TRUST

First CO\textsubscript{2} injection experiment at Heletz (Israel): determination of dissolution trapping and capillary trapping via a single well push pull experiment

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The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP72012– ENERGY.5.2 - CO\textsubscript{2} STORAGE - Topic: ENERGY.2012.5.2.1 under grant agreement n° 309607]
1. Objectives of TRUST

- **Contribute to process understanding** via a series of small scale highly controlled CO$_2$ injection experiments, including:
  - Trapping mechanisms (dissolution and residual trapping);
  - Impurities (geochemical and physical);
  - Impact of heterogeneity;

- **Test CO$_2$ injection strategies**:
  - “Hot” injection versus “cold” injection;
  - Injection of “trapped” (dissolved) CO$_2$;
  - Alternating CO$_2$ and formation brine to enhance trapping.

- **CO$_2$ Leakage detection**.

- **Use and extensive portfolio of MMV (Measurement, Monitoring and Validation) technologies**:
  - Downhole P/T monitoring at different vertical levels (as of now 2);
  - P/T monitoring above the ground (from the CO$_2$ tank to the wellhead);
  - Distributed temperature sensing via optic fiber;
  - Downhole fluid sampling and onsite characterization;
  - Seismic monitoring.
2. Heletz deep CO$_2$ injection experiment site

- Scientifically motivated CO$_2$ injection experiment site;
- Deep – allows storage of scCO$_2$
- Static pressure of 143 bar and temperature of 64 C.
- Low concentration brine (35,000 ppm Cl/l)
Heletz wells: Deep injection and monitoring and shallow seismic.
3. Extensive site characterization

- Data from oil exploration wells was collected and re-analyzed;
- Geological structure and regional values of hydraulic parameters (porosity/permeability) are relatively well known;
- Surface and borehole geophysics;
- Geological characterization;
- Hydraulic testing on cores and in-situ;
- Mineralogy;
- Two-phase flow CO₂-Brine properties;
- Rock-mechanical properties;
- Thermal properties.


Permeability and porosity

Table: Statistical data for Heletz sand layer permeabilities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Layer</th>
<th>Data base</th>
</tr>
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<tbody>
<tr>
<td>σ, σ (mD and mD)</td>
<td>-13.25, 1.1</td>
<td>A</td>
<td>borehole porosity logs</td>
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<td>of model to logs</td>
<td>2.1, 1.1</td>
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<td>converted data</td>
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<tr>
<td>σ, σ</td>
<td>-12.9, 1.1</td>
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<td>Data from old wells in the vicinity of experimental area</td>
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<td>μ, μ (mD)</td>
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<td>Layers</td>
<td>Borehole porosity logs, wells H-13, H-18 and H-38 only</td>
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<td>from log-converted data</td>
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<td>A, W, K</td>
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<td>h, maget (Ca), sill (ss)</td>
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<td>Data from the new drilled wells</td>
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<tr>
<td>Range of values (mD)</td>
<td>100-410</td>
<td>Layer A</td>
<td>Core samples, only tests with in-situ P/T conditions included</td>
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<tr>
<td>Range of values (log transformed, mD)</td>
<td>13-12.4</td>
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<tr>
<td>Horizontal/Vertical permeability (mD)</td>
<td>735/135</td>
<td>Layers</td>
<td>In-situ well test, provides an &quot;up-scaled&quot; value for the entire layer</td>
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<td></td>
<td></td>
<td>A, W</td>
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Data from old oil wells for the entire region gave a good basis, locally refined based on data from the new wells.
The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP72012- ENERGY.5.2 - CO₂ STORAGE - Topic: ENERGY.2012.5.2.1 under grant agreement n° 309607]
3. Wells Completion and site preparation for CO$_2$ injection
CO\(_2\) system

CO\(_2\) Tank

CO\(_2\) pump skid (booster + 2 pumps)

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CO₂ system

CO₂ heater

CO₂ tank, heater and wellhead
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<table>
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<td>1.995</td>
<td>2.67</td>
<td>5,316.03</td>
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<td>6</td>
<td>1 Joint 7 7/8” Perforated Pipe</td>
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<td>2.441</td>
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<td>5,318.70</td>
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<td>5</td>
<td>X-O Pup</td>
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<td>6.05</td>
<td>5,351.25</td>
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<td>Dual Gauge Carrier</td>
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<td>5.67</td>
<td>5,357.33</td>
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<td>3</td>
<td>X-O Pup and Fiber Termination Sub</td>
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<td>5.62</td>
<td>5,363.00</td>
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<td>2</td>
<td>Wireline Re-entry Guide and XN Nipple</td>
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<td>0.000</td>
<td>0.00</td>
<td>5,370.00</td>
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</tbody>
</table>

Comments: Perforations:

Total Length of BHA = 2440.45 ft
Total BHA w/o Pipe = 743.85 ft
94.96 ft
28.94 ft
Residual trapping: key CO₂ trapping mechanism

Evolution of the role of various trapping mechanisms with time

Residual trapped zone left behind the mobile CO₂ rich phase

(IPCC, 2005)

How to measure residual trapping in the field?

First we need to create a zone with residual saturation in the field

- injection-withdrawal of scCO2 and brine
- Hydraulic tests
- Thermal tests
- Tracer tests

Estimate of residual trapping when performed with and without residual CO2

Otway, Australia experiment demonstrated that pressure signal was an effective measure for differentiating residual saturation of gas ($S_{gr}$)

Paterson et al, 2011. CO2CRC report RPT11-3158
Creating the residually trapped zone

**Option 1:** Inject CO$_2$, then inject water to push the CO$_2$ further and leave the residual zone behind

**Option 2:** Inject CO$_2$, then pump it back and leave the residual zone behind

Option 2 was implemented, the achievement of residual zone was followed by evolution (i) tracers$^1$ and (ii) pressure difference in the injection/withdrawal test.

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How to measure field scale dissolved CO₂?

U-tube

N₂ Drive (In)
(1)&(3) P= 220 bar (3200 psi)
(2) P= 1 atm

Sample (Out)
P= 1 atm

Inj In

Inj Out

Ball valve

Gravitational check valve
(Ball that stops the flow)

Borehole
P= 145 bar (2103 psi)

Z=0 ground
Z=200 m water level
Z=1640 m

Wellhead
Water

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<table>
<thead>
<tr>
<th>Low pressure</th>
<th>High pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH (a)</td>
<td>Conductivity (d)</td>
</tr>
<tr>
<td>Temperature (a)</td>
<td>pH (e)</td>
</tr>
<tr>
<td>Conductivity (a)</td>
<td>Scaling vessel (density) (f)</td>
</tr>
<tr>
<td>Alkalinity (b)</td>
<td>Temperature (g)</td>
</tr>
<tr>
<td>Gas composition (QMS) (c)</td>
<td>Gas partial pressure (GPM) (h)</td>
</tr>
</tbody>
</table>

(a) Low pressure
(b) Conductivity
(c) Gas composition
(d) High pressure
(e) Scaling vessel
(f) Temperature
(g) Gas composition
(h) Gas partial pressure
CO₂ Leakage detection

Injection well

\[ Z(z=0 \text{ wellhead}) = 8, 303, 357, 371 \text{ m} \]
4. The first experiment

- Determine field-scale values of two key trapping mechanisms: dissolution and residual – capillary trapping.
- The experimental sequence comprised the following phases:
  - Heating of the formation;
  - Two hydraulic tests;
  - Injection of formation water (previously produced and stored) with tracers.
  - \( \text{CO}_2 \) injection;
  - Pressure relief;
  - Production until free \( \text{CO}_2 \) is removed.
  - Hydraulic test.
  - P/T was continuously monitored and recorded.
  - \( \text{CO}_2 \) mass flowrate, temperature, pressure and density was recorded during the production phase;
  - DTS was recorded during the entire sequence;
  - Downhole fluid sampling and measurement of high pressure pH and low pressure alkalinity and gas composition, as well as measurement of partial pressure of \( \text{CO}_2 \) were measured during the production phase.
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During the experiment

CO2 release, pipes’ froze

Auli released pressure
During the experiment
During the experiment
TRUST

Measured pressure sequence at two different vertical levels

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Pressure difference

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First estimate of the pressure response
simple analytical solution

Analytical solution with Theis, fit the hydraulic test data before and after creating the residual zone

The result indicates that there is very little effect of CO₂, the difference in pressure decrease can be explained by the difference in pumping rate.
Multiphase flow model – sensitivity to relative permeability function

Relative permeability curves

- B-C krg S 0.01 (Benson krg)
- B-C krg S 0.2
- B-C krg S 0.1
- Benson krl data-Drainage
- data-Imbibition

Water saturation

Comparison of model and measured data – effect of residual saturation

Pressure at the bottom of the injection well

Comparing data and simulation with different residual gas saturation

- data
- $S_g^{0.1}$
- $S_g^{0.2}$
- $S_g^{0.01}$
Simulated CO2 saturation $S_{gr} = 0.01$
Simulated CO2 saturation $Sgr = 0.1$
Simulated CO2 saturation $S_{gr} = 0.2$

Gas saturation at the end of simulation
Conclusions and next steps

Preliminary results analysis of a single-well push-pull experiment to quantify residual saturation of CO$_2$ has been presented. The results so far indicate low residual trapping

Next steps

• Inclusion of hysteresis in $k_{rl}$ function (observed in core data)
• Incorporating the detailed analysis of tracer data, pressure information in the test interval and well hydraulics.
• Effect of heterogeneity.
• Effect of anisotropy.
• A comparative push-pull test with different approach for creating the residual zone and with additional reference tests is planned later on this year.
Especially acknowledged co-workers contributing to earlier phases of this work

Vladimir Shtivelman, GII
Linda Luguot, CSIC
Philippe Pezard, CNRS
Katriona Edlmann, UEDIN
Sally Benson, Stanford University
Ferdinand Hingerl, Stanford University
Barry Freifeld, Class VI Solutions
Jesus Carrera, CSIC

and all MUSTANG and TRUST partners
Carbon Capture and Storage (CCS) is an expanding technique, with globally addressed scientific and technical challenges, aimed at reducing carbon dioxide in the atmosphere and thereby combatting the climate change.

This course will provide the participants with the current state of the art knowledge concerning some key scientific and technical issues related to CO₂ sequestration in deep, brine-containing geological formations. The focus will be on the processes related to CO₂ injection and storage, spreading and trapping in the target formation, their mathematical and numerical modelling as well as experimental characterization and monitoring. Experts will lecture on site characterization and investigations of critical processes by laboratory studies and field techniques, as well as on planning of experimental projects and monitoring techniques aimed at verifying the conceptual models. Emphasis will be on understanding the flow and transport mechanisms that provide the foundation for planning of full scale projects. Risk issues and societal aspects will also be presented and discussed.

The course is organized by the European Commission FP7 TRUST project. The recently released text book “Geological Storage of CO2 in Deep Saline Formations” (Editors: Auli Niemi, Jacob Bear and Jacob Bensabat). Springer, 2017. will be used as background reading.
Thank you

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