Gas Migration in Clay-Based Materials – International Collaboration Activities as Part of the DECOVALEX Project

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Clay Gas Transport Team

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International Collaboration
DECOVALEX-2019 Task Lead: Jon Harrington, British Geological Survey
DECOVALEX-2019 Research Teams (8 teams from 8 countries)
Sources of Gas

- In a repository for heat emitting radioactive waste gas will be generated through a number of processes including:
  - Corrosion of metals (Hydrogen)
  - Radioactive decay of the waste (Radon etc)
  - Radiolysis of water (Hydrogen)
  - Microbial activities

- If production exceeds diffusion capacity a gas phase forms

- Gas will accumulate until its pressure becomes sufficiently large to enter the engineered barrier system (EBS) or host rock

- Understanding gas generation and migration is a key issue in the assessment of repository performance
Relevance to Performance

Example layout from the Swiss Concept (Seiphoori, 2015)

The gas production may impair the safety functions of the EBS and host rock:

- Where will produced gas go?
- Rate of gas production vs migration and release?
- Permanent damage to the buffer, EDZ, seals or host rock?
- Could the gas de-hydrate the buffer?
- Colloid transport and erosion of buffer material?
- Microbial activities?

Damage to seal and EDZ? Fracturing host rock? Gas release Pressure build-up
International URL Portfolio in a Nutshell

Key R&D Issues
- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior

Salt

Crystalline
- Streaming Potential
- Bedrichov Tunnel
- LTDE
- CFM
- GREET
- BRIE
- FEBEX & HotBENT

Far-Field

Argillite/Mudstone

Gas Migration
- TDSE (Asse)
- EBS
- BATS
- HE-E
- CI
- DR-A
- HG-A
- FE
- TED and ALC

J. Rutqvist, Gas Migration in Clay (NWTRB April 2019)
Repository Phases and Relevant Processes

Key R&D Issues
- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior

Diagram showing phases and processes:
- Disequilibrium, Thermo-Hydraulic-Mechanical-Chemical (THMC) Processes
- Equilibrium
- Release of radionuclides sorption and diffusion
- Canister failure
- Canister corrosion with hydrogen generation, microbial activity
- Sealing of EDZ
- Saturation of bentonite
- Normal hydrological conditions
- Normal geothermal conditions
- Oxidising conditions
- Reducing conditions
- Formation of EDZ
- Access sealing
- Monitoring
- Gallery backfilling
- Waste emplacement
- Repository construction

Phases:
- Construction and Open Drift Stage
- Exploitation Stage
- Long-Term Post-Closure Stage
State of the Art with R&D Gaps and Needs

- Transport of gases in clay-based buffer materials has been the subject of several international projects (e.g. LASGIT, FORGE)
- Substantial insight has been gained on gas transport processes
- Still the basic mechanisms of gas transport in bentonite and low permeability host rocks are not understood in sufficient detail, and therefore the predictive capacities are limited
Transport of gases in clay-based buffer materials has been the subject of several international projects (e.g. LASGIT, FORGE)

Substantial insight has been gained on gas transport processes

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⇒ Predictive capabilities are being developed along with participation in DECOVALEX-2019 with access to experimental data for model testing and validation
DECOVALEX-2019 Task: Modeling Gas Injection Gas Experiments

The purpose is to better understand the processes governing the advective movement of gas in low permeability materials (Bentonite and Claystone)

- British Geological Survey (BGS) provides laboratory data, expertise and lead this DECOVALEX-2019 task
- 8 Research Teams from 8 countries analyze and model the data
DECOVALEX-2019 Research Teams

(i) BGR/UFZ (Germany): Federal Institute for Geosciences and Natural Resources and the Helmholtz Centre for Environmental Research.
(ii) CNSC (Canada): Canadian Nuclear Safety Commission.
(iii) KAERI (Korea): Korea Atomic Energy Research Institute
(iv) LBNL (United States of America): Lawrence Berkeley National Laboratory.
(v) NCU/TPC (Taiwan): National Central University and the Taiwan Power Company (Taipower).
(vi) Quintessa/RWM (United Kingdom): Quintessa Ltd on behalf of Radioactive Waste Management.
(vii) SNL (United States of America): Sandia National Laboratories.
(viii) UPC/Andra (Spain/France): Universitat Politècnica de Catalunya, funded by l’Agence nationale pour la gestion des des déchets radioactifs.
Gas Flow Experimental Data on Bentonite

**BGS Test Cell:**

- MX80 bentonite confined into the cell
- Saturate the sample with water to develop swelling stress
- Inject hydrogen gas
- Monitor pressure, gas outflow, and stress during 4 month

(Harrington et al., 2003)

**Stage 1A: 1D Gas Flow Test**

- Radial filters
- Injection filter
- Monitoring rod

**Stage 2A: Radial Gas Flow Test**

- Radial filters
- Injection filter
- Monitoring rod

(Tamayo-Mas et al., 2018)
Complex hydraulic and mechanical responses during 120 days test

1) Bentonite emplacement
2) Saturate and swelling stress
3) Inject gas (to the system)
4) Pressure and stress response
5) Gas outburst
6) Slow seepage

(Tamayo-Mas et al., 2018)
LBNL-Continuum Using TOUGH-FLAC

**Material conceptual model:**
- Multiphase flow
- Poro-elasticity
- Linear moisture swelling/shrinkage
- Stress dependent gas permeability
- Gas entry pressure

Dilatant gas flow through aggregate boundaries
LBNL-Continuum Best Matched Case

- Abrupt gas entry (gas entry pressure)
- Peak flow rate depends on stress-k function
- Flow and stress after peak?
- Hydro-mechanical model quite simple with several calibration parameters

Before Gas Breakthrough

- Pressure
- Liquid Saturation
- Vertical Strain

Dashed lines = Modeling
Solid lines = Lab data
LBNL-Discrete Fracture Model (TOUGH-RBSN)

Model Grid Stage 2A

- Rock matrix and fractures conduct fluid flow and deform
- Fracturing is represented by the breakage of the springs (lattice elements) linking adjacent cells
- Fracture permeability depend on aperture

RBSN = Rigid Block Spring Network
LBNL-Discrete Fracture Model (TOUGH-RBSN)

Movie of fracture (dilatant flow path) evolution:

(Kim et al., 2018, TOUGH Symposium)
LBNL-Discrete Fracture Model (TOUGH-RBSN)

- Outflow more homogeneous (all 3 arrays) in the model

(Kim et al., 2018, TOUGH Symposium)
Modelling Approaches of DECOVALEX Teams

- **Two-phase flow continuum models**
  1. UPC/Andra-H: rigid medium
  2. LBNL-C-E: elasticity
  3. CNSC-E: elasticity
  4. CNSC-D: damage
  5. KAERI-D: damage
  6. BGR/UFZ-P: elastoplasticity
  7. CNSC-P: elastoplasticity
  8. NCU/TPC-E: elasticity
- **With preferential pathways**
  9. Quintessa/RWM-Cap: capillary model
  10. UPC/Andra-HM-E1: elasticity
  11. UPC/Andra-HM-E2: elasticity
  12. UPC/Andra-HM-P: elastoplasticity
- **Discrete approaches**
  13. LBNL-D: discrete fracture network
- **Other**
  14. SNL: chaotic model (conceptual)

- **A wide range of model approaches**
- **Some models match the data better**

But:
- **Do they correctly model the underlying micro-to-macro scale mechanisms?**
- **Can they be up-scaled and applied at the repository scale?**

(Tamayo-Mas et al., 2018)
Dual Structure of Bentonite

Gas flow expected to go through a network connected macro pores

- Poured, $e = 0.83$
- As compacted, $e = 0.53$
- Grain, $e = 0.28$

(Seiphoir 2015: Pore structure from Mercury Intrusion Porosimetry (MIP) analysis Scanning Electron Microscopy (SEM) observations)
Dilatant Flow Observations

• Gas injection test (with nanoparticles) designed to demonstrate the presence of pressure-induced dilatant pathways in Boom Clay
Avenue for Future Model Developments?

1) TOUGH-FLAC simulator with Barcelona Expansive Model considers the two structural levels and could be applied to study gas migration

Schematics of dual-continuum model
Senger et al., (2018)
TOUGH 2018 symposium

2) TOUGH-RBSN discrete fracture model can be further developed to consider long-term sealing and healing of dilated flow paths

But, need to be validated against laboratory and (if possible) field data, and to be demonstrated for application at the large scale....
The installation phase, including the deposition of canister and buffer, was finalized in 2005.

- Hydration of bentonite
- Several hydraulic and gas injection tests since 2008.

⇒ Access to a unique data set for model validation at a relevant field scale!

(SKB, 2017, TR-17-10)
Input to Geologic Safety Assessment Analysis (GDSA) and Performance Assessment (Pa)

- Near field of emplacement tunnels in different parts of a repository, for different FEPs such as nominal case or cases of extensive gas generation.

- Output to the PA model: (1) changes in flow properties (e.g. permeability and porosity) in the near-field, including the buffer and EDZ, (2) inform PA about local flow created by coupled processes.

Coupled Processes Model of an Emplacement Tunnel

Example layout from the Swiss Concept (Seiphoori, 2015)
Summary

• The study of gas flow migration in clay-based material has been a topic of several international studies, increasingly over the last 5-10 years.

• Still, the basic mechanisms of gas transport in bentonite and low permeability host rocks are not understood in sufficient detail, and therefore the predictive capacities are limited.

• Further work should strive to better represent the correct underlying physics, such as dual structure behavior, in models that should still be efficient to be applied at a repository tunnel scale.

• International projects, such as the DECOVALEX project, provide avenues for faster capability developments through exchanges of ideas and collaborations, and through access to experimental data.
References


# Acronyms and Abbreviations

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ANDRA</td>
<td>National Radioactive Waste Management Agency, France</td>
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<tr>
<td>BGR</td>
<td>Federal Institute for Geosciences &amp; Natural Resources, Germany</td>
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<td>BGS</td>
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<tr>
<td>CNSC</td>
<td>Canadian Nuclear Safety Commission, Canada</td>
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<td>DECOVALEX</td>
<td>DEvelopment of COupled Models and their VALidation Against EXperiments</td>
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<td>DOE</td>
<td>Department of Energy, USA</td>
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<tr>
<td>EBS</td>
<td>Engineered Barrier System</td>
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<td>EDZ</td>
<td>Excavation Damage Zone (or Excavation Disturbed Zone)</td>
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<td>FEPs</td>
<td>Features, Events, and Processes</td>
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<td>FLAC</td>
<td>Fast Lagrangian Analysis of Continua</td>
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<td>FORGE</td>
<td>Fate Of Repository Gases</td>
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<td>KAERI</td>
<td>Korea Atomic Energy Research Institute, Republic of Korea</td>
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<td>LASGIT</td>
<td>Large-scale Gas Injection Test</td>
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<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory</td>
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<td>NAGRA</td>
<td>Swiss waste management organization</td>
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<td>NCU</td>
<td>National Central University, Taiwan</td>
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<td>PA</td>
<td>Performance Assessment</td>
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<td>RBSN</td>
<td>Rigid Block Spring Network</td>
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<td>RWM</td>
<td>Radioactive Waste Management Limited, UK</td>
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<tr>
<td>SKB</td>
<td>Swedish Nuclear Fuel and Waste Management, Sweden</td>
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<tr>
<td>SNL</td>
<td>Sandia National Laboratory</td>
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<tr>
<td>STP</td>
<td>Standard Temperature and Pressure</td>
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<td>TOUGH</td>
<td>Transport Of Unsaturated Groundwater and Heat</td>
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<tr>
<td>TPC</td>
<td>Taiwan Power Company, Taiwan</td>
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<tr>
<td>UFZ</td>
<td>Helmholtz Centre for Environmental Research</td>
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<tr>
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Questions?