Post-Injection Monitoring to Ensure Safety of CO\textsubscript{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

Monitoring
Post-injection Monitoring

Design
CO₂ Injection
Preparation
Decommissioning

Characterization
Performance & Risk
Management

Site Selection
Surveillance

(After David White, IEA GHG International Summer School 2007 on CCS)
What happens after stopping CO₂ injection? (CO₂ behaviors at the post-injection)

- **Mobile CO₂** (Physical process)
- **Immobile CO₂** (Physical process)
- **Dissolved CO₂** (Geochemical process)
- **Mineralized CO₂** (Geochemical process)

Image of trapping processes over time (IPCC 2005)
Outline

1. Overview of the Nagaoka pilot CO\textsubscript{2} injection project

2. Results from \textit{Geochemical monitoring} for CO\textsubscript{2}-fluid-rock interaction (CHDT sampling)

3. Results from \textit{Geophysical monitoring} for mobile & immobile CO\textsubscript{2} (Well loggings, seismic tomography)

4. Suggestions for CO\textsubscript{2} monitoring at post-injection
Location of the Nagaoka Pilot CO₂ Injection Site

Active oil and gas field at Minami Nagaoka (INPEX Co.)

Nagaoka

1100m Reservoir

Tokyo

RITE (Kyoto)

Nagaoka

1100m Gas production

5000m Gas production

Miocene Rocks
Overview of the Nagaoka Pilot Project

• Duration; FY2000-2007 funded by METI, Japan
• Total amount of the injected CO\textsubscript{2}; \textbf{10,400 ton} (2003.7~2005.1)
• Reservoir; Pleistocene sandstone (Haizume Formation), \textbf{60m thick}
• Target injection layer; Zone 2, \textbf{12m thick}
• Conditions; \textbf{48\textdegree}C, \textbf{11MPa}
• Permeability; ave. \textbf{7mD} (pumping test)
• Porosity; \textbf{23%}
Field measurements during and post CO₂ injection

(Geophysical monitoring)

Elapsed time from 7 July 2003 (day)

Seismic tomography

Well Loggings
- Neutron
- Sonic
- Induction

Injection rate (t-CO₂/day)

Rate: 20~40 ton/day

Total: 10,400 ton

Cumulative amount (t-CO₂)

OB-2
OB-3
OB-4

2002/01/01 2003/01/01 2004/01/01 2005/01/01 2006/01/01 2007/01/01 2008/01/01

2002/01/01 2003/01/01 2004/01/01 2005/01/01 2006/01/01 2007/01/01 2008/01/01

Rate; 20~40 ton/day
Total; 10,400 ton
Neutron Logging (Neutron porosity; $\phi_n$) @ OB-2

Changes of the $\phi_n$

End of $CO_2$ injection

Post-injection

Latest

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

![Diagram showing changes of P-wave velocity (Vp) over time, with a color-coding indicating post-injection changes.](image)

- **End of \( \text{CO}_2 \) injection**
- **Latest**
- **BL**

Changes of the Vp:
- Post-injection

Depth (mMD):
- 1108
- 1112
- 1116
- 1120
Induction Logging (Resistivity; $\rho$) @ OB-2

- Changes of the $\rho$:
  - $0.5$ to $1.5$

- Depth (mMD):
  - 1108 to 1120

- Post-injection

- Latest

- End of $CO_2$ injection

- BL
Field measurements during and post CO$_2$ injection (Geochemical monitoring)

Elapsed time from 7 July 2003 (day)

Seismic tomography

Well Loggings
- Neutron
- Sonic
- Induction

Fluid sampling @ IW-1

Fluid sampling by CHDT @ OB-2

Injection rate (t-CO$_2$/day)
Rate; 20~40 ton/day
Total; 10,400 ton

Cumulative amount (t-CO$_2$)

Date

0
10000
20000

2002/01/01 2003/01/01 2004/01/01 2005/01/01 2006/01/01 2007/01/01 2008/01/01
Resistivity Changes with Time @ OB-2

Fluid sampling by Cased Hole Dynamics Tester

Delta from the base line data

Depth (mMD)

Elapsed time from 7 July 2003 (day)

CHDT @ 1108.6 m
CHDT @ 1114.0 m
CHDT @ 1118.0 m

CO₂ injection  Post-injection
Sampling result-1

OB-2 @ 1114m : Mostly free CO₂

Gas composition

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol%</th>
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<tr>
<td>H₂</td>
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<tr>
<td>O₂</td>
<td>0.2</td>
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<tr>
<td>N₂</td>
<td>0.7</td>
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<tr>
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<td>0.3</td>
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<tr>
<td>C₂H₆</td>
<td>0.0</td>
</tr>
<tr>
<td>CO₂</td>
<td>98.8</td>
</tr>
</tbody>
</table>

Sample Chamber (volume 3.8 L)

for details see
The change in salinity by increasing of HCO$_3^-$ (7.2%) is roughly consistent with the change in resistivity (6.5%) @ 1118m.
Sampling result-3

OB-2 @ 1108.6m&1118m:
Cations in the formation water

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)

Pressure (MPa)

Bottom Hole Pressure

Injection rate (t-CO$_2$/day)

Cumulative amount (t-CO$_2$)

Date

2003/01/01 2004/01/01 2005/01/01 2006/01/01 2007/01/01 2008/01/01
Driving Force of \( \text{CO}_2 \); Pressure and/or Buoyancy

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

Delta from the base line data

-0.4
0 ohm-m
0.4
0.8

Depth (mMD)

Elapsed time from 7 July 2003 (day)

Post-injection

End of CO$_2$ injection

Latest
Drainage and Imbibition Phase
(1116.0m @ OB-2)

CO₂ injection period

Date

CO₂ injection period

Date

breakthrough

Imbibition

Sgr?
P-wave velocity and resistivity vs CO$_2$ 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!
Formation Water Sampling (Prior to the CO₂ Injection)

Pump-up test

- May 2002
- From IW-1
- By air lift
Fluid sampling at OB-2 on Dec 2005
(Post-CO$_2$ injection)

**CHDT** (Cased Hole Dynamic Tester, Schlumberger)
Schematic showing CHDT and its sampling line

- Anchor shoes
- Drill
- Formation cement
- Casing
- 35% NaBr
- Sample unit 1
- Sample unit 2
- Sample unit 3
- Probe module
- Pretest chamber
- Resistivity sensor
- Flow filter
- Tool packer
- Borehole port
- Quartz pressure gauge
- Sample chamber
- Balance gas
- Strain pressure gauge
Low salinity: High potential to dissolve CO2

Typical range in Japan

Nagaoka
Sleipner
Frio

from Rochell et al. (2004), originally reported by Enick and Klara (1990)
Changes in the value for geophysical monitoring and results of CHDT sampling

At the 1118.0m depth, arrival of dissolved CO₂ was detected as a decrease of resistivity. The change in salinity by increasing of HCO₃⁻ (7.2%) is roughly consistent with the change in resistivity (6.5%).
Long-Term Prediction for the Nagaoka Case (by ChemTOUGH)

Input data

- Mineral composition --- the actual reservoir rock
- Solution composition --- the actual formation water
- Equilibrium constants --- thermodynamics data base
- Rate constants --- literature
- Activation energy --- literature
- Reactive surface area --- based on sensitivity analysis of solution composition change (CO$_2$-water-rock reactions using Nagaoka samples)
- Geophysical modeling --- White et al. (2006)
Preliminary results of long-term prediction

- **Gas trapping**
- **Solubility trapping**
- **Mineral trapping**

**Time since injection stops (years)**

- $S_{gr} = 0.05$
- $S_{gr} = 0.30$
Decrease and Increase of Resistivity during Drainage Phase
(1114.8m @ OB-2)

\[ \phi_n \]

\[ \rho \text{ (ohm-m)} \]

\[ V_p \text{ (km/sec)} \]

\( CO_2 \) injection period

breakthrough

Date

2003/01/01  2004/01/01  2005/01/01  2006/01/01  2007/01/01  2008/01/01
P-wave velocity and resistivity vs CO$_2$ saturation

(1114.8m @ OB-2)
Detection and monitoring of CO$_2$ at the observation wells

Seismic Tomography

Well loggings