Post-Injection Monitoring to Ensure Safety of CO$_2$ Storage
- A case study at Nagaoka pilot site -

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The CO₂ Storage Project Workflow

Pre-Operation Phase
3-5 years

Operation Phase
10~50 years

Post-CO₂ injection Phase
100+ years

Post-injection Monitoring

(After David White, IEA GHG International Summer School 2007 on CCS)
What happens after stopping CO$_2$ injection?
(CO$_2$ behaviors at the post-injection)

**Mobile CO$_2$**
(Physical process)

**Immobile CO$_2$**
(Physical process)

**Dissolved CO$_2$**
(Geochemical process)

**Mineralized CO$_2$**
(Geochemical process)

Image of trapping processes over time (IPCC 2005)
Outline

1. Overview of the Nagaoka pilot CO$_2$ injection project

2. Results from Geochemical monitoring for CO$_2$-fluid-rock interaction (CHDT sampling)

3. Results from Geophysical monitoring for mobile & immobile CO$_2$ (Well loggings, seismic tomography)

4. Suggestions for CO$_2$ monitoring at post-injection
Location of the Nagaoka Pilot CO₂ Injection Site

Active gas field at Minami Nagaoka (INPEX Co.)

5000m Gas production

1100m Reservoir

Uonuma Formation
Haizume Formation
Nishiyama Formation
Teradomari Formation

5000m Gas production

Miocene Rocks

Nagaoka City

Shibumi River

The Shinano River

Nagaoka

RITE (Kyoto)

Tokyo
Overview of the Nagaoka Pilot Project

- Duration: FY2000-2007 funded by METI, Japan
- Total amount of the injected CO₂: 10,400 ton (2003.7~2005.1)
- Reservoir: Pleistocene sandstone (Haizume Formation), 60m thick
- Target injection layer: Zone 2, 12m thick
- Conditions: 48°C, 11MPa
- Permeability: ave. 7mD (pumping test)
- Porosity: 23%

Well Configurations
Field measurements during and post CO\textsubscript{2} injection

(\textit{Geophysical monitoring})

- Seismic tomography
- Well Loggings
  - Neutron
  - Sonic
  - Induction

Injection rate (t-CO\textsubscript{2}/day)
- Rate: 20~40 ton/day
- Total: 10,400 ton

Cumulative amount (t-CO\textsubscript{2})
- Date: Elapsed time from 7 July 2003 (day)
Neutron Logging (Neutron porosity; $\phi_n$) @ OB-2

Changes of the $\phi_n$

$0.0 \quad 0.2 \quad 0.4$

End of CO$_2$ injection

Post-injection

Latest

Depth (mMD)
Sonic Logging (P-wave velocity; $V_p$) @ OB-2

Vp (km/sec)

1.5  2.5  3.5

Depth (mMD)

1120  1116  1112  1108

End of $CO_2$ injection

BL

Latest

Latest

Changes of the Vp

-1.0  0.5

14th  16th  18th  20th  21st  23rd  24th  26th  27th  28th  29th  30th  31st  33rd  35th  37th

Post-injection
Induction Logging (Resistivity; $\rho$) @ OB-2

Changes of the $\rho$

Post-injection

End of $CO_2$ injection

Latest
Field measurements during and post CO₂ injection

(11/25)

Geochemical monitoring

Elapsed time from 7 July 2003 (day)

Seismic tomography

Well Loggings

- Neutron
- Sonic
- Induction

OB-2

OB-3

OB-4

37th

7th

Fluid sampling @ IW-1

Fluid sampling by CHDT @ OB-2

Injection rate (t-CO₂/day)

Rate: 20~40 ton/day

Total: 10,400 ton

Cumulative amount (t-CO₂)
Resistivity Changes with Time @ OB-2

Fluid sampling by Cased Hole Dynamics Tester

Delta from the baseline data

-0.4
0 ohm-m
0.4
0.8

CO₂ injection

Post-injection

Elapsed time from 7 July 2003 (day)

CHDT @ 1108.6 m

CHDT @ 1114.0 m

CHDT @ 1118.0 m
Sampling result-1

OB-2 @ 1114m: Mostly free CO₂

Gas composition

<table>
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<tr>
<th>Comp.</th>
<th>mol%</th>
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<tr>
<td>H₂</td>
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<td>0.7</td>
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<tr>
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<td>0.3</td>
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<td>C₂H₆</td>
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<tr>
<td>CO₂</td>
<td>98.8</td>
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</tbody>
</table>

Sample Chamber (volume 3.8 L)

Water

for details see
The change in salinity by increasing of $\text{HCO}_3^-$ (7.2%) is roughly consistent with the change in resistivity (6.5%) @ 1118m.
At the depth of 1118m (HCO$_3^-$ conc. increased),
concentrations of Ca, Mg and Fe also increased.
Geochemical Reactions at Nagaoka

Verified from the field data using CHDT

- \( \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3^* \) --- *Solubility trapping*
- \( \text{H}_2\text{CO}_3^* \rightarrow \text{H}^+ + \text{HCO}_3^- \) --- *Ionic trapping*

Inferred from the field data and batch experiments

- Calcite + \( \text{H}^+ \rightarrow \text{Ca}^{2+} + \text{HCO}_3^- \)
- Plagioclase + \( \text{H}^+ \rightarrow \text{Ca}^{2+} + \text{Na}^+ + \text{aluminosilicate} \)
- Smectite + \( \text{H}^+ \rightarrow \text{Mg}^{2+} + \text{Fe}^{2+} + \text{Fe}^{3+} + \text{K}^+ + \text{Na}^+ + \text{Ca}^{2+} \)
  + aluminosilicate

Simulated by ChemTOUGH

- \( \text{Ca}^{2+} + \text{HCO}_3^- \rightarrow \text{Calcite} + \text{H}^+ \) --- *Mineral trapping*
Summary of Geochemical Monitoring

• The CHDT (Cased Hole Dynamics Tester, Schlumberger) sampling confirmed stored CO$_2$ as gas and dissolved phase.

• Because of low salinity (0.8wt%), dissolved CO$_2$ was detected by the induction logging.

• We are working on modification of our long-term geochemical model to integrate the well logging results now.
Return to the Initial Formation Pressure

Elapsed time from 7 July 2003 (day)

Bottom Hole Pressure

Pressure (MPa)

Injection rate (t-CO₂/day)

Cumulative amount (t-CO₂)

Date

IW-1

OB-4
Driving Force of CO$_2$; Pressure and/or Buoyancy

(Juanes et al., 2006)
Resistivity Change during Imbibition Phase @ OB-2

Delta from the baseline data

-0.4 to 0.8 ohm-m
Drainage and Imbibition Phase
(1116.0m @ OB-2)

- Imbibition breakthrough
- CO₂ injection period

Graph showing
- $\phi_n$ vs Date
- $\rho$ (ohm-m) vs Date
- $V_p$ (km/sec) vs Date
P-wave velocity and resistivity vs CO₂ saturation
(1116.0m @ OB-2)
Summary of Geophysical Monitoring

- CO₂ saturation has been decreasing at the lower part of the injection layer. The residual gas saturation will be determined in the actual reservoir at the Nagaoka site.

- Delay of P-wave velocity slowed down when CO₂ saturation exceeded 20%. But changes in resistivity with CO₂ saturation have kept increasing.

- Monitoring post-injection period is needed to clarify the relationship between the P-wave velocity & the resistivity and CO₂ saturation. We are trying to adapt a methodology for accounting of CO₂ in the reservoir.
Suggestions for CO$_2$ monitoring at post-injection

- **Dissolved CO$_2$ vs Resistivity;**
  Dissolution and mineral trapping are expected to reduce degree of rapid migration of mobile CO$_2$. Understanding of **geochemical reactions** helps to explain the **long-term behavior of CO$_2$** and the changes in geophysical logs such as resistivity.

- **CO$_2$ saturation vs P-wave verosity and Resistivity;**
  **Joint inversion** of monitoring results of sonic wave and resistivity is key to **account CO$_2$ saturation**.

- **Geochemical & Geophysical;**
  Feedback of geochemical and geophysical monitoring results is necessary to improve long-term prediction of CO$_2$ behavior.
Acknowledgements

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Thank you for your attention!