COMSOL CONFERENCE
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Hydro-mechanical modelling of gas migration in host rocks for nuclear waste repositories

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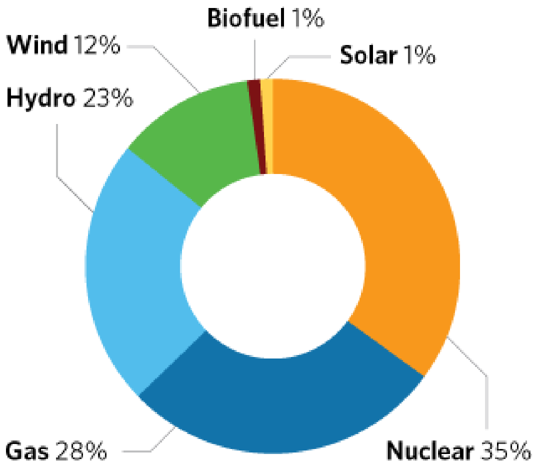
Outline

Introduction

- Nuclear power



Nuclear	13,009 MW or 35%
Gas/Oil	10,277 MW or 28%
Hydro	8,499 MW or 23%
Wind	4,486 MW or 12%
Biofuel	295 MW or 1%
Solar	424 MW or 1%

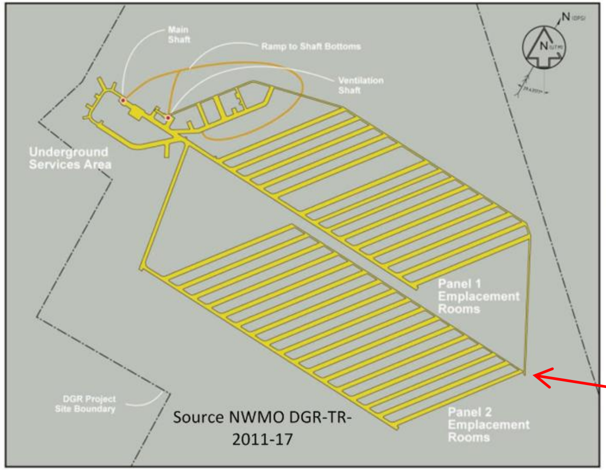
https://consciouslifestylesradioblog.com/?s=nuclear

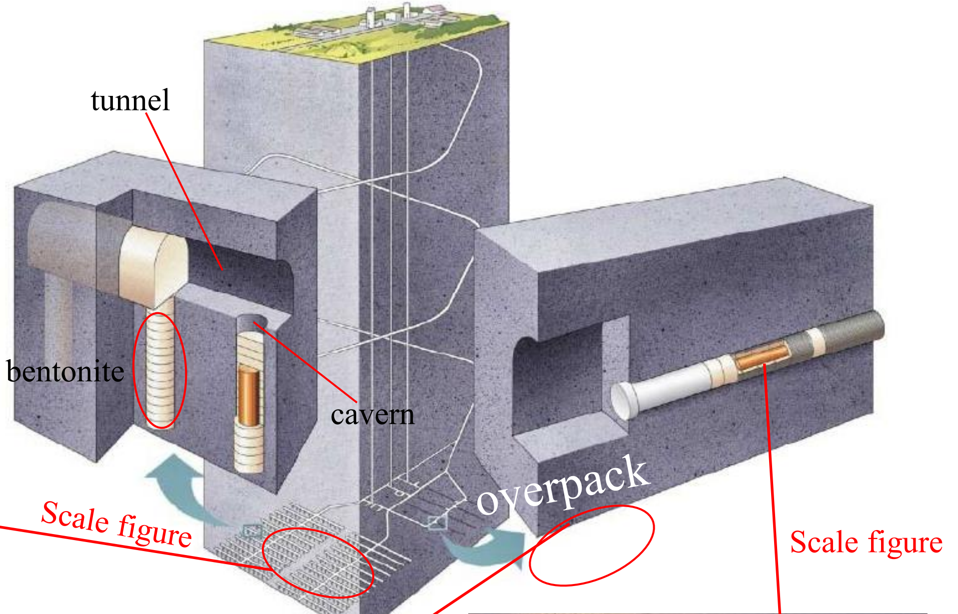
Current installed energy capacity in Ontario (from 18-Months Outlook)

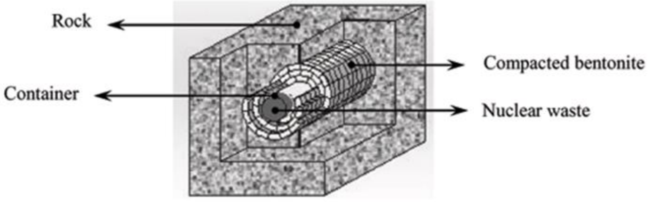
Nuclear waste disposal

Waste types	Option	Examples
LLW and short-lived ILW	Near-surface disposal, or in caverns below ground level (at depths of tens of meters)	Implemented in Finland and Sweden.
Long-lived ILW and HLW	Deep geological repository (DGR) at depths 250-1000 m, or deeper boreholes	DGR is being investigated or constructed.

➢ The concept of DGR

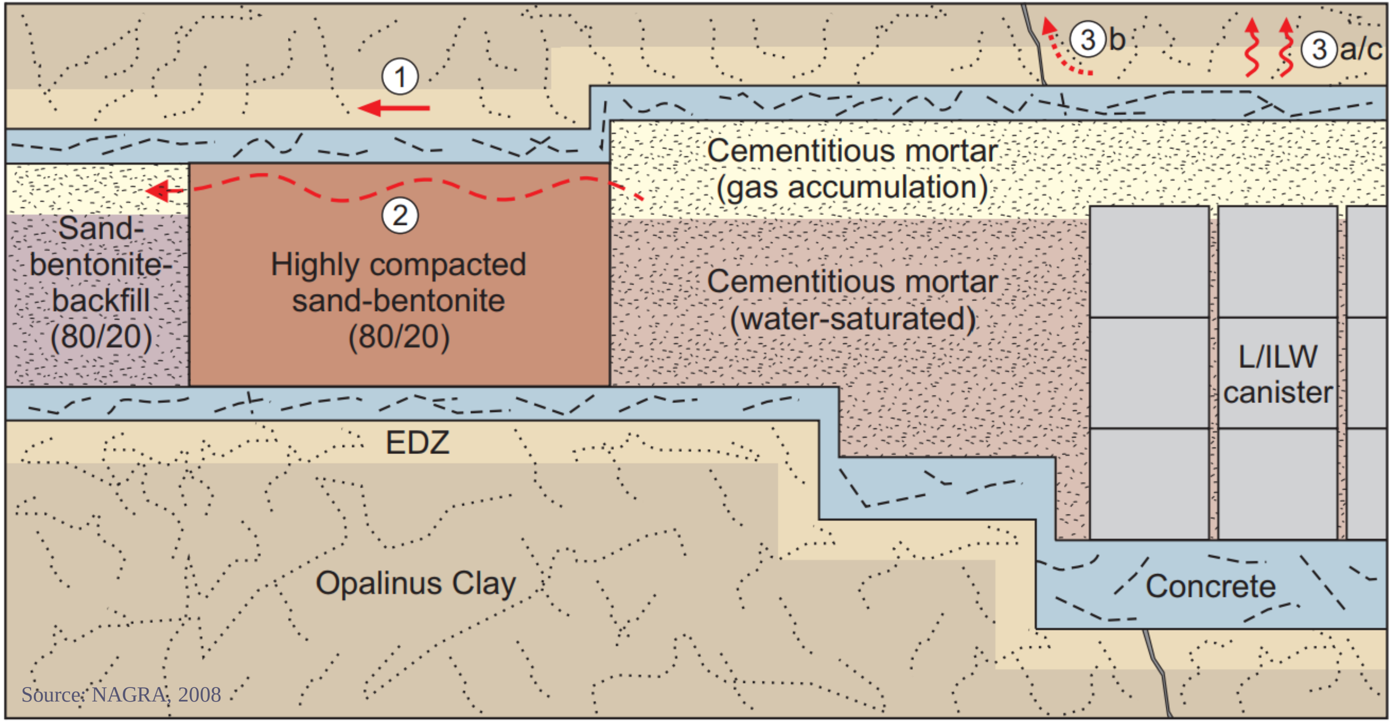






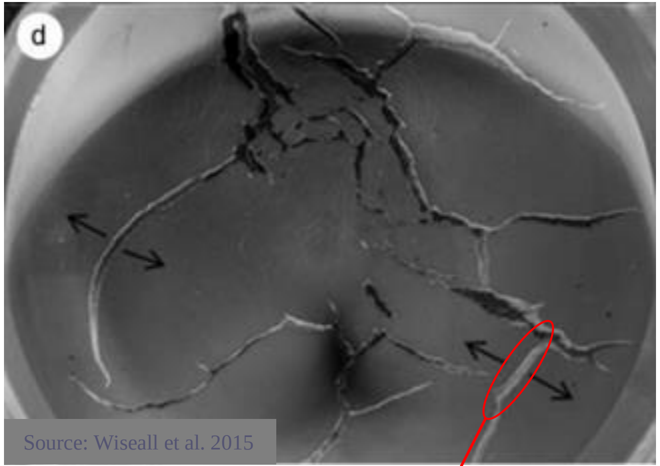
Source: Sanchez,2005

Gas pathways



Gas pathways: ①EDZ; ②sealing material; ③host rock: [a] pores [b] existing fractures [c]induced fractures

Research status

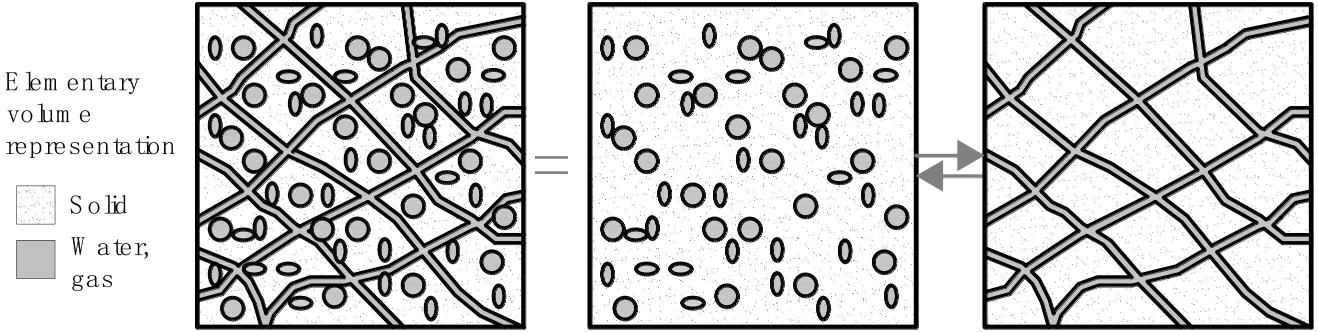


Gas induced fracturing

Numerical consideration:

- Hydro-mechanical coupled process
- Unsaturated fluid flow
- Fractures contained in the rock

Double porosity approach



Source: Zhang et al. 2003

FPM with double porosity = Porous continuum (PC) ⇄ Fractured continuum (FC)

Volume: $V_t = V_{s(p)} + V_p = V_{s(f)} + V_f$

Bulk modulus: $\frac{1}{K} = \frac{1}{K_p} + \frac{1}{K_f}$

Shear modulus: $\frac{1}{G} = \frac{1}{G_p} + \frac{1}{G_f}$

Porosity: $\phi_p = V_p / V_t$ $\phi_f = V_f / V_t$

Main assumptions

① Two phase flow takes place in the FC only.

② The PC is kept fully saturated.

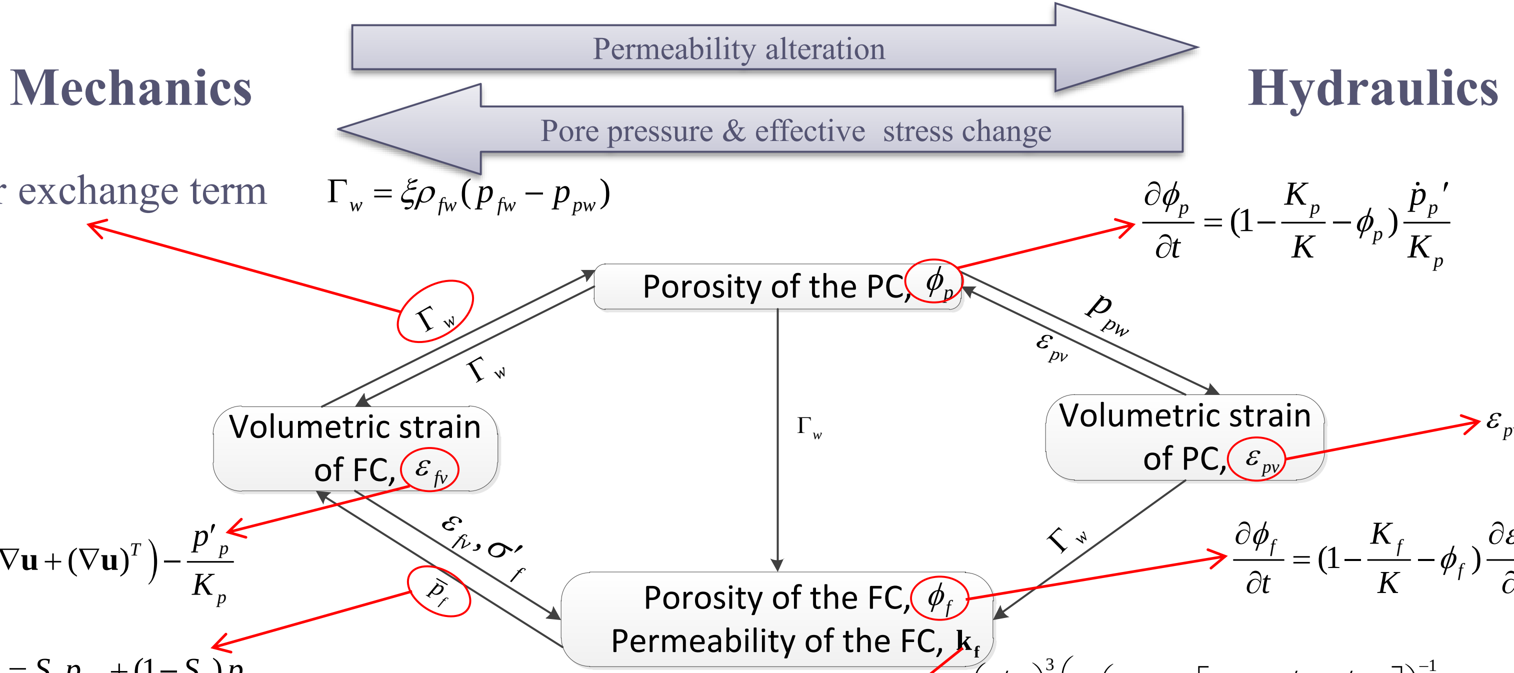
③ The PC and FC are subjected to the same total stress.

④ Fluid flow in each subcontinuum is independent.

⑤ PC is assumed to be volumetrically elastic, FC shows linear elastic behavior.

Coupled variables

Primary variables: p_{fg}, p_{fw}, p_{pw}, $\mathbf{u}$, ϕ_p, ϕ_f



Water exchange term $\Gamma_w = \xi \rho_{fw} (p_{fw} - p_{pw})$

$$\frac{\partial \phi_p}{\partial t} = (1 - \frac{K_p}{K} - \phi_p)\frac{\dot{p}_p'}{K_p}$$

$$\varepsilon_{pv} = \frac{p'_p}{K_p}$$

$$\frac{\partial \phi_f}{\partial t} = (1 - \frac{K_f}{K} - \phi_f)\frac{\partial \varepsilon_{fv}}{\partial t}$$

$$\varepsilon_{fv} = \frac{1}{2} tr\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right) - \frac{p'_p}{K_p}$$

$$\bar{p}_f = S_e p_{fw} + (1 - S_e) p_{fg}$$

$$\mathbf{k_f} = \mathbf{k_{f0}} \left(\frac{\phi_f}{\phi_{f0}}\right)^3 \left(b_1 \left(1 + \exp\left[b_2 (1 - \frac{\phi_f - \phi_{f0}}{\phi_{cr}}) \right]\right)^{-1} - b_1 \left[1 + \exp(b_2)\right]^{-1} + 1 \right)$$

Governing equations

- Mass balance equations

FC

$$\rho_{fg}\left(\frac{\phi_f(1-S_e)M}{\rho_{fg}RT}+\phi_f C_s\right)\frac{\partial p_{fg}}{\partial t}+\nabla\cdot(\rho_{fg}\mathbf{v}_{fg}^D)=\rho_{fg}\phi_f C_s\frac{\partial p_{fw}}{\partial t}-\rho_{fg}(1-S_e)(1-\frac{K_f}{K})\frac{\partial \varepsilon_{fv}}{\partial t}$$

$$\rho_{fw}\left(\phi_f S_e\chi_w+\phi_f C_s\right)\frac{\partial p_{fw}}{\partial t}+\nabla\cdot(\rho_{fw}\mathbf{v}_{fw}^D)=\rho_{fw}\phi_f C_s\frac{\partial p_{fg}}{\partial t}-\rho_{fw}S_e(1-\frac{K_f}{K})\frac{\partial \varepsilon_{fv}}{\partial t}+\xi\rho_{fw}(p_{fw}-p_{pw})$$

PC

$$\rho_{pw}\phi_p\chi_w\frac{\partial p_{pw}}{\partial t}=-\rho_{pw}(1-\frac{K_p}{K})\frac{\dot{p}_p'}{K_p}-\xi\rho_{fw}(p_{fw}-p_{pw})$$

- Momentum balance equation

$$\nabla\cdot\dot{\boldsymbol{\sigma}}+\dot{\rho}\mathbf{g}=0,\quad \rho=(1-\phi_f-\phi_p)\rho_s+(\phi_f S_e+\phi_p)\rho_w+\phi_f(1-S_e)\rho_g$$

Constitutive equations

Mechanical relation

$$\square_f : (\boldsymbol{\varepsilon} - \frac{1}{3}\frac{p_p'}{K_p}\mathbf{I}) = \boldsymbol{\sigma} + (1 - \frac{K_f}{K})[S_e p_{fw} + (1 - S_e) p_{fg}]\mathbf{I}$$

Hydraulic relation

$$\mathbf{v}_{f\pi}^{D} = -\frac{\mathbf{k_f} k_{r\pi}}{\mu_\pi}(\nabla p_{f\pi} - \rho_\pi \mathbf{g}) \qquad \pi = g, w$$

→ Darcy's law

$$p_c = p_{fg} - p_{fw}$$

$$S_e = \begin{cases} \left[1 + \left(\frac{p_c}{p_{gev}}\right)^{\frac{1}{1-m}}\right]^{-m} & p_c > 0 \\ 1 & p_c \le 0 \end{cases}$$

Capillary model

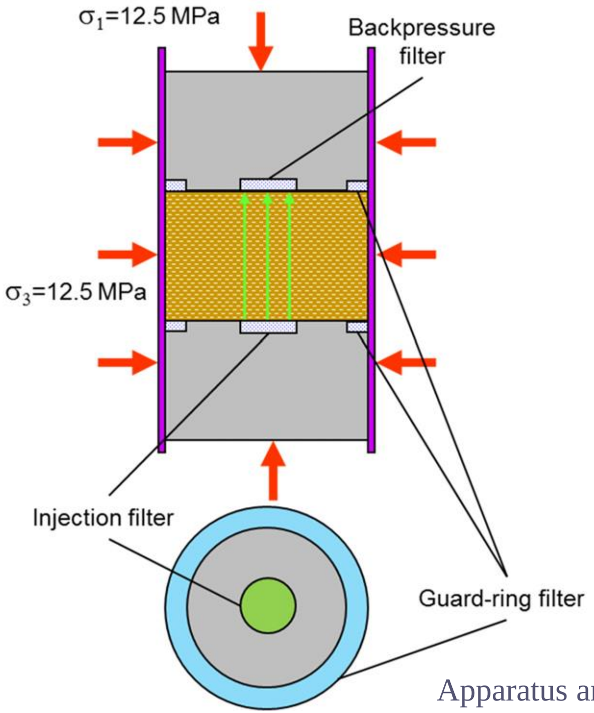
$$k_{rw} = \sqrt{S_e}[1 - (1 - S_e^{1/m})^m]^2$$

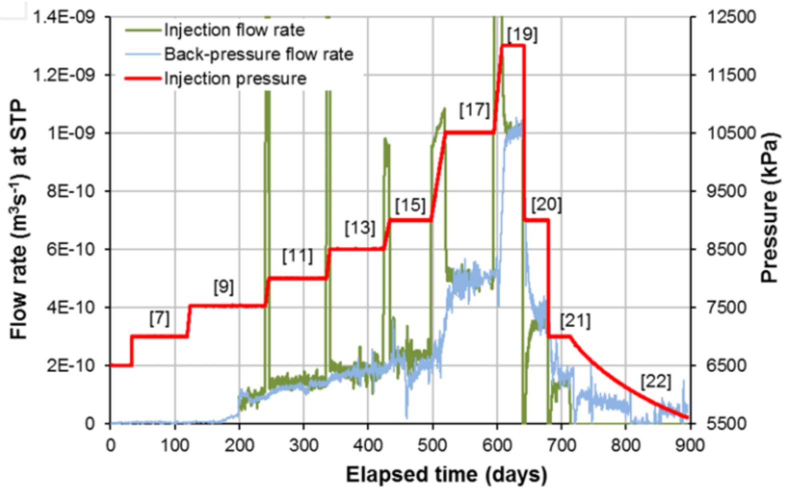
$$k_{rg} = (1 - S_e)^3$$

Relative permeability

Model validation

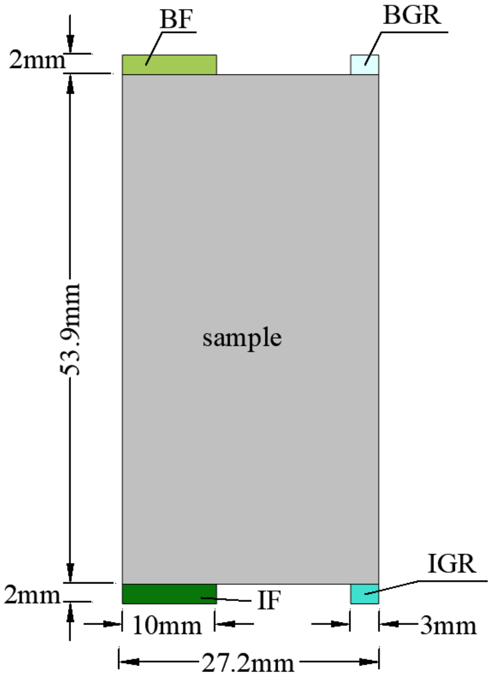
- Gas injection test





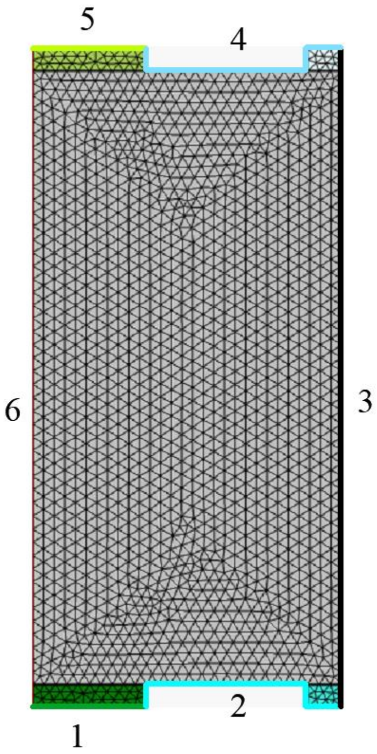
Apparatus and results (from Harrington et al. 2017)

Model parameters

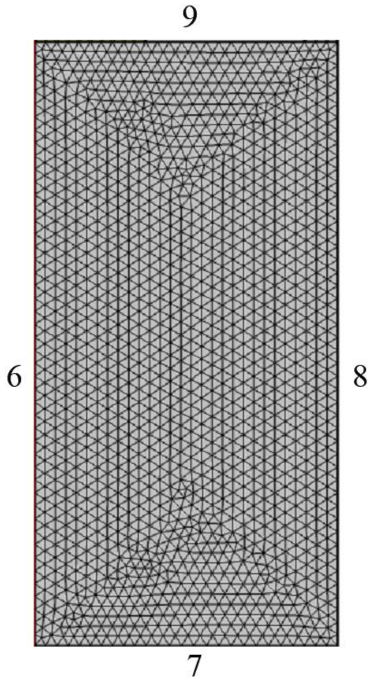


ρ_s , g/cm^3	2.31	G, MPa	769
ϕ_{f0}	0.04	K_p , MPa	1667
ϕ_{p0}	0.11	K_f , MPa	1500
S_{e0}	97%	b_1	72
$k_{f0//}$, m^2	3.5×10^{-19}	b_2	1
$k_{f0\perp}$, m^2	1.4×10^{-20}	ϕ_{cr}	0.0014
p_{gev} , MPa	1	ξ, m*s/kg	3×10^{-13}
m	1/3		

Boundary conditions



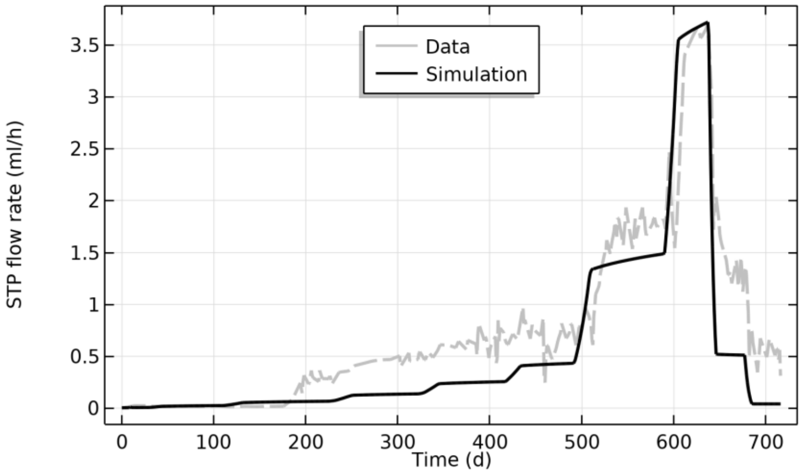
Hydraulic BCs



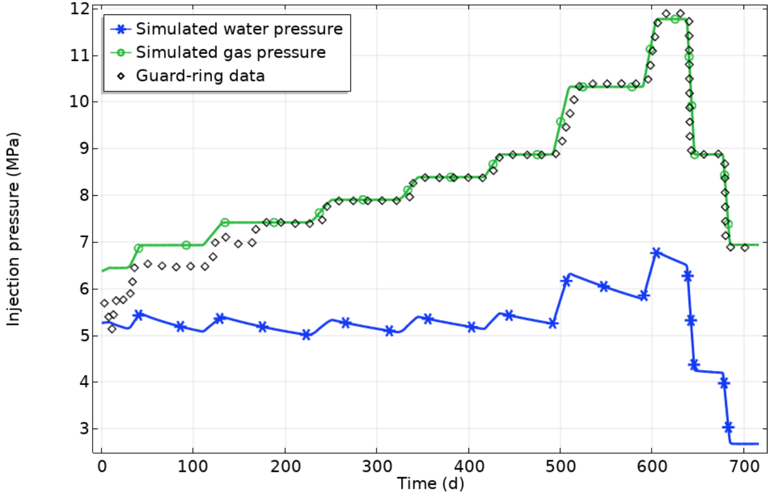
Mechanical BCs

BC No.	Hydraulic BCs			Mechanical BCs
	Gas in FC	Water in FC	Water in PC	
1	Applied	No flow	No flow	-
2	No flow	No flow	No flow	-
3	No flow	No flow	No flow	-
4	No flow	No flow	No flow	-
5	4.71 MPa	4.5 MPa	No flow	-
6	Axisymmetric			
7	-	-	-	Roller
8	-	-	-	12.5 MPa
9	-	-	-	12.5 MPa

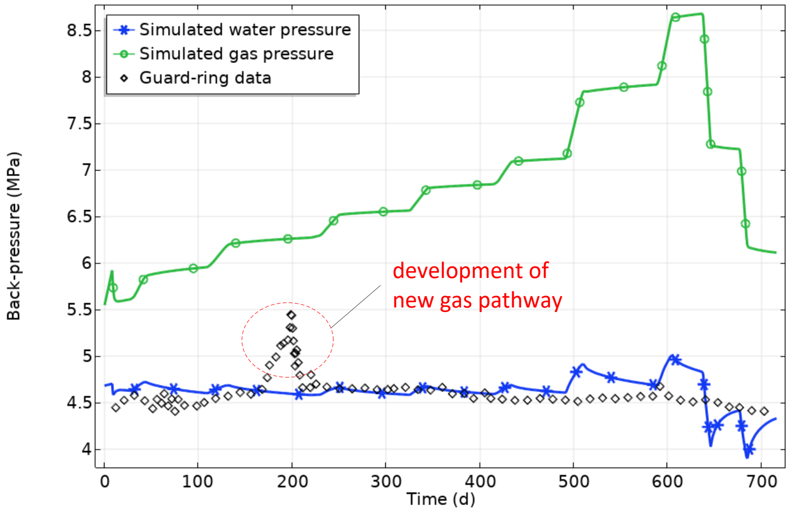
Simulated results



Simulated results



Pressure in the IGR



Pressure in the BGR

Conclusions

- To capture the experimental observations of gas induced fracturing, the conventional HM model with single porosity is unsuitable to be used.
- The new developed model with double porosity shows good results compared with the experimental data.
- Further improvements can be made by introducing a 3D model with a non-symmetrical geometry and heterogeneous HM properties.

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Thank you!

Questions?