U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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

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Jonny Rutqvist
Senior Scientist
Energy Geosciences Division
Lawrence Berkeley National Laboratory
Berkeley, California

Clay Gas Transport Team

Lawrence Berkeley National Laboratory

Jonny Rutqvist, Kunhwi Kim, Jens Birkholzer

Sandia National Laboratories

Yifeng Wang

International Collaboration

DECOVALEX-2019 Task Lead: Jon Harrington, British Geological Survey

DECOVALEX-2019 Research Teams (8 teams from 8 countries)

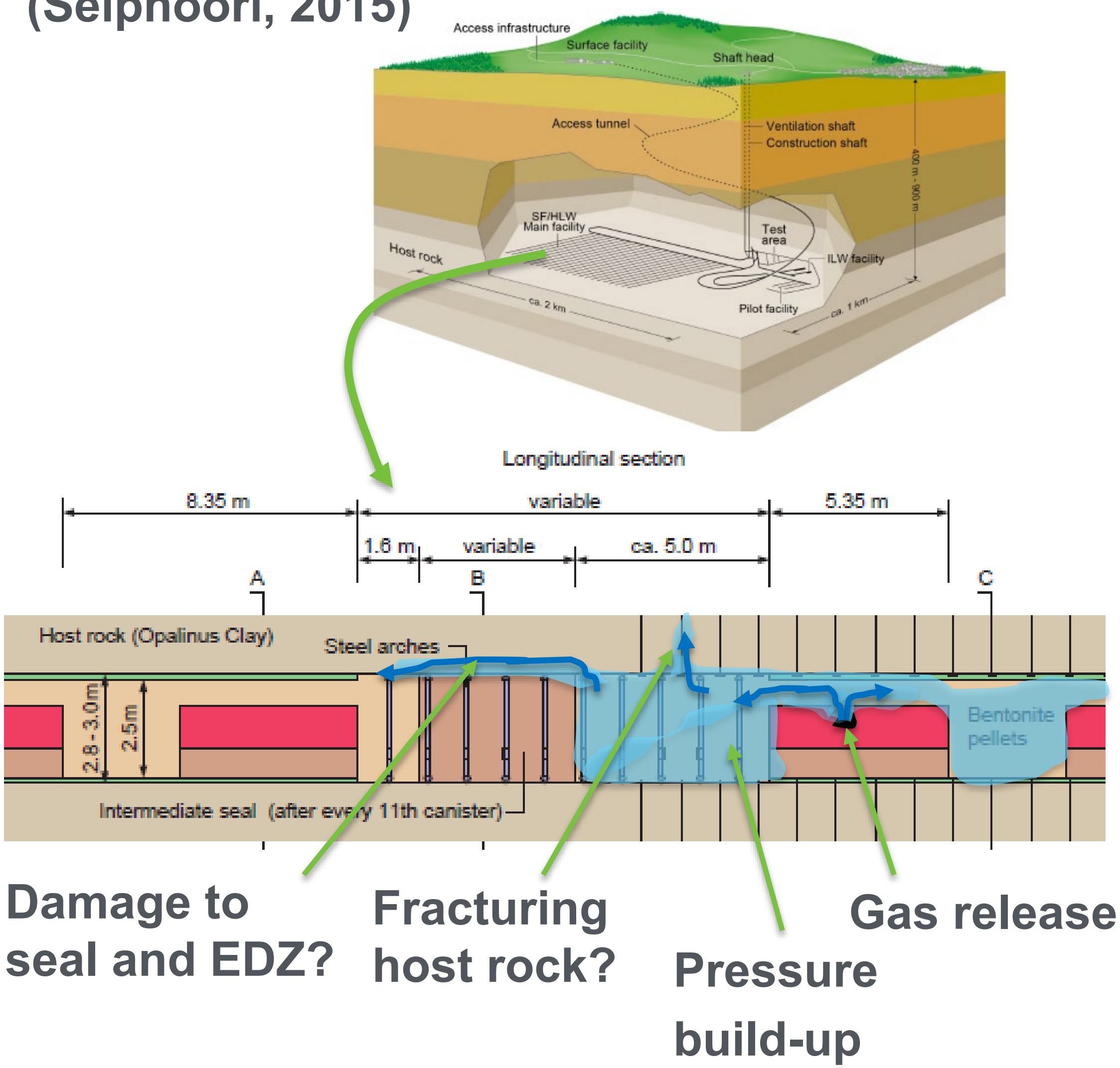
Sources of Gas

- 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)

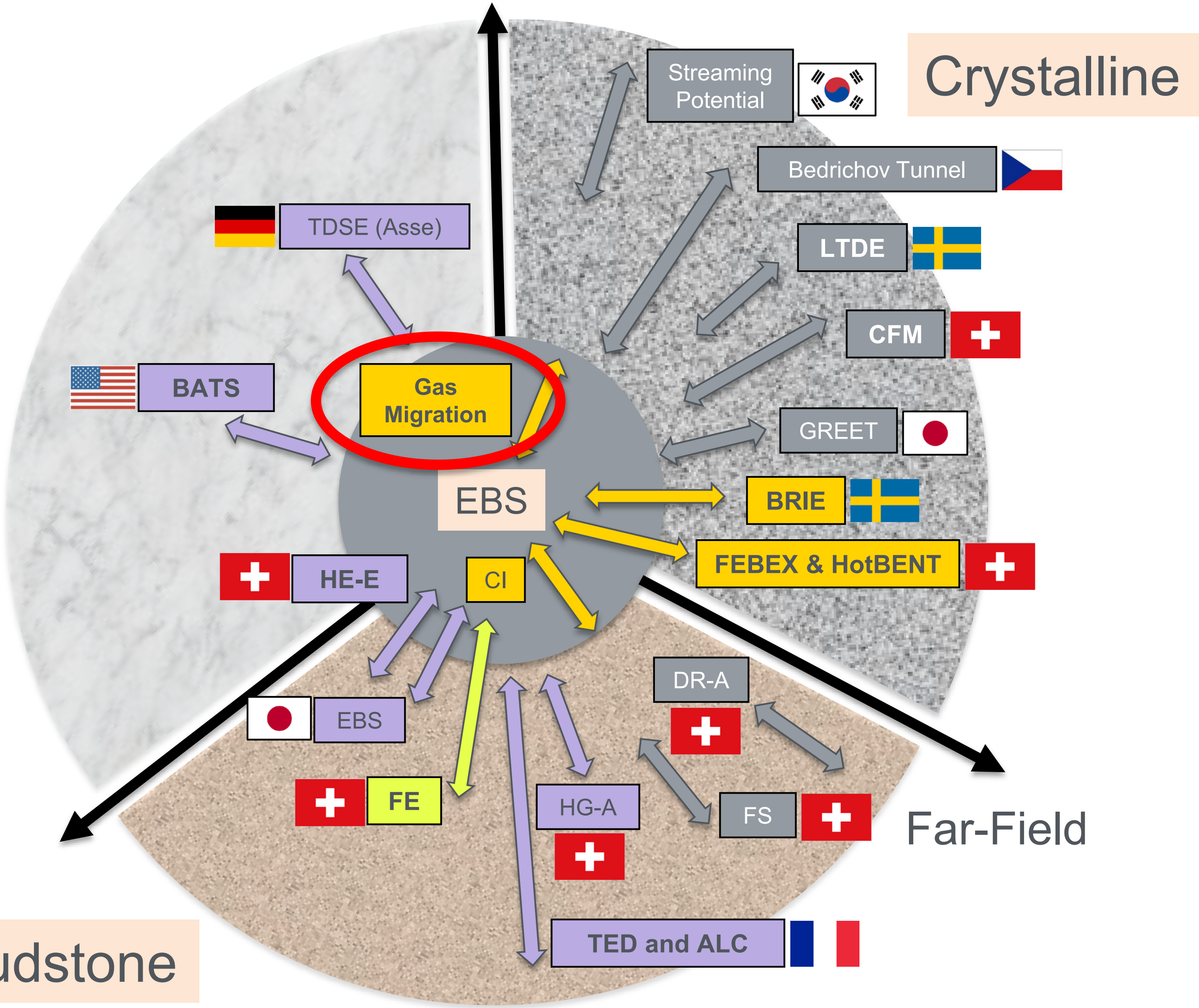


The gas production may impair the safety functions of the EBS and host rock:

- **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?**

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



Repository Phases and Relevant Processes

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

BATS

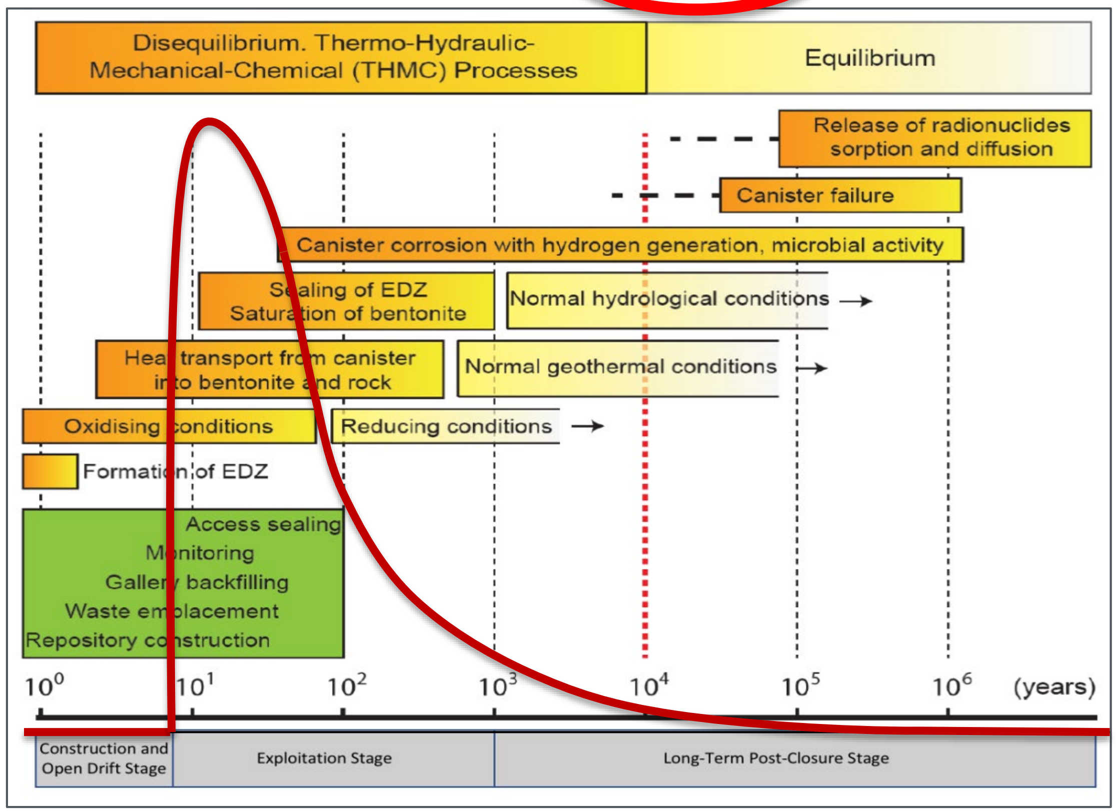
FEBEX & HotBENT

BRIE

Gas Migration

CFM

LTDE



TED, ALC, HE-E

FE

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

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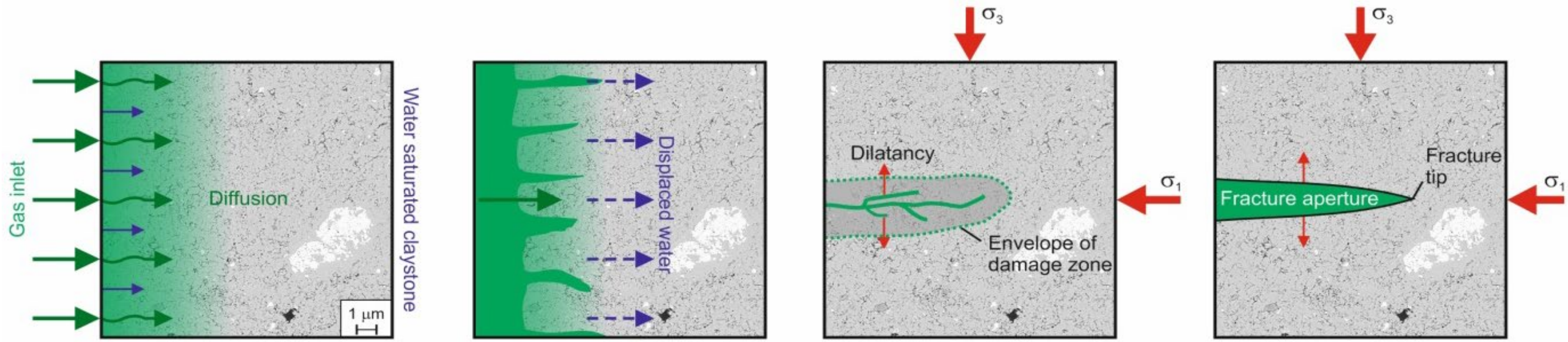
⇒ **Predictive capabilities are being developed along with participation in DECOVALEX-2019 with access to experimental data for model testing and validation**

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)



Advection and diffusion of dissolved gas | Visco-capillary flow of gas and water phase ("two-phase flow") | Dilatancy controlled gas flow ("pathway dilation") | Gas transport in tensile fractures ("hydro-/gasfrac")

(Marcshall et al., 2005)

- 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.

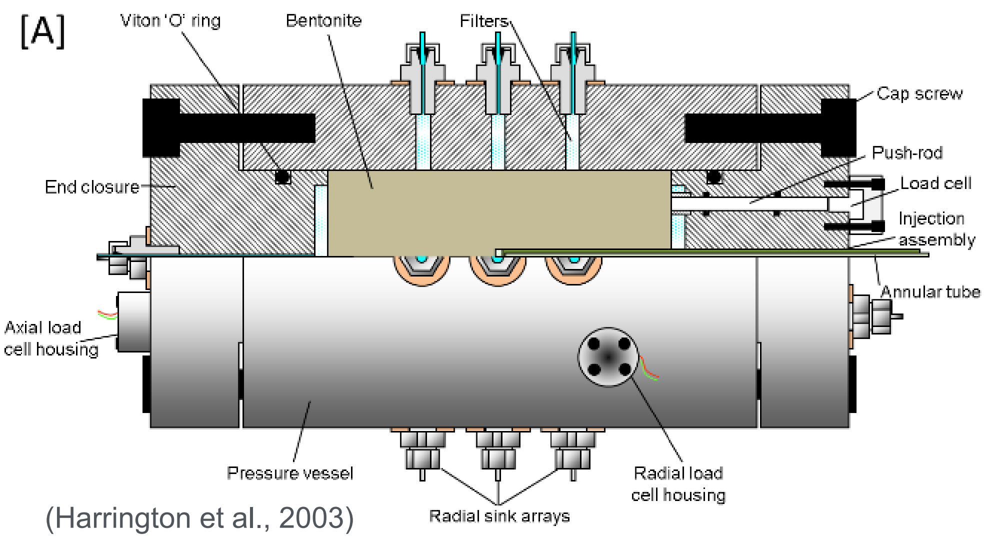

(vii) SNL (United States of America): Sandia National Laboratories.



(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

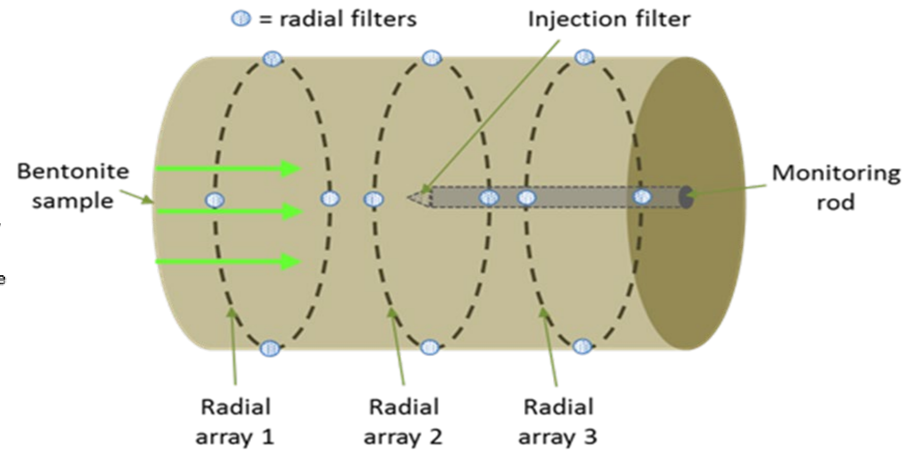
BGS Test Cell:



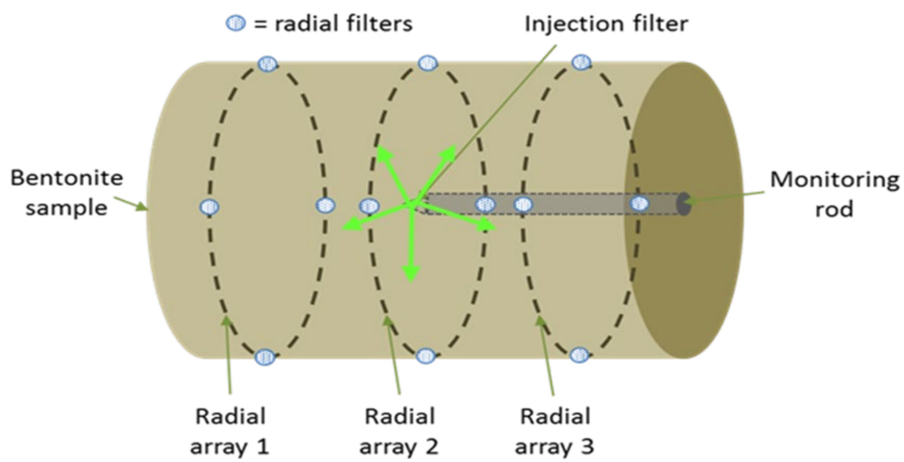
(Harrington et al., 2003)

- **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**

Stage 1A: 1D Gas Flow Test



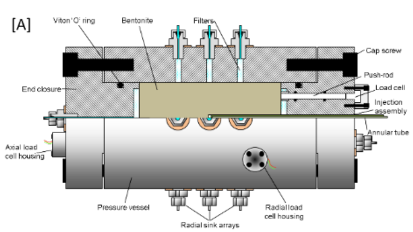
Stage 2A: Radial Gas Flow Test

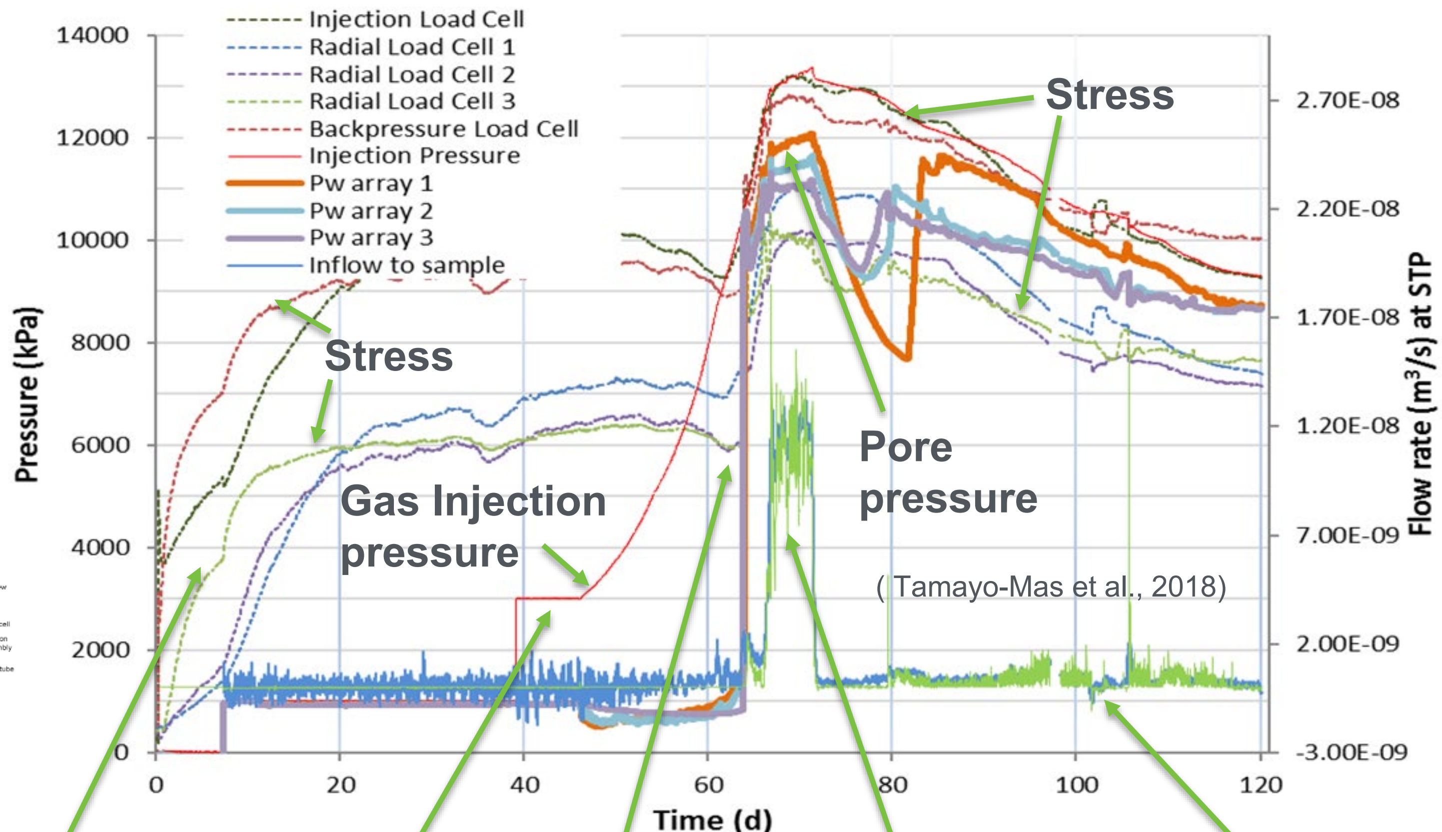


(Tamayo-Mas et al., 2018)

Stage 1A Tests Data (1D flow, stress, pressure)

Complex hydraulic and mechanical responses during 120 days test





1) Bentonite emplacement

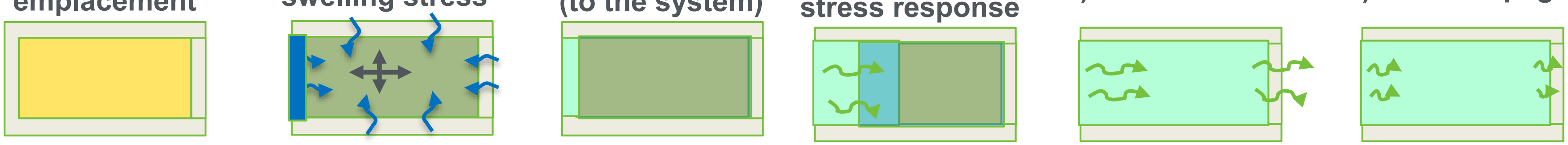
2) Saturate and swelling stress

3) Inject gas (to the system)

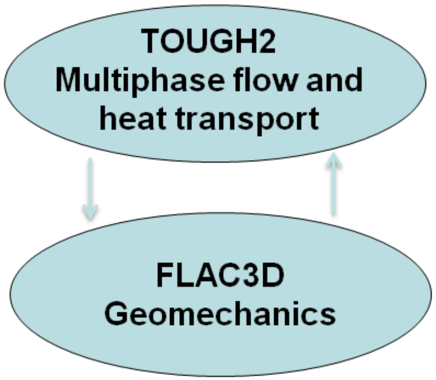
4) Pressure and stress response

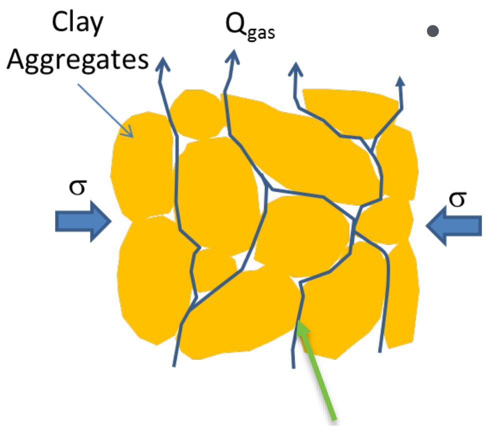
5) Gas outburst

6) Slow seepage



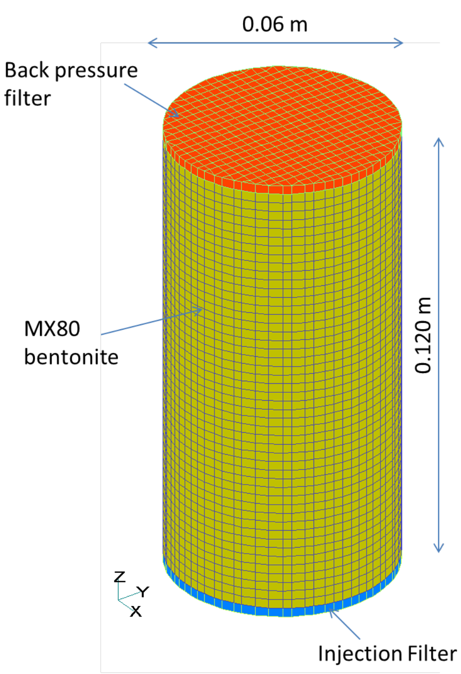
LBNL-Continuum Using TOUGH-FLAC

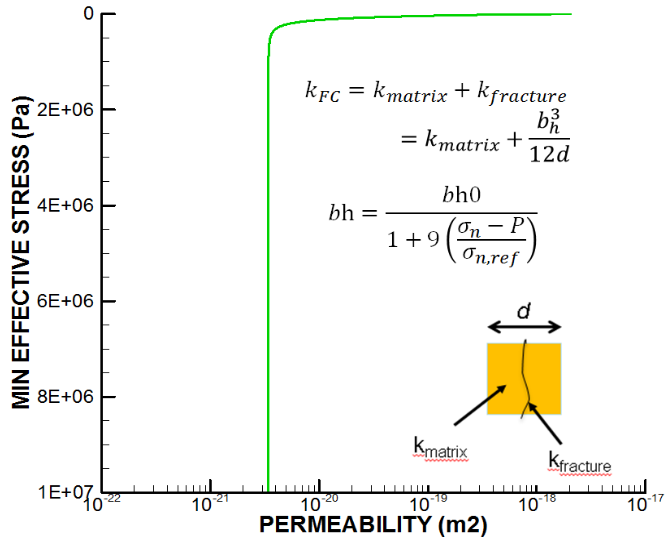


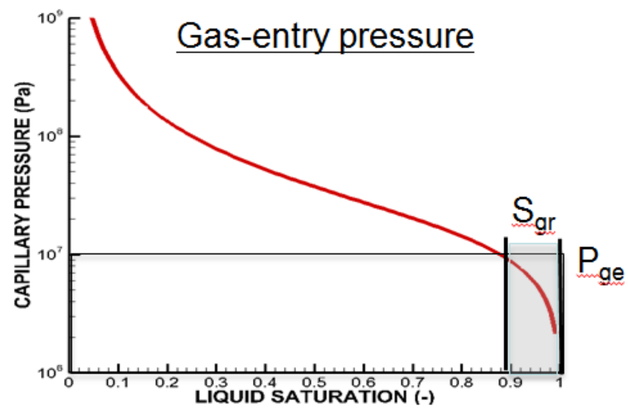


Dilatant gas flow through aggregate boundaries

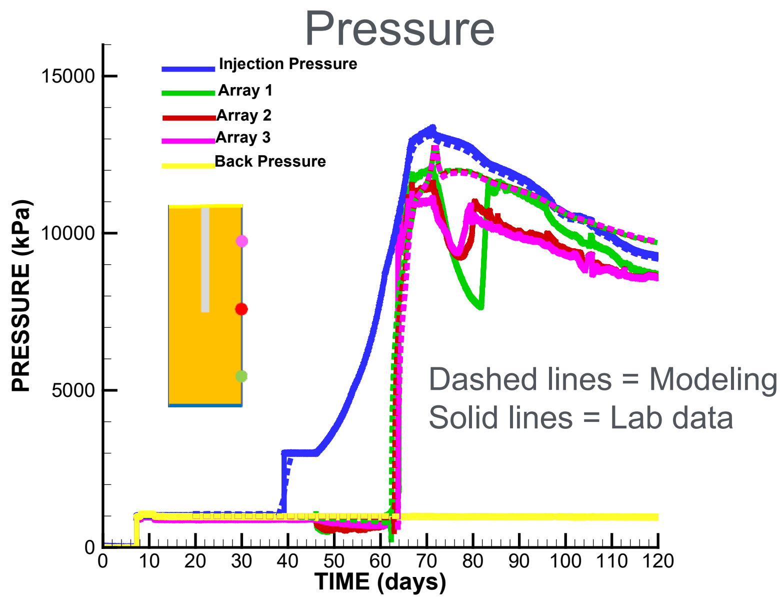
- Material conceptual model:
  - Multiphase flow
  - Poro-elasticity
  - Linear moisture swelling/shrinkage
  - Stress dependent gas permeability
  - Gas entry pressure

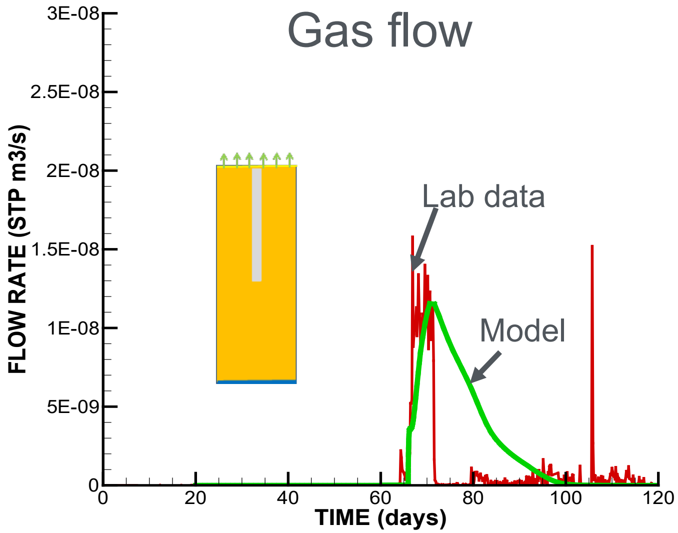




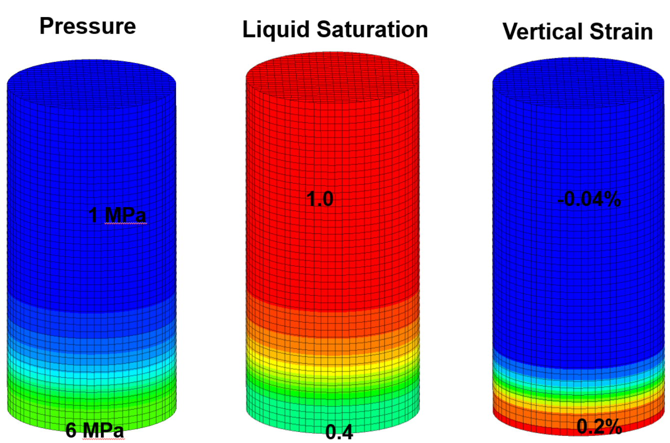


LBNL-Continuum Best Matched Case



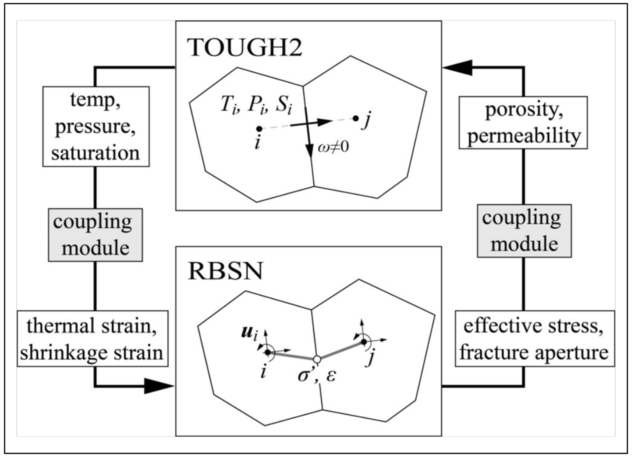


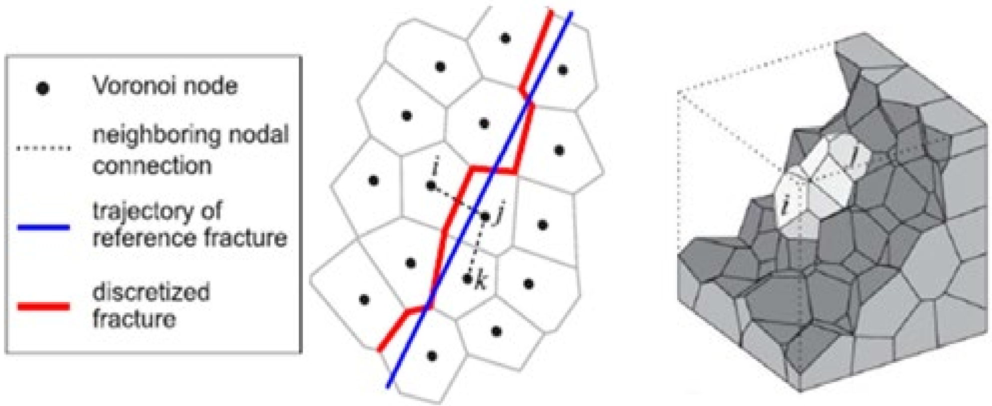
Before Gas Breakthrough



- 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

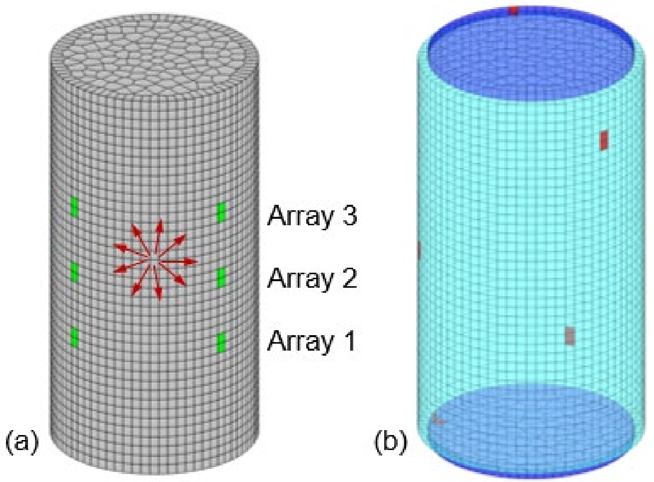
LBNL-Discrete Fracture Model (TOUGH-RBSN)





RBSN = Rigid Block Spring Network

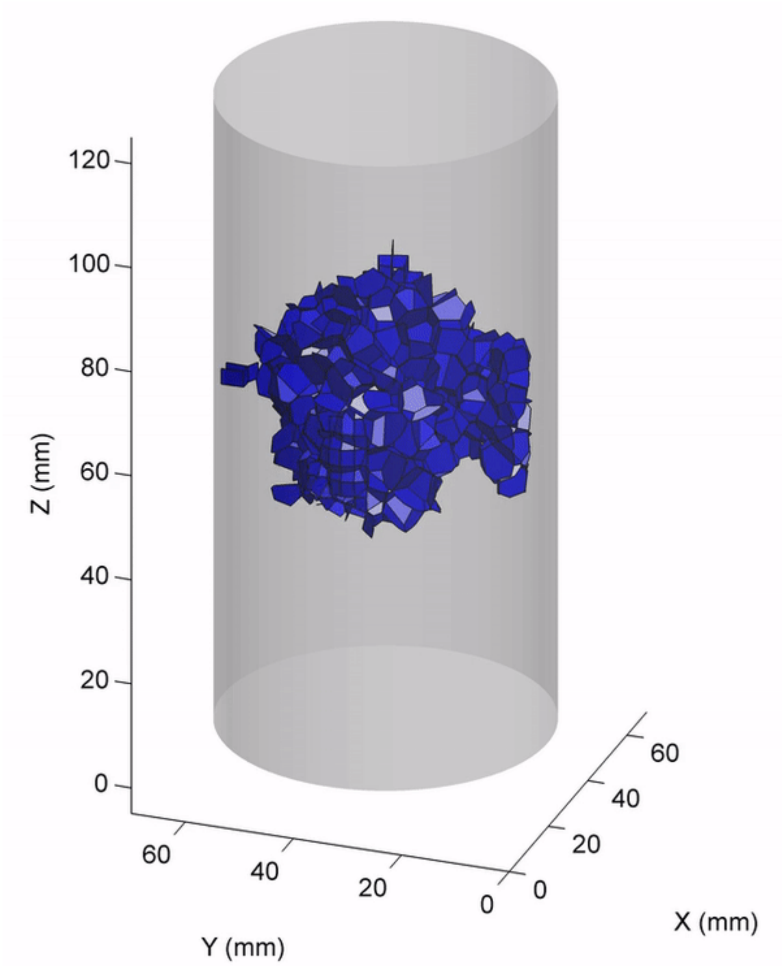
Model Grid Stage 2A

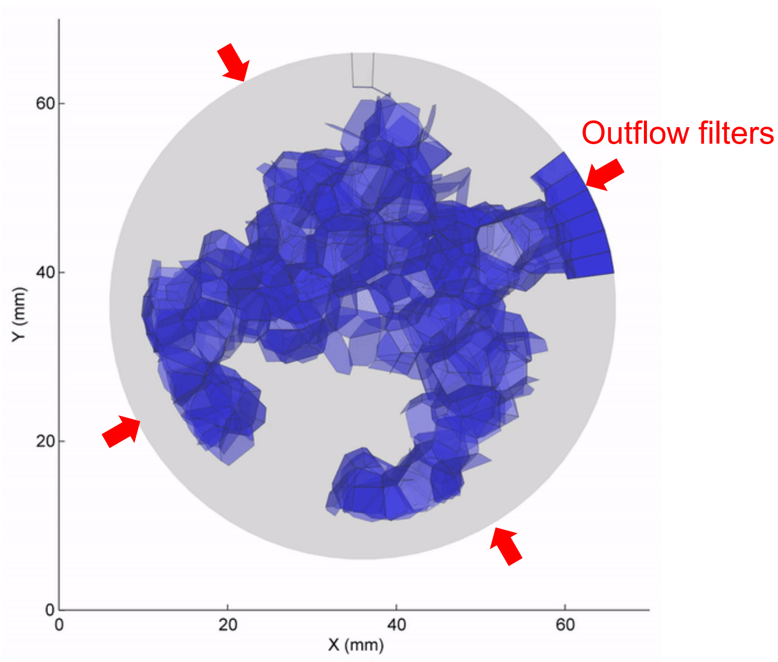


- Rock matrix and fractures conduct fluid flow and deform
- Fracturing is represented by the breakage of the springs (lattice elements) linking adjacent cells
- Fracture permeability depend on aperture

LBNL-Discrete Fracture Model (TOUGH-RBSN)

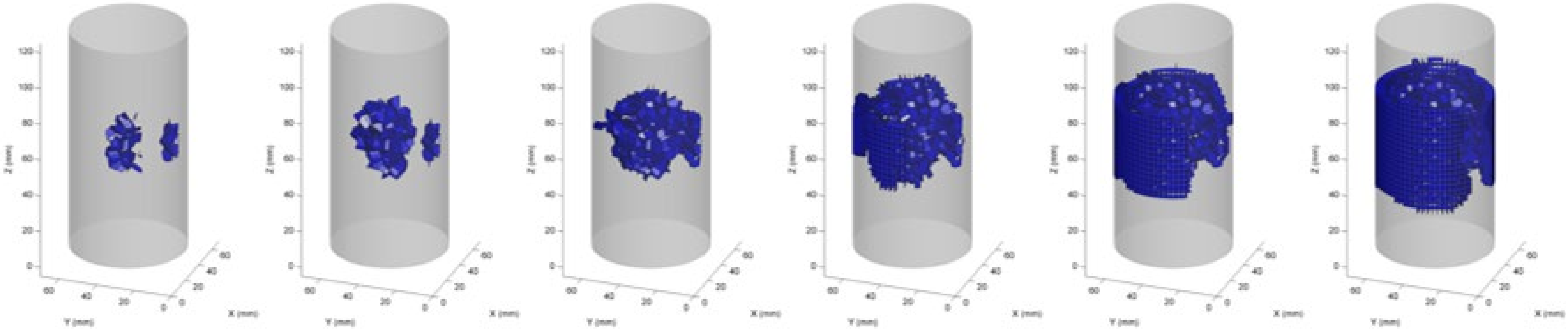
Movie of fracture (dilatant flow path) evolution:

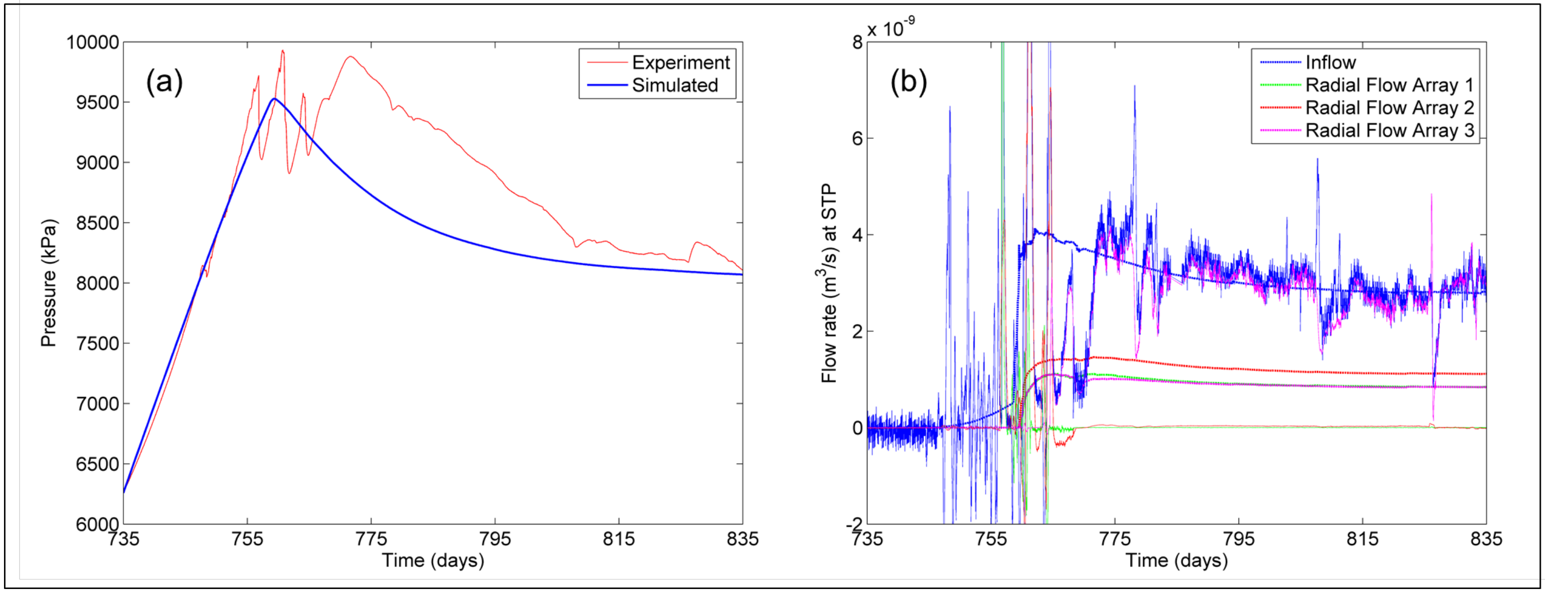




(Kim et al., 2018, TOUGH Symposium)

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)

(Tamayo-Mas et al., 2018)

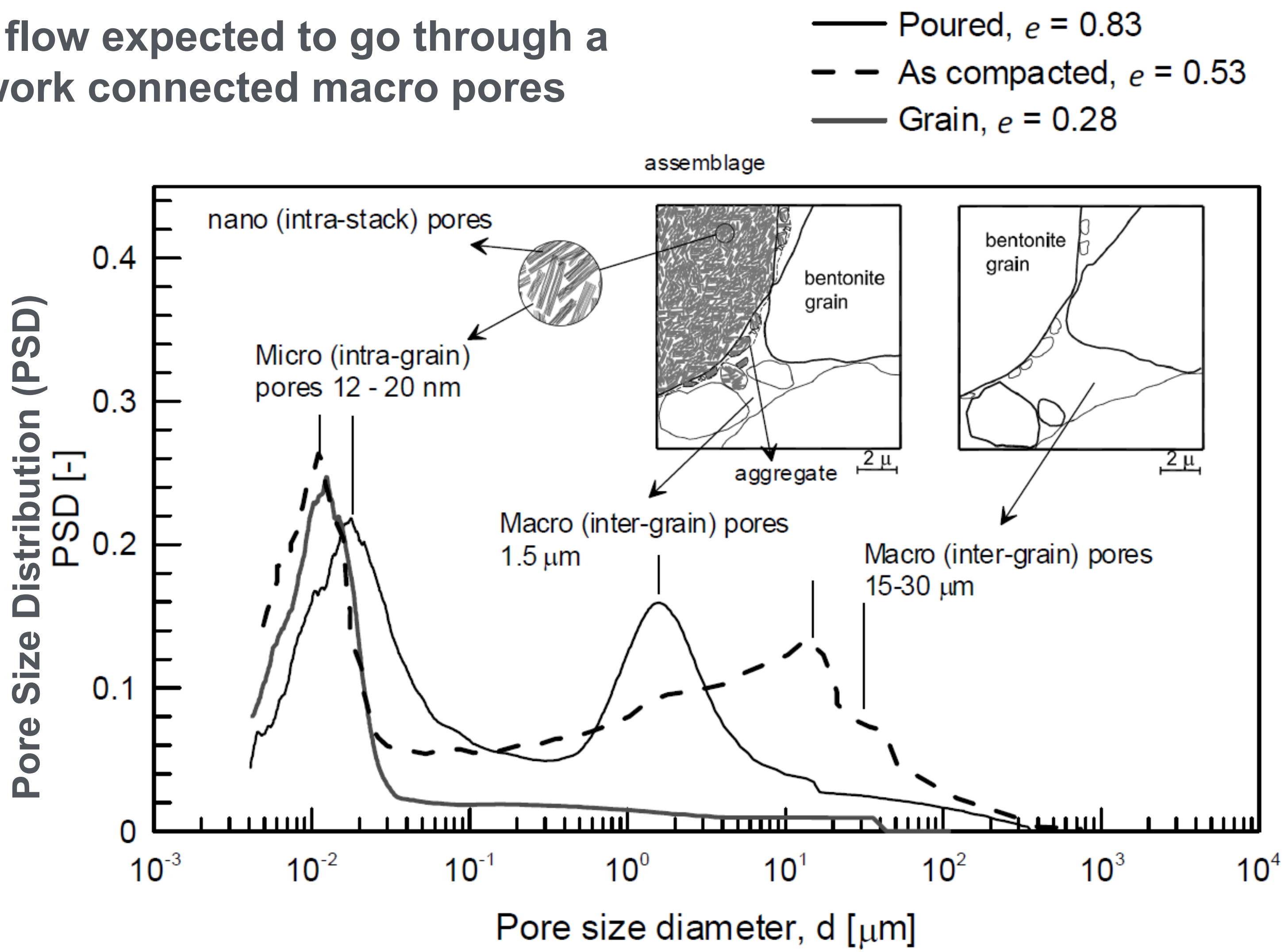
- **A wide range of model approaches**
- **Some models match the data better**

But:

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

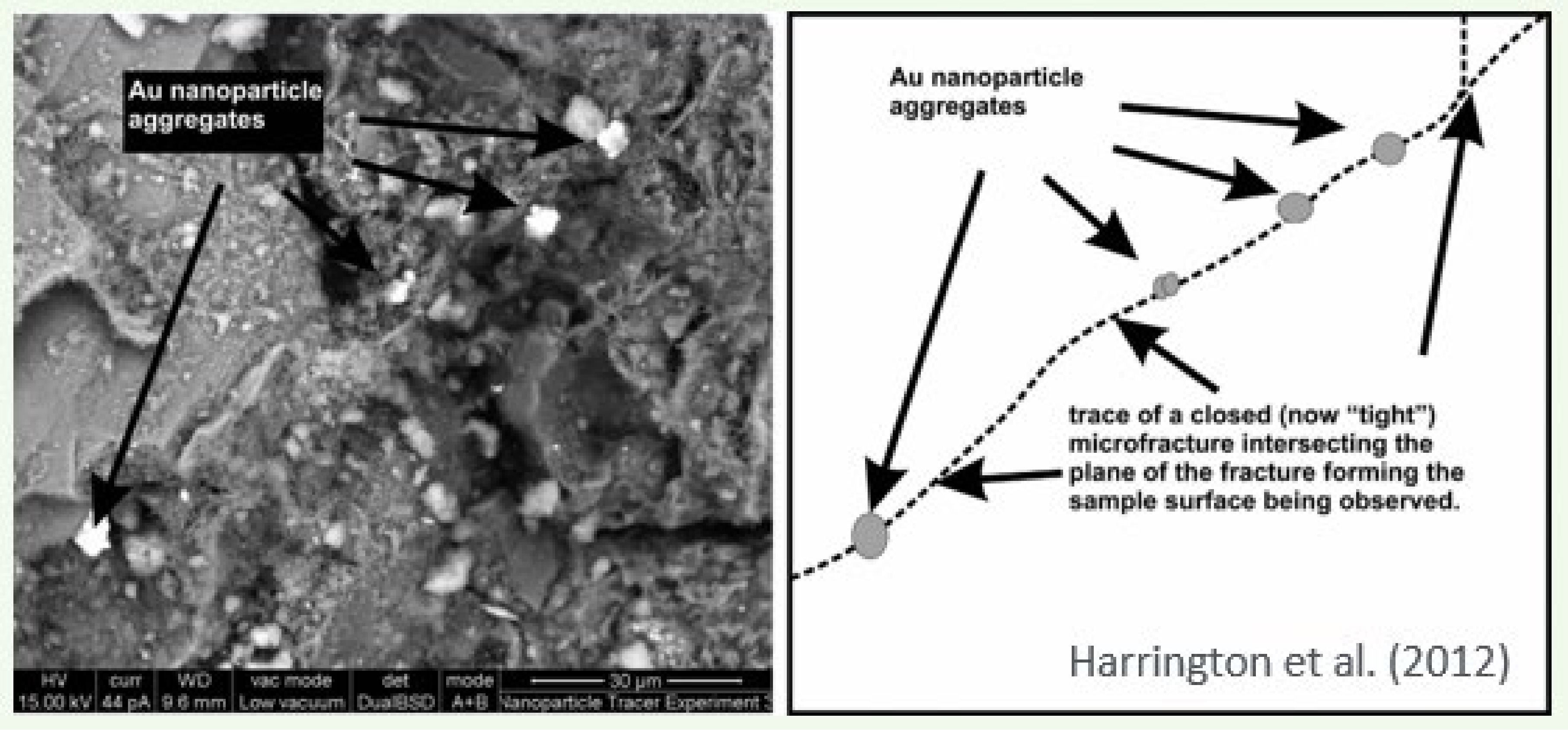
Dual Structure of Bentonite

Gas flow expected to go through a network connected macro pores



(Seiphooir 2015: Pore structure from Mercury Intrusion Porosimetry (MIP) analysis Scanning Electron Microscopy (SEM) observations)

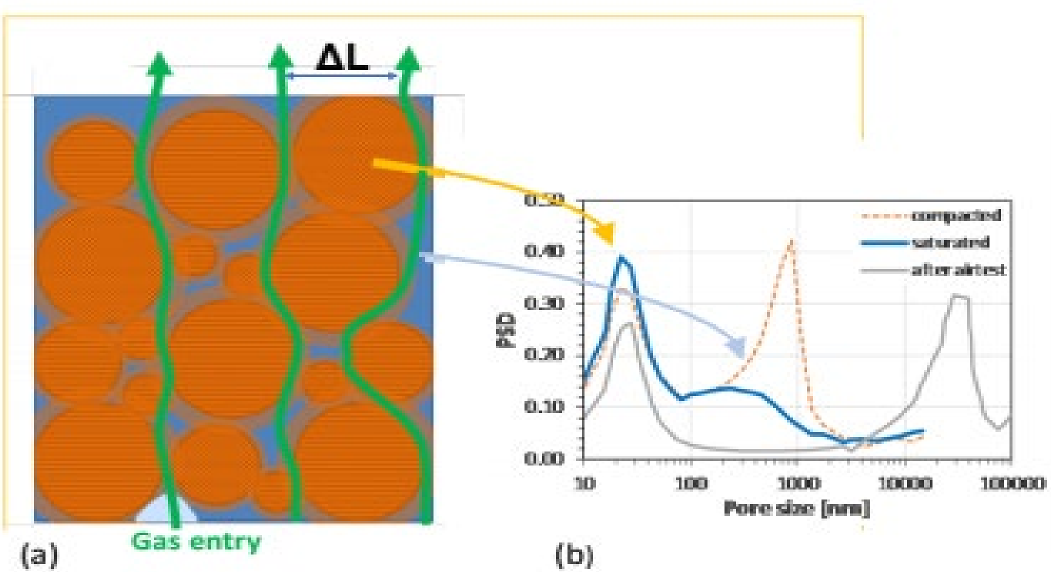
Dilatant Flow Observations



- 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



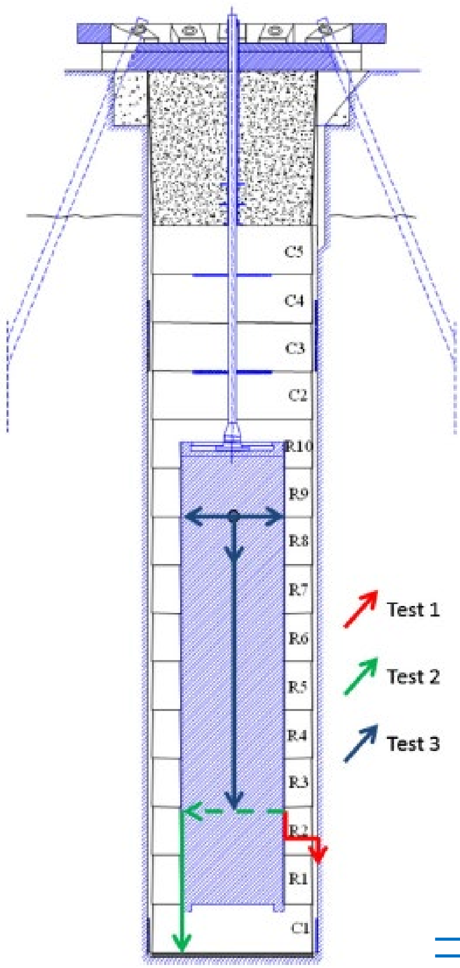
Schematics of dual-continuum model

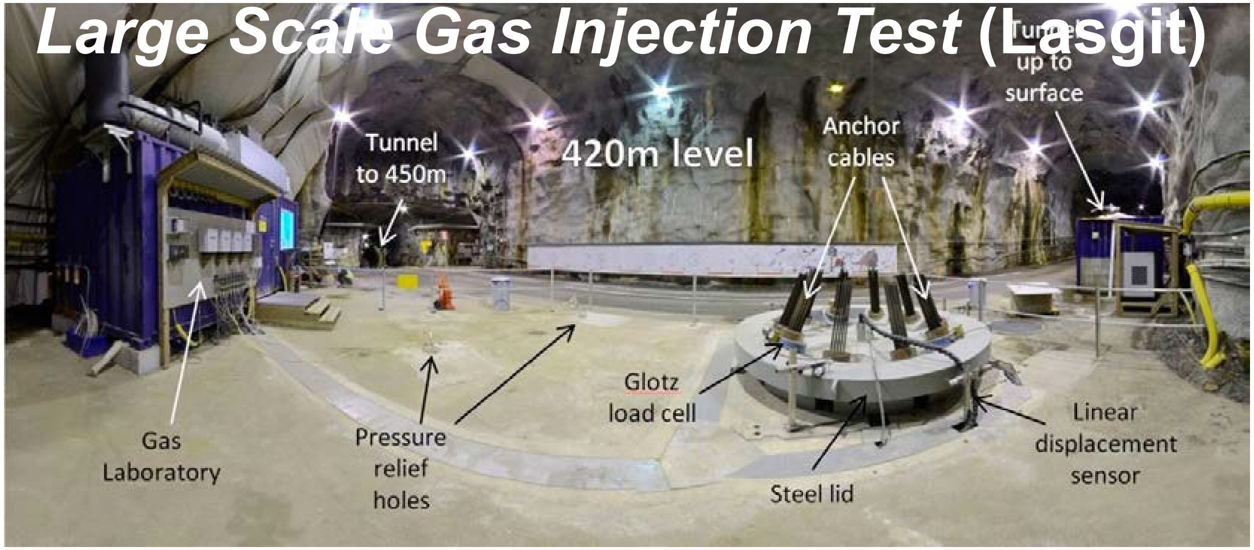
Senger et al., (2018) TOUGH 2018 symposium

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….

Potential DECOVALEX-2023 Task (Lasgit)





- 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.

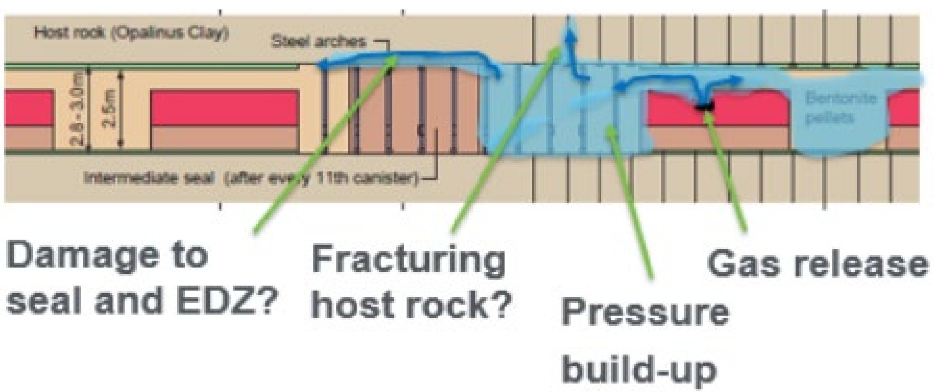
⇒ Access to a unique data set for model validation at a relevant field scale!

(SKB, 2017, TR-17-10)

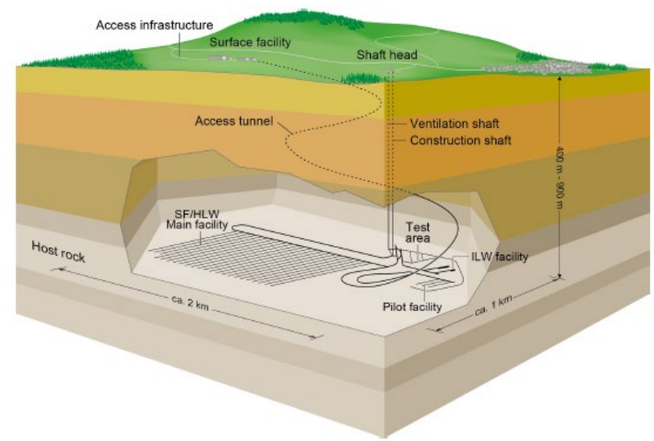
Input to Geologic Safety Assessment Analysis (GDSA) and Performane Assessment (Pa)

- **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



PA Model of Entire Repository



Example layout from the Swiss Concept (Seiphoori, 2015)

Summary

- The study of gas flow migration in clay-based material has been to 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

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Acronyms and Abbreviations

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

Questions?

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