; RN release & transport

- Full saturation of buffer materials
- Thermal pulse

- EBS chemistry
- In-package chemistry
- EBS&DRZ thermal & hydrologic environments
- Waste package degradation
- Waste form degradation
- RN release from WPs
- RN mobility & solubility
- RN release to biosphere
- Flow & transport through access ramps/shafts
- Flow & transport through far field
- RN transport through backfill
- RN transport through DRZ
- Buffer & backfill material performance

- Work initiated

- Significant level of understanding achieved
- Some level of understanding achieved

SFWST
Next steps

- Develop a sensible GDSA model for sensitivity analyses.
  - Provide a minimum set of process models to GDSA
- Move model development more towards model validation with real data.
- Develop reduced order models for incorporation into the GDSA model.
- Continue with buffer material development.
- Develop and refine engineered barrier system (EBS) models, especially waste package (WP) degradation models.

Towards a more realistic representation of fluid flows in crystalline rocks: Crystalline rocks are generally quite impermeable.


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Questions?