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WESTCARB Annual Business Meeting

CO_2 Storage in Natural Gas Reservoirs: Significance of the Rosetta Resources Pilot

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Phoenix, AZ
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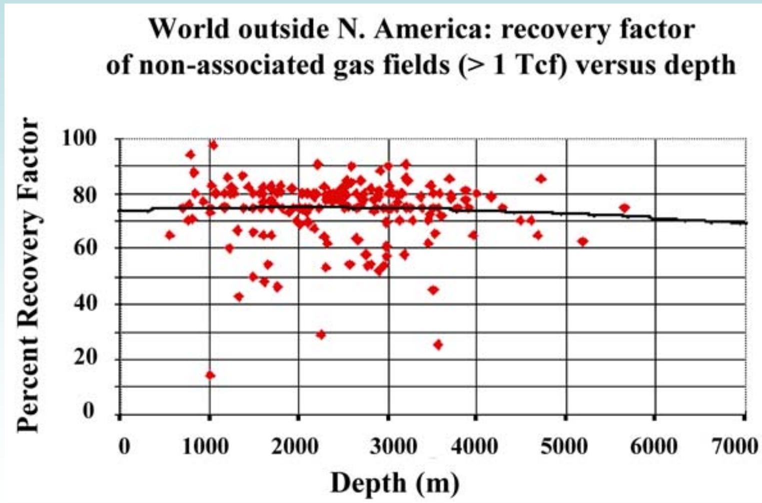
Outline

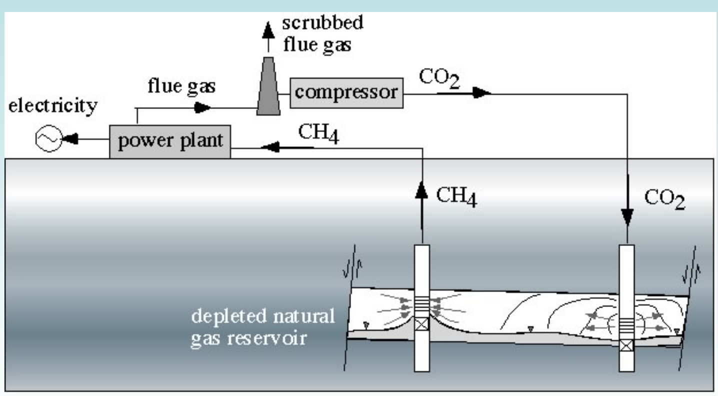
- Carbon Sequestration with Enhanced Gas Recovery (CSEGR)
  - Opportunity
  - Concept and its history
  - Technical feasibility
  - Benefits and challenges of CSEGR
- Three pilots world-wide on CSEGR
  - K12B, Netherlands
  - Otway Basin, Australia
  - Rosetta Resources, California
- Results from Rosetta Resources CSEGR Pilot will be of world-wide interest

CSEGR Opportunity



Source: Laherrère (http://www.hubbertpeak.com/laherrere/iea1997/)

CSEGR Concept and History



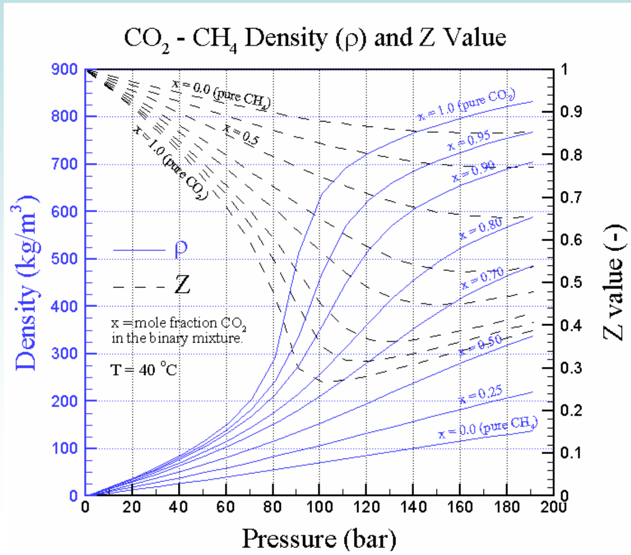
<u>Early papers:</u>

Van der Burgt, Cantle, and Boutkan, *Energy Conv. & Mgt.*, *33*(5-8), 603-610, 1992.

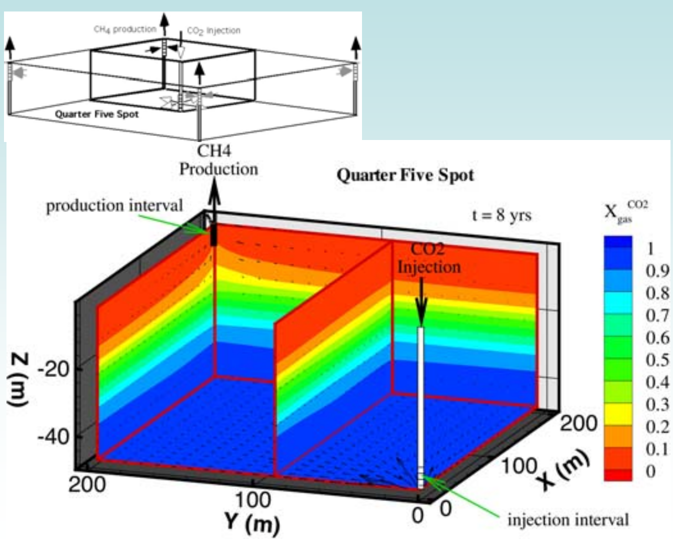
Blok, Williams, Katofsky, and Hendriks, *Energy*, *22*(2-3), 161-168, 1997.

Oldenburg, Pruess, and Benson, *Energy & Fuels*, *15*(2), 293-298, 2001.

Density Contrast Is the Key to CSEGR



Technical Feasibility



Oldenburg, Stevens, and Benson, *Energy 29*, 1413-1422, 2004.

CO_2 in Depleted Gas Reservoirs

Benefits

- **Maintain/increase reservoir pressure.**
  - **Decrease water entry**
  - **Avoid subsidence**
- **Enhance/accelerate/control methane recovery**
  - **Primary gas recoveries approx.:**
    - **80-90% for depletion drive**
    - **60-70% for water drive**
- **Utilize idled wells (for production and injection).**
- **Develop value of depleted reservoirs as CO_2 storage sites.**
- **Use CO_2 as cushion gas for natural gas storage.**
- **Promote new technologies against global warming.**
- **Join new industry of geologic CO_2 storage.**

Key Issues for CSEGR

Challenges

- Early breakthrough
- Mixing of CO_2 and CH_4 that degrades gas quality
- Injectivity decline due to halite precipitation
- Pressurization due to mixing
- Joule-Thomson cooling (hydrate formation)

CO_2 Projects Related to Gas Reservoirs

Name	Country	Organizations	Status	Environ.	Depth	Storage	CO_2 Injection	CO_2 source
K12B	Netherlands	Gaz de France	Operating	Offshore	4000 m	EGR	30,000 up to 475,000 t/yr	Natural gas
Rosetta	U.S. (Calif.)	Rosetta Resour., WESTCARB	2007 pilot	Onshore	1000 m	EGR	500 t	Commercial
Otway	Australia	CO2CRC	2007 pilot	Onshore	2000 m	EGR (water leg)	100,000 t	Natural gas
Altmark	Germany	BGR	Under evaluation	Onshore	3000 m	EGR	Unknown	Various
Atzbach, Schwnst.	Austria	Rohoel	Under evaluation	Onshore	1600 m	EGR	200,000 t/yr	Various
Ketzin	Germany	GFZ	Experimental site	Onshore	700 m	Exptl.	< 10,000 t/yr	Commercial
In Salah	Algeria	BP, Statoil, Sonatrach	Operating > July 2005	Onshore	1900 m	Water leg	> 1 Mt/yr	Natural gas
Gorgon	Australia	Chevron	Pending approval	Onshore (Barrow Is.)	2300 m	Aquifer	3 Mt/yr	Natural gas
Snøhvit	Norway	Statoil	2007	Offshore	2500 m	Aquifer below	750,000 t/yr	Natural gas
Sleipner	Norway	Statoil	Operating > 1996	Offshore	900 m	Aquifer above	1 Mt/yr	Natural gas

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K12B-Offshore Netherlands (Gaz de France)

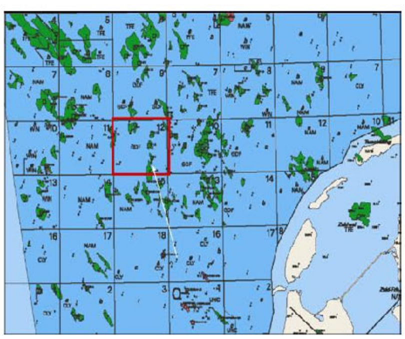

Figure 1: Field location map

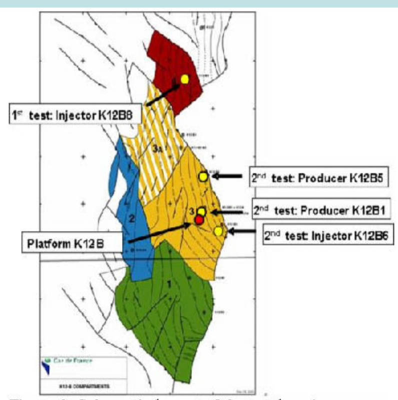

Figure 2: Schematic layout of the test locations.

- Phase 1. Feasibility of capture and injection
- Phase 2. Injection of separated CO_2.
  - Test 1. Injection into isolated compartment
  - Test 2. Injection into producing gas reservoir (30,000 t/yr)
- Phase 3. Injection into gas reservoir at up to 475,000 t/yr

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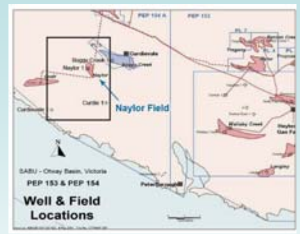
Otway Basin Pilot, Australia



- 100,000 t CO_2
- Injection into water leg, with EGR

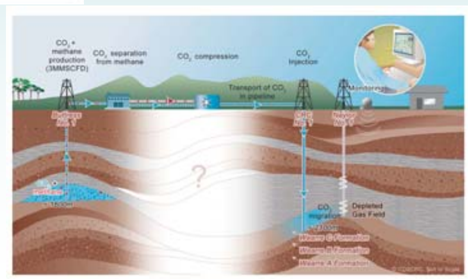


Figure 5: Conceptual representation of the Otway Basin Pilot Project.

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Ketzin	Germany	GFZ	Experimental site	Onshore	700 m	Exptl.	< 10,000 t/yr	Commercial
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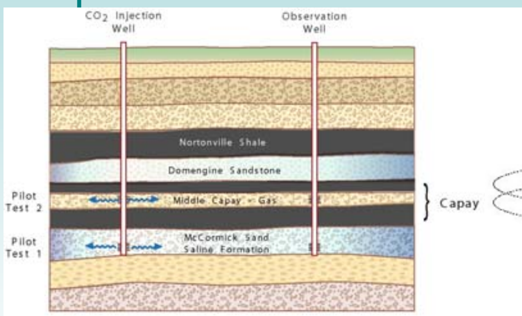
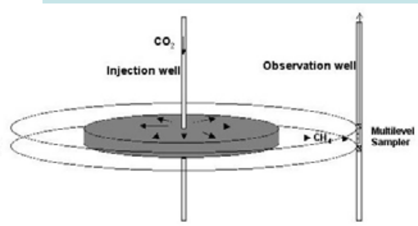
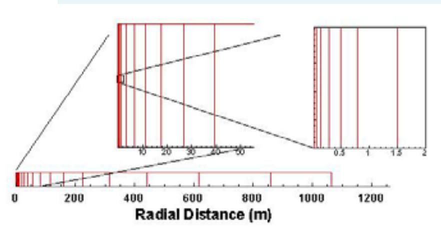
Rosetta Resources Pilot, Thornton CA

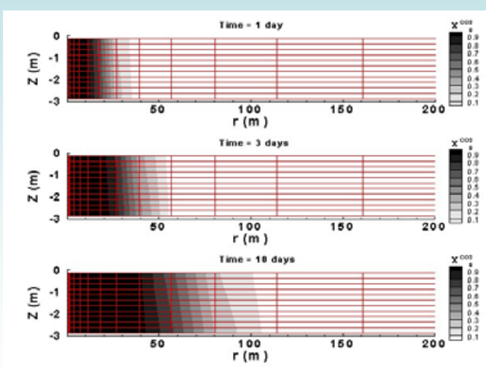


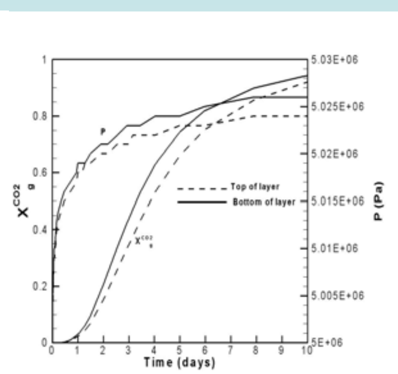




- Radial Geometry for Simplicity.
- 12 layers.
- High-resolution grid near injection well.

Results for Capay

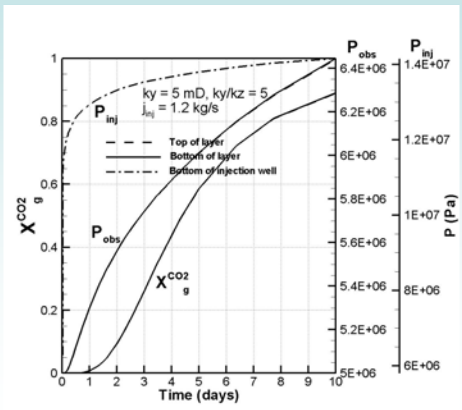


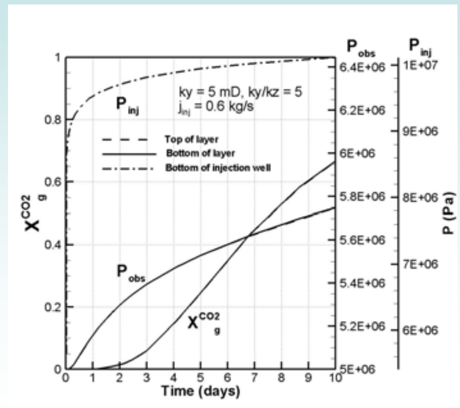


Breakthrough occurs after 1-2 days of injection.

Results for Capay

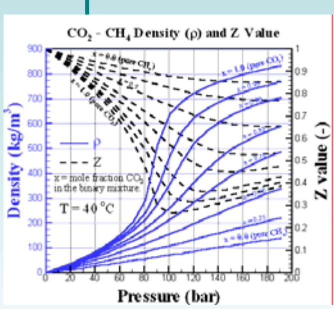
k = 5 mD
Two different injection rates
Obs. well is at r = 39 m

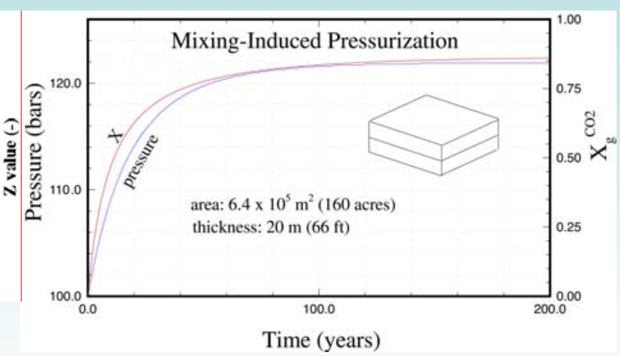




Breakthrough occurs after 1-2 days of injection.

Pressurization Due to Mixing





Supercritical CO_2 and CH_4 will eventually mix in the reservoir.

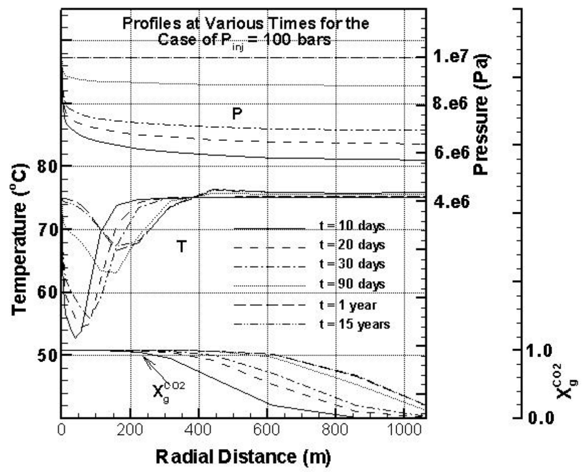
Pressure rises after injection stops due to compositional effect on CO_2 density.

(see Oldenburg, Geological CO_2 sequestration: CO_2 transport in depleted gas reservoirs, in Ho and Webb, eds., *Gas Transport in Porous Media (Theory and Applications of Transport in Porous Media)*, Springer, 2006)

J-T Cooling for High-Pressure Injection

Table 2. Properties of the 1-D radial gas reservoir.

Property	Value	Alt. Units
Radius	1130 m	0.70 mi
Thickness	50 m	164 ft
Porosity	0.30	0.30
Permeability	10^{-12} m^2	1 Darcy
Residual liquid saturation	0.2	0.2
Rock density (ρ_R)	2600 kg m^{-3}	-
Rock heat capacity (C_R)	1000 J kg^{-1} °C^{-1}	-
Formation thermal conductivity	2.51 J m^{-1} °C^{-1}	-
Relative Permeability	Liquid: immob. Gas: unity	Liquid: 0. Gas: 1.
Molec. diffusivity (1 bar, 0 °C)	Liquid: 10^{-10} m^2 s^{-1}, Gas: 10^{-5} m^2 s^{-1}	- -
T at $t = 0$	75 °C	167 °F
P at $t = 0$	50 bars	725 psi
P_{inj}	100 bars CO_2	1470 psi
CH_4 production rate	0.0 kg s^{-1}	0.0 Mcf/day
Final reservoir pressure after 15 yrs (high-P inj. case)	100 bars	1470 psi

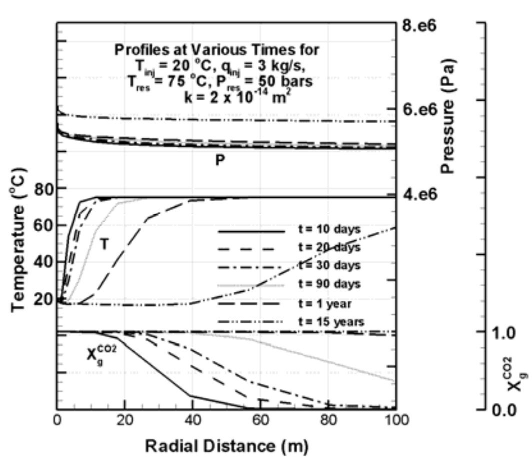


Joule-Thomson cooling causes ~20 °C cooling near injection well.

J-T Cooling for Constant-Rate Injection

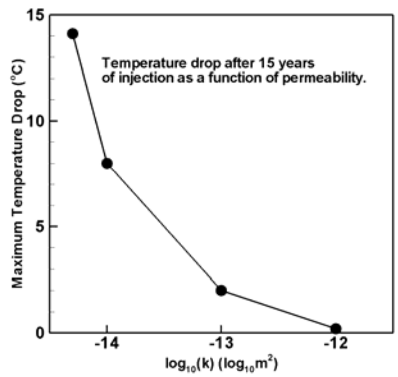
Table 2. Properties of the 1-D radial gas reservoir.

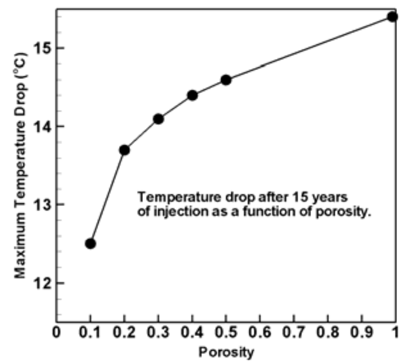
Property	Value	Alt. Units
Radius	1130 m	0.70 mi
Thickness	50 m	164 ft
Porosity	0.30	0.30
Permeability	10^{-12} m^2 (base case) 2 x 10^{-14} m^2 (low-k case)	1 Darcy 20 mD
Residual liquid saturation	0.2	0.2
Rock density (ρ_R)	2600 kg m^{-3}	-
Rock heat capacity (C_R)	1000 J kg^{-1} °C^{-1}	-
Formation thermal conductivity	2.51 J m^{-1} °C^{-1}	-
Relative Permeability	Liquid: immob. Gas: unity	Liquid: 0. Gas: 1.
Molec. diffusivity (1 bar, 0 °C)	Liquid: 10^{-10} m^2 s^{-1}, Gas: 10^{-5} m^2 s^{-1}	- -
T at $t = 0$	75 °C	167 °F
P at $t = 0$	50 bars	725 psi
CO_2 injection rate	3 kg s^{-1}	280 t/day
T_{inj}	20 °C	68 °F
CH_4 production rate	0.56 kg s^{-1}	2514 Mcf/day
Final reservoir pressure after 15 yrs (base case)	55.6 bars	817 psi



k_{res} = 20 mD => small ΔP => small ΔT.

J-T Cooling Trends with k and ϕ





As k_{res} decreases => ΔT increases.

As porosity increases => ΔT increases.

Summary

- CO_2 injection into gas reservoirs is the focus of pilot tests world-wide, but only a few involve EGR
- Pilot tests will answer key questions for CSEGR
  - Density effects (gravity underride)
  - Mixing and early breakthrough
  - Injectivity (halite formation, hydrate formation)
  - Pressurization due to mixing
- Rosetta Resources Pilot
  - Reservoir is too thin to observe gravity underride
  - Useful for mixing, breakthrough, injectivity, pressurization
- Results of the Rosetta Resources Pilot will be of world-wide interest

Acknowledgments

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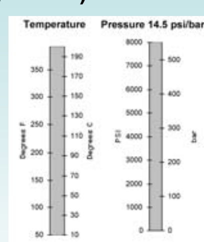
Handy Conversions

- **Standard conds. in U.S. are 14.7 psia, 60 F (~1 bar, 15.5 C)**
- **1 MMBtu ≈ 1 Mcf CH_4**
- **1 Mcf = 10^3 cf = 28 m^3**
- **1 Mcf = 19 kg CH_4 at (1 bar, 15.5 C)**
- **1 Mcf = 1.96 x 10^3 kg CH_4 at (100 bar, 40 C)**
- **1 Mcf = 53 kg CO_2 at (1 bar, 15.5 C)**
- **1 Mcf = 1.77 x 10^4 kg CO_2 (100 bar, 40 C)**
- **1 tonne CO_2 = 10^3 kg = 18.8 Mcf = 526 m^3 (1 bar, 15.5 C)**
- **1 tonne CO_2 = 10^3 kg = 0.056 Mcf = 1.58 m^3 (100 bar, 40 C)**



Density
ρ_{CH4} (1 bar, 15.5 C) = 0.68 kg/m^3
ρ_{CH4} (100 bar, 40 C) = 70.0 kg/m^3
ρ_{CO2} (1 bar, 15.5 C) = 1.9 kg/m^3
ρ_{CO2} (100 bar, 40 C) = 632 kg/m^3

Viscosity
1 poise = 100 cp = 0.1 Pa s = 0.1 kg/(m s)
μ_{H2O} = 1 cp = 10^{-3} Pa s
μ_{CH4} = 1.4 x 10^{-5} Pa s (100 bar, 40 C)
μ_{CO2} = 5.0 x 10^{-5} Pa s (100 bar, 40 C)