PANACEA & TRUST Projects
Status update

Jacob Bensabat – Coordinator
EWRE, Haifa Israel.

and Auli Niemi, Uppsala University, Sweden

Leading the way in CCS implementation
PANACEA (www.panacea-co2.org)
Predicting and monitoring the long-term behavior of CO₂ injected in deep geological formations

• Started - January 1st, 2012.
• Duration – 36 months.
• Budget – 5.21 Million Euro – EU contribution 3.68 Million Euro.

• Consortium: EWRE (Israel), Uppsala University (UU-Sweden), Technion Israel Institute Of technology (IIT-Israel), Goettingen University (UGOE-Germany), CSIC (Spain), CNRS (France), Edinburgh University (UEDIN-Scotland), Cambridge University (UCAM-England), STATOIL (Norway), University of Nottingham (UNOTT-England), IMAGEAU (France) and Bureau Veritas (BV- France).
TRUST (www.trust-co2.org)

High resolution monitoring, real time visualization and reliable modeling of highly controlled, intermediate and up-scalable size pilot injection tests of underground storage of CO2

- Duration – 60 months.

- Consortium: EWRE (Israel), Uppsala University (UU-Sweden), Technion Israel Institute Of technology (IIT-Israel), Goettingen University (UGOE-Germany), CSIC (Spain), CNRS (France), IMAGEAU (France), Cambridge University (UCAM-England), VIBROMETRIC (Finland), Imperial College (IMPCOL-England), ETH (Switzerland), KLOE (France), Karlsruhe Institute of Technology (KIT-Germany), Bureau Veritas (BV- France), Israel Electric Corporation (IEC-Israel), MERI (Spain) and Lapidoth Oil Explorers (Lapidoth-Israel).
Natural analogues show

World wide study included 49 natural CO₂ reservoirs, of which 6 were leaking and 3 were inconclusive.

**CO₂ state and density control leakage**
40% of gaseous reservoirs and 8% of supercritical reservoirs leak. Leaking reservoirs have a low average density of CO₂ (<250 kg/m³) compared to non-leaking reservoirs (~550 kg/m³).

**Overburden thickness and pressure** controls leakage.
Average thickness: 160m (leaking), 220m (sealing).
Reservoirs with overpressured overburden are more likely to seal than reservoirs with normal pressured overburden.

**Faults** are the preferred leakage pathways.
5 out of 6 leaking reservoirs leak along faults.
However, faults often are sealing and part of the trap in non-leaking reservoirs.
Experimental Work – natural analogues

- Confining pressure increased during the period
- This resulted in:
  - Fracture aperture decrease with time due to the increased normal stress across the fracture
  - An increase in differential pressure
  - Associated with a decrease in fracture permeability
• Pumping/hydraulic tests
• Brine Push-Pull tests: inert and reactive tracers
• High-pressure brine injection: to test maximum injection pressure and caprock
• CO$_2$ Push-Pull test: with inert, reactive + partitioning tracers
Sleipner L9 layer

Uppermost point L9 model = -800 m b.s.l. Sea bed ~80 m b.s.l. (T=7 °C). Injection location, (spill/leakage from underneath layer): x~1600m, y~2100m.
20% SPE 134891 Injection rate

\[ T_{inj} = 32 \degree C \]

\[ T_{inj} = 35 \degree C \]
WP3 - MIXING and TRAPPING

Numerical study of Convectively-Enhanced Dissolution

Dynamic of the convection-diffusion boundary layer at large Rayleigh number and concurrent induced mega plume at the core of the domain.

Zoom of the boundary layer and mega plumes dynamics near the top layer

Due to the interaction between the highly intensive small plumes at the boundary layer, large plumes of slower insensitive are induced and migrated to the core of the domain.
Boundary Element numerical solution of viscous fingering

Recently it have been experimental reported in the literature that the pattern evolution of high mobility ratio immiscible viscous fingering displacement is completely different to those of low mobility ration, as is the cases of air-brine and CO2-brine displacements.

Viscous fingering evolution of air-brine displacement in a Hele-Shaw cell

In the case of low mobility ratio, due to the interaction between neighbouring fingering, it is possible to occur fingering braking and bubble formation.

Viscous fingering evolution of CO2-brine displacement in a Hele-Shaw cell
Effect of heterogeneity on Convectively-Enhanced Dissolution

Heterogeneous permeability field $K$ with mean dimensionless value 1.21

Dimensionless dissolution rate (SF): homogeneous $K$, SF=4.81, heterogeneous $K$, SF=3.84


Empirical cumulative distribution function of the rate of dissolution (SF) computed by using Monte Carlo and Gaussian Processes emulator with a *Matern* 3/2 covariance function.

Comparison between Monte Carlo and GP emulator rate of dissolution predictions, for an emulator design of 174 points.
Stable trapping by convective dissolution

1. Nondimensional convective flux at high $Ra$ \( \text{Nu} \sim Ra \)

Planform of convection: long downwelling fingers \( k \sim Ra^{2/5} \)

2. Long-term dissolution parameterised by simple box models

\[
\frac{d\theta}{dt} = \frac{F}{Ra_0} = \frac{|\theta|}{Ra_0} \text{Nu}[Ra(t)]
\]

3. Coupling these models to propagating currents predicts finite runout distance.
WP4 – LEAKAGE

H-18 Heletz caprock mineralogy
WP4 – LEAKAGE  scCO₂ fracture flow experiments

• Simple method developed for creating artificial fractures in core samples

• Laser scanner used for capturing fracture surface topography (in collaboration with Strathclyde University)

• Flow experiments to investigate effect of stress anisotropy, temperature, pressure and fluid pressure on CO₂ fracture flow
Cyclic scCO$_2$ and brine flow experiments

- 6 brine / scCO$_2$ cycles of flow
- No mineral dissolution and precipitation reactions.
- Residual trapping is the dominant mechanism accounting for the overall increase in differential pressure
WP4 – LEAKAGE

Reactivity of cement, caprock and reservoir

• Test **new cement formulations** for improving the CO₂ buffering effect, using MgO-based cement. Conduct the experiments under the desired conditions, from atmospheric pCO₂ to 50 bar and temperature from 25 to 90 °C.

• Determine the **reactivity of the cap-rock**, with samples from Hontomin by means of flow-through experiments to evaluate the leakage risk. Conduct CO₂-rich brine injection at in situ conditions through fractured claystone sample and characterize the permeability change for different flow rate.

• Characterize the **reservoir rock reactivity** and the **multi-phase flow parameters** change during dissolution and precipitation processes. Conduct flow-through experiment through limestone sample and characterize the different dissolution patterns and the flow parameters change due to dissolution and precipitation processes.
Characterization and modeling well integrity (fractured cements)

- Study of the permeability changes of fractured cements flowed by scCO$_2$ or CO$_2$-rich brine

Experiment using fractured Portland cement (Class G)
Fracture aperture = 37 µm
CO$_2$-saturated brine @ $Q = 2$ ml.min$^{-1}$

ICARE Lab CO$_2$ sequestration evaluation flow system

Healing due silica-gel growing
Characterization and modeling well integrity (fractured cements)

- Determine the reaction kinetics & effective diffusion

Set of experiment @ constant flow injection through Holed Portland cement disks.
Measuring front position and size at increasing times

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Silica gel layer (mm)</th>
<th>Carbonates front (mm)</th>
<th>Alteration front (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.0075</td>
<td>0.035</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0.065</td>
<td>0.325</td>
</tr>
<tr>
<td>44</td>
<td>0.134</td>
<td>0.307</td>
<td>0.476</td>
</tr>
<tr>
<td>66</td>
<td>0.158</td>
<td>0.342</td>
<td>0.592</td>
</tr>
<tr>
<td>100</td>
<td>0.187</td>
<td>0.381</td>
<td>0.625</td>
</tr>
<tr>
<td>160</td>
<td>0.294</td>
<td>0.539</td>
<td>0.902</td>
</tr>
</tbody>
</table>
Coupled THM-simulations for Heletz site for fault re-activation due to injection

TOUGH2-FLAC code
Propagation in confined aquifers with large viscosity contrasts

Leakage from confined aquifers
Evaluation of the pressure plume

- A modeling approach developed combining different methods for evaluation of different aspects of the pressure impacts, e.g. Caprock fracturing, fault slip and far-field brine migration
- These methods involve different degrees of complexity:
  - Single-phase analytical solution (e.g. Theis solution)
  - Two-phase two-component analytical solution (e.g. Mathias et. al. 2011)
  - Single-phase numerical modeling
  - Multiphase numerical modeling (e.g., based on TOUGH2/ECO2N)
- Site modeling performed for the pressure impacts:
  - the South Scania site (Upper Jurassic and Lower Cretaceous)
  - the Baltic sea region (Mid Cambrian)
- Estimation of pressure-limited capacity and pressure plume-induced Area of Review (AoR);
- Coupled hydro-geochemical modeling performed on the risk of mobilization of hazardous minerals due to leaked CO₂.
CO$_2$ injection and flow regimes

For a typical industrial scale injection scenario at 50 years (with injection rate $\sim$ 1 Mt/yr)

$R_{\text{dry-out}} \sim 10^2 \text{m}$

$R > R_{\text{two-phase}}$, brine flow

$R_{\text{two-phase}} \sim 1-10 \text{ km}$

Illustration of typical scales relevant for pressure buildup
Evaluation of the pressure plume

Conceptualization for two-phase analytical method to evaluate the effect of number of injectors on injection pressure

Estimation of max. injection rate based on pressure threshold

If $\Delta P/P_{ini} < 1.5$, max rate = 1.69 Mt/yr
If $\Delta P/P_{ini} < 1.3$, max rate = 0.96 Mt/yr

Effect of number of injectors

Sensitivity of injection pressure to permeability

TOUGH2 simulation results
Single-phase analytical / Theis solution gives good approximation for far field pressure behavior

→ Demonstration of the semi-analytical solution with the method of image wells (Ferris et al. 1962) for the no-flow boundaries (faults)
BRINE MIGRATION & CO2 LEAKAGE

• Study of the combined flow process of brine and CO2 through reservoir boundaries and fault.
• Focus on medium spatial and temporal scales.
• Calculations of outward fluxes, velocities in the fault, composition of fluid leaking into a freshwater aquifer.
• Comparison: fluxes through side boundaries vs. leakage through fault.
BRINE MIGRATION & CO2 LEAKAGE

Results
- reservoir - horizontal cross section - typical profiles vs. time

Temperature

CO2 Saturation

Pressure

Fault – co2 saturation vs. time (k=5.e-13)

Fluxes: total / co2, all boundaries / fault only

5/8/2014
The present study of combined reservoir/fault process examines realistic features of brine migration/co2 leakage.

Depending on fault permeability and fault width: It takes 2-7 years for the co2 to climb the 1300m fault, 50m away from the injection point, starting from -1600m, with injection rate of 1.5kg/s. It becomes gaseous at depth of approx. 500m.

Several years after reaching the upper freshwater aquifer, traces of co2 spread all over but significant saturation  is very localized around the entrance point.

Comparison: fluxes through side boundaries vs. leakage through fault.: 0.004% for narrow fault, after 5 years, high perm. 0.1% for wide fault, after 7 years, low perm. Additional calc. to come.

In real reservoirs faults are not vertical, but split and branch – the leakage is even less effective
Prototyping of MMV technologies at Maguelone
• Hydrogeophysical monitoring experiments at Maguelone with CO₂ injection (CNRS, IMAGEAU) in the context of ‘‘SIMEx’’ (Shallow Injection Monitoring Experiments).

• **Objectives:**
  • Further develop the Maguelone shallow experimental site with 3 new holes (for injection at 9 m, and monitoring with a WestBay multipacker string and the new RTSG).
  • Test new integrated downhole monitoring instrument.
  • Conduct CO₂ injection experiments to test the relative sensitivity of an integrated set of monitoring methods and instruments (surface and downhole).
Maguelone experimental site development as part of PANACEA

New injection & pumping hole in the shallow sands (9 m)

New WestBay multipacker system with Permanent p/T sensors

New RTSG downhole observatory

Melbourne, March 12th, 2014
Dissemination, communication and public acceptance
PANACEA - WP9 - Bureau Veritas

PANACEA website

www.panacea-co2.org

All the project findings in the sections:

• Publications and events
• Deliverables

PANACEA flyer

Available for download on the website
(“Public Downloads” section)
A large number of papers in scientific journals

- International journal of Greenhouse Gas Control
- Advances in Water Resources
- Journal of Fluid Mechanics
- Water Resources Research
- Physics of Fluids
- Annual Reviews of Fluid Mechanics
- Physical Review Letters
- European Journal of Mineralogy
- Energy Procedia
- Procedia Earth and Planetary Science
- ...

Frequent participation in CCS events

- American Geophysical Union, 2012 & 2013
- European Geosciences Union, 2012 & 2013
- UKSSCRC meetings, 2012 & 2013
- Trondheim CCS Conference, 2013
- International Conference on Boundary Element and Meshless Techniques, 2013
- European Current Research on Fluid Inclusions, 2013
- ...

5/8/2014
Brainstorming Day on the long-term fate of geologically stored CO2

One-day workshop on the long-term fate of geologically stored CO2
June 3rd 2013, Trondheim (Norway)

Press release of the event:

Joint organization of 5 EU-funded projects (FP7):
Meeting kindly hosted by

High resolution monitoring, real time visualization and reliable modeling of highly controlled, intermediate and up-scalable size pilot injection tests of underground storage of CO2

Technical Work Packages
- Sites and Field tests (Heletz, Hontomin, Swedish/Baltic Sites)
- MMV technologies and real-time reporting and visualization
- Modeling
- Strategies for storage management (optimal injection strategies etc.)
- Leakage detection and mitigation
- Risk Assessment: Procedures, Protocols for Certification and Licensing
- Extrapolation
- Training and capacity building
WP2 – SITES AND EXPERIMENTS
Heletz
Enhanced Injection System
WP3 – MMV TECHNOLOGIES
New generation of monitoring wells for CO2

• **Behind-the-casing completion** (the well is not perforated and all the monitoring technologies are installed in the cemented part of the well (between the outer casing and the borehole wall); much safer approach as no perforation is conducted.

• **Novel temperature sensors, using Bragg sensors** (direct measurement of temperatures at any vertical separation, possibility to extend in order to measure other parameters such as strain, CO2 saturation etc.);

• **Tube-in-tube** fluid sampling;

• **ERT** (Electrical Resistivity Tomography)

• Standard **P/T** sensors

• **Optical fiber** for DTS (to compare with the Bragg sensors) and for acoustic sensing;

• **Movable geophones** for seismic monitoring.
**Basic principle:**

- **Acquisition module (monitoring unit)**
- **Signal modulator**
- **Wireline (~1500m)**

**Design/Construction** by imaGeau of a resistivity device for deep deployment (1630m)

**Developments:**

1) A suitable communication protocol (FSK)

2) A secure chamber (electronic cartridge) in the borehole for electronic modules used for the electrical array.

3) Electrical array on line developed for high pressure and high temperature
K-FBG / K-BGS Monitoring Unit

FBG based technology (using Bragg sensors):
- Temperature (-180°C; +300°C, standard)
- Strain, Pressure

Gas sensing technology:
- CH₄ to C₄H₁₀ (< 1% volume)
- H₂S, CO₂ (to be developed)

KLOE Optical fiber monitoring system (T, CH₄, strain, …)
The first set of objectives is to assess the plume position, monitor its extension and interaction with the host formation, or to predict its evolution, including the potential migration into adjacent formations.

A second set of objectives is to assess the sustainability of CO2 storage in relation to well and reservoir integrity, either during injection or in the long run.

The main advantage of surface images is the large-scale coverage of the site from above, allowing the detection of the horizontal extension of the injected CO2 body. Borehole geophysical surveys are used to obtain more local but more precise data, valuable either to improve the inversion of surface images or to constrain in-situ models. While the former have been more extensively used in the past, the latter have been deployed thus far to a lesser extent, partly due to logistical difficulties in performing frequent surveys in boreholes when CO2 is present. Such logistical difficulties are reduced when installing permanent geophysical sources and receivers in shallow and dedicated observation boreholes, providing near continuous recording.
VIBROMETRIC design of borehole seismic instruments

3-component, wide-band digital receivers deployed in 3 boreholes, 300 m deep each, tentatively installed in arrays of five units per borehole
KIS Tracers: Motivation

What is happening to the CO2 in the subsurface and how can it be monitored during and after injection?

Development of tracers which indicate the size of the interface scCO2/brine AND its development with time

- Standard partitioning tracers
  - Volume sensitive
  - Partitioning equilibrium

- Novel KIS-Tracers
  - Interface sensitive
  - Time-dependent
  - Reaction kinetics

Influence of pressure stimulation on mixing
Significance of fingering at field scale
Residual saturation of CO2
Max. interfacial area

Variable interface

Min. interfacial area

saturation of the non-wetting phase

depth below surface [m]

0.05 0.15 0.25 0.35 0.45 0.55 0.65 [-]
WP4 – MODELING

Modelling Fracture Propagation in Caprocks Cooled by Supercritical CO2 Injection

Objectives:
The objective of this work package is to perform computational modelling of poroelastic and thermoelastic behaviour of the caprock during CO₂ injection. In particular, we will run simulations that will evaluate caprock failure over a realistic time-scale covering the CO₂ injection period, as a function of geomechanical deformation, for a range of injection scenarios. These simulations will be validated using data gathered in WP 3. The resulting models will serve to identify injection scenarios that may jeopardise containment.

Methodology:
Stresses, deformations and temperatures in the reservoir and caprock will be modelled with an in-house finite element simulator that accounts for thermoelastic effects, poroelastic effects, and two-phase flow. Fracture propagation is modelled by calculating the stress intensity factors at the tips of pre-existing cracks that are assumed to be present in the rock. Specific focus will be placed on evaluating the effect of the temperature shock at the onset of CO₂ injection on the propagation of pre-existing fractures in the caprock.
Right: Simulated fracture growth. Unlike in almost all existing codes, in our simulations, the fractures are not artificially restricted to follow the computational mesh; instead, the mesh conforms to the evolving fracture geometry.

Right: A fracture at the interface between the reservoir and the caprock grows upwards due to the build-up of thermal strains. Fluid pressure contours around the tip before (a) and after (b) growth are plotted.
Leakage detection and mitigation

- New technology for leakage prevention & remediation based on composite organic silica fluids (Patent REMEDIASOL)

Ongoing task: Determine the optimal reagent fluid formulation and use.

Scaled Radial Remediation Injection Simulator (ICARE Lab - SRRIS) for testing sealing reagent efficiency & optimal formulation
Leakage detection and mitigation

- New technology for fracture leakage remediation based on catalyzed self-healing slurries  *(Pending Patent SECAREM)*

Ongoing task:
Determine the optimal mixture composition and injection protocol

*ICARE Lab - Slurry flow & reaction evaluation system* - for testing sealing efficiency in fractured geomaterials
Injection Strategies /effects for trapping and economy

Different injection modes tested at Heletz and Hontomin.:

(i) Varying P and T (e.g., liquid injection)

(ii) Pulsed injection schemes and alternating CO2 and water injections

The results on trapping (residual and dissolution), pressure buildup, and size of the CO2 plume and energy use at the injection well will be measured.

This task includes 1) design and predictive model simulations, 2) carrying out the actual experiments and 3) analysis and modeling of the results of the experiments (in collaboration with WP04).
**Injection Strategies – example study**

Energy requirements from typical storage conditions (-20\(^\circ\)C, 20 bar)

<table>
<thead>
<tr>
<th>Injection conditions at the wellhead</th>
<th>T, (^\circ)C</th>
<th>p, MPa</th>
<th>Energy consumption, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-phase</td>
<td>35</td>
<td>6.5</td>
<td>409.6</td>
</tr>
<tr>
<td>Near-critical point</td>
<td>31</td>
<td>7.0</td>
<td>368.2</td>
</tr>
<tr>
<td>Supercritical phase</td>
<td>40</td>
<td>8.0</td>
<td>361.9</td>
</tr>
<tr>
<td>Liquid-phase (high T and p)</td>
<td>25</td>
<td>8.0</td>
<td>154.7</td>
</tr>
<tr>
<td>Liquid-phase (low T and p)</td>
<td>5</td>
<td>4.2</td>
<td>83.6</td>
</tr>
</tbody>
</table>

*Under transport conditions (Liquid, P=10 Mpa, T=30 \(^\circ\)C), you may even recover energy*
Temperature, pressure and density along the well

T (°C)  P (Mpa)  Density (kg/m³)

gas-phase  near critical point  supercritical phase  liquid-phase (high P and T)  liquid-phase (low P and T)
Stability (mobilized friction angle) under normal initial stress state (3 m away from inj well, 8 months after start)

Improved stability at caprock good! (increased tightness)

Worsened stability at reservoir good! (increased permeability)
High resolution monitoring, real time visualization and reliable modeling of highly controlled, intermediate and up-scalable size pilot injection tests of underground storage of CO2.

Latest News

Last consortium meeting was held on 17th and 18th February 2014 in Barcelona, Spain.