# Numerical simulation of pressure and $CO_2$ saturation above the fractured seal as a result of $CO_2$ injection: implications for monitoring network design


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## ABSTRACT

A numerical model was developed to simulate pressure and $CO_2$ saturation evolution above a fractured caprock. The fractured region of the caprock was 1,400 m away from the $CO_2$ injection well. A pressure increase of $10^5$ Pa was observed throughout the formation (10 km x 10 km) above the caprock after 111 years (30 years of active $CO_2$ injection of 1 million tons per year + 81 years of post $CO_2$ injection), while the diameter of the $CO_2$ plume at the formation above the caprock was only 539 m. Therefore, pressure travels much faster than $CO_2$ plume in the formation above the caprock. $CO_2$ flux calculation results show that very significant amount of $CO_2$ leakage (larger than 4% of total $CO_2$ injected within130 years) occurred when the fractured region permeability was above $10^{-17}$ $m^2$. If the fractured region permeability was less than $5\times10^{-19}$ $m^2$, the amount of $CO_2$ leakage was small (less than 0.04% of total $CO_2$ injected within 130 years). It took 3.2 years for a pressure monitoring well right above the fractured region to detect a $CO_2$ leakage signal (a pressure increase of $10^5$ Pa). Results presented suggest that pressure response from fluid leakage allows early detection, but $CO_2$ saturation monitoring may be more useful in locating the source of such leakage.

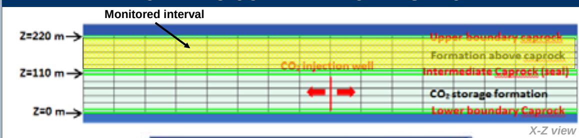

## BACKGROUND

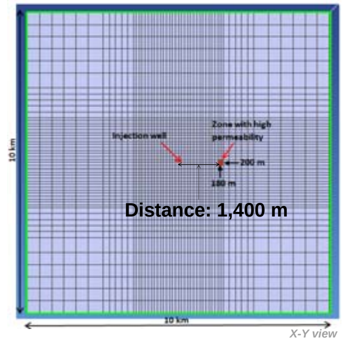
- Deep saline aquifers have the highest $CO_2$ storage capacity of all candidate geologic storage targets - ~1,738 Gigatonnes of $CO_2$ in North America alone (The North American Carbon Storage Atlas, 2012).
- $CO_2$ leakage through caprock may be detected by monitoring pressure and $CO_2$ saturation response in porous and permeable zones above that caprock.
- This study employs TOUGH2 to simulate $CO_2$ and brine leakage through fractured caprock. The goal of this study is to answer the following questions: 1) how fast a $CO_2$ leakage can be detected at the above zone monitoring interval (AZMI) above a fractured caprock; 2) how the permeability change of the fractured caprock affects the amount of leaking $CO_2$ and the time required to detect the leakage.

## MODELING CODE AND MODEL SET UP

- **Modeling code: TOUGH2**
- **Model set up: 3-D model with 37,908 active grid blocks**
- **Eqn-of-state: ECO2N (water, $CO_2$ and NaCl)**
- **Isothermal simulation with no heat exchange considered**

## MODELING CODE AND MODEL SET UP




**Model set-up with the location of the fractured caprock (high-permeability zone in red)**

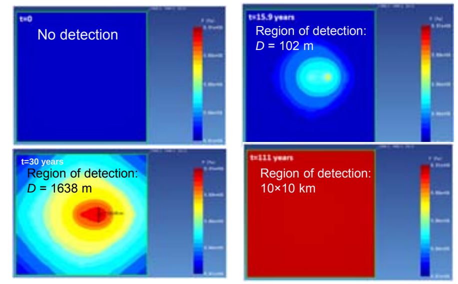
### Modeling parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Density of rock in Layers 1-5 | 2600 kg/$m^3$ | $CO_2$ injection rate (constant rate from t=0 to t=30 years) | 31.7 kg/s (1M tons per year) |
| Initial pressure at Z=100 m | 10.1 MPa | Brine residual saturation | 0.025 |
| Pressure gradient | $10^4$ Pa/m | $CO_2$ residual saturation | 0.1 |
| Temperature | 47 °C | Capillary pressure | $2\times10^4$ Pa |
| Horizontal permeability (storage formation and formation above caprock) | $10^{-13}$ $m^2$ (0.1 D) | Thickness of caprock layers | 10 m |
| Vertical permeability (storage formation and formation above caprock) | $10^{-14}$ $m^2$ (0.01 D) | Thickness of the storage formation | 100 m |
| Horizontal permeability (caprock) | $10^{-19}$ $m^2$ ($10^{-7}$ D) | Thickness of the formation above caprock | 90 m |
| Vertical permeability (caprock) | $10^{-20}$ $m^2$ ($10^{-8}$ D) | Salt (NaCl) mass fraction in brine | 0.1 |
| Horizontal permeability (fractured caprock) | $10^{-19}$ $m^2$ ($10^{-7}$ D) | Porosity (storage formation and formation above caprock) | 0.1 |
| Vertical permeability (fractured caprock) | $10^{-17}$ $m^2$ ($10^{-5}$ D) | | |
| $CO_2$ injection period | 30 years | Porosity (caprock) | 0.05 |
| Post-$CO_2$ injection period | 100 years | Maximum simulation time | 130 years |
| Domain size | 10×10 km | Simulation time step | Automatic adjustment (initial step = 100 s) |
| Boundary condition | Open boundary | | |

## RESULTS

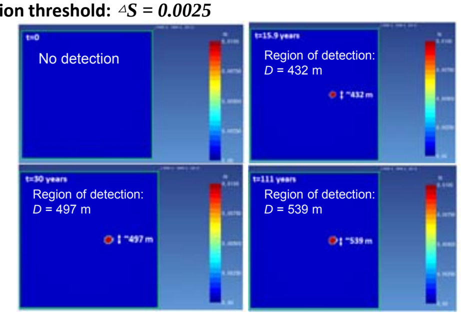
**Pressure above the fractured caprock**

**Detection threshold:** $\Delta P = 10^5$ *Pa*

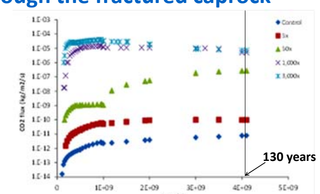



**$CO_2$ saturation above the fractured caprock**

**Detection threshold:** $\Delta S = 0.0025$

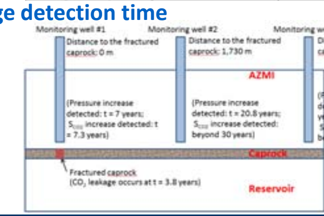



**$CO_2$ flux through the fractured caprock**




| Scenario | Total amount of $CO_2$ leaked during 130 years (kg) | Total amount of $CO_2$ leaked/total amount of $CO_2$ injected (%) |
|---|---|---|
| Control (no fractured seal) | 514 | 1.71E-06 |
| 5x higher fractured seal permeability | 9.47E3 | 3.16E-05 |
| 50x higher fractured seal permeability | 1.29E7 | 4.28E-02 |
| 1,000x higher fractured seal permeability | 1.23E9 | 4.09 |
| 3,000x higher fractured seal permeability | 2.33E9 | 7.75 |

**Leakage detection time**




*t* = time elapsed after $CO_2$ injection begins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