West Coast Regional Carbon Sequestration Partnership
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WESTCARB Annual Business Meeting

Screening of Oil Pools on Alaska North Slope and Phase Behavior Study of Viscous Oil and CO_2 System in Conjunction with CO_2 Sequestration

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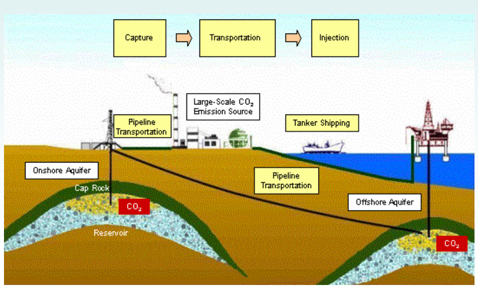
Introduction

Global Warming and Arctic Environment

- Increase in average winter temperature
- Reduction in the extent of the summer ice pack in the Arctic Ocean
- Either change could accelerate warming
- Change could substantially reduce winter drilling window, thus threatening oil and gas developmental drilling and related activities



Source: http://www.irccm.de/greenhouse/files/greenhouse06.png

Why Geological Sequestration?

- CO_2 is an important GHG gas
- Geological formation has potential
- Experience from the oil and gas industry
- Global storage capacity is around 24 gigatons

Introduction (cont'd)

Why store CO_2 in Alaska?

- Arctic: impact of climate change is more pronounced
- Viscous oil production by CO_2 flooding
- IEA estimates 6000 SCF CO_2 stored for 1 STB of oil (Fanchi, 2001)
- Annual CO_2 generation on North Slope

Gas turbines + handling facilities = 14 million tons

Gas sales = 8 million tons

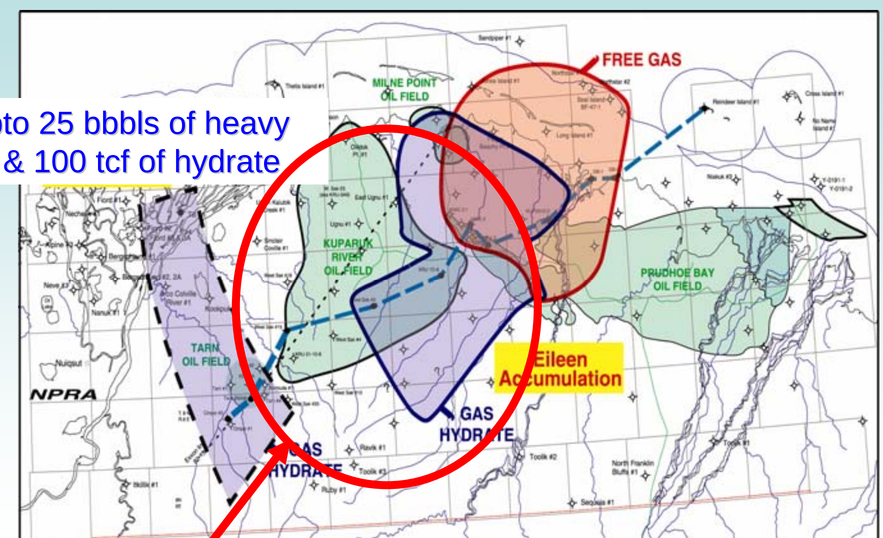
TOTAL = 22 million tons

Necessity: Advances in drilling technology to develop engineered well bores to avoid communication between injected CO_2 and producer wells.

Benefits: Increased oil and gas production in an environmentally friendly manner, leading to economic development.

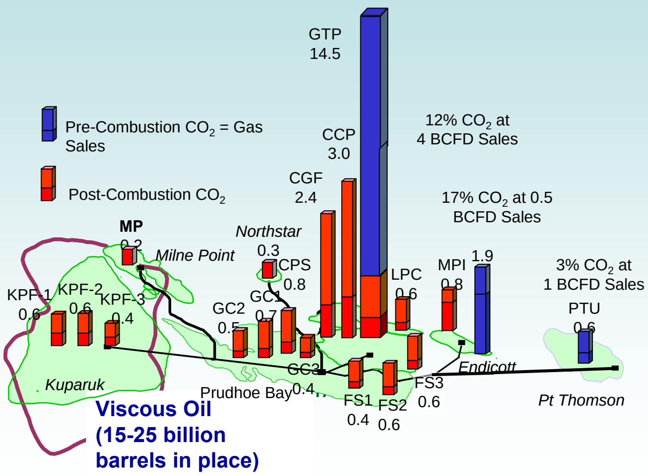
FOSSIL ENERGY RESOURCES AT STAKE

Upto 25 bbbls of heavy oil & 100 tcf of hydrate



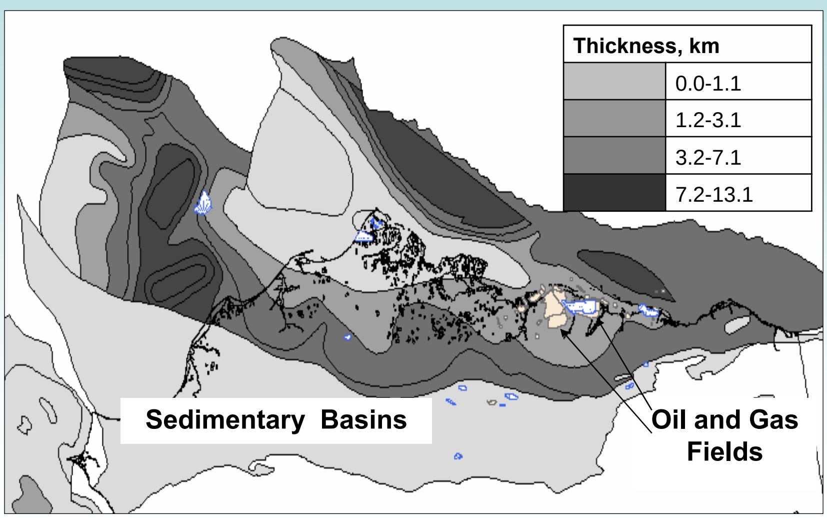
Viscous Oil and Gas Hydrate Resource Focus Area

CO_2 Sources on ANS

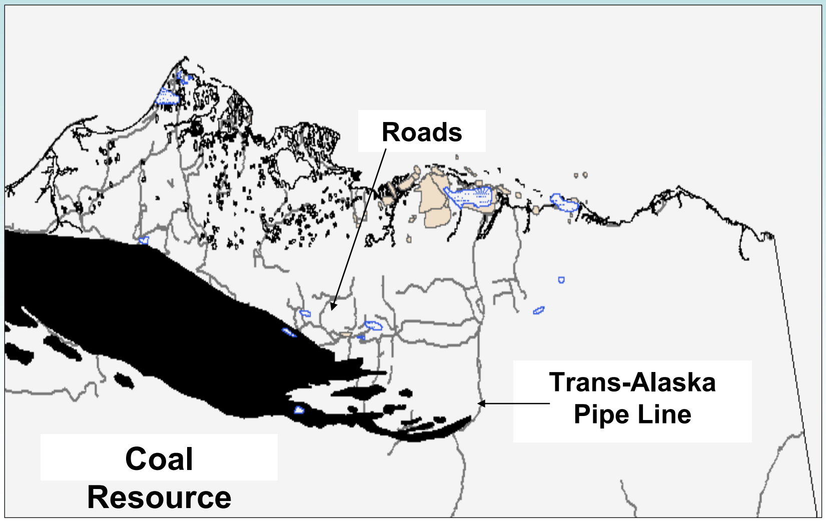


(Courtesy BP)

Proximity of Potential Sinks on ANS



Coal Resource on ANS



Objectives of the Study

- Characterize oil pools, amenable to CO_2-EOR, on ANS by parametric screening technique
- Simulate phase behavior by tuning Equation-of-State
- Prediction of oil production by CO_2 injection with compositional simulator as well as related economics
- Study of long-term CO_2 storage in a saline aquifer

Screening of Oil Reservoirs

- Influencing parameters for CO_2-EOR studies:
  Temperature, Pressure, Porosity,
  Permeability, API gravity, Oil saturation,
  Minimum Miscibility Pressure (MMP),
  and Net pay zone thickness

- Parametric study is adopted – Optimum values of above factors are considered to screen out reservoirs best for EOR

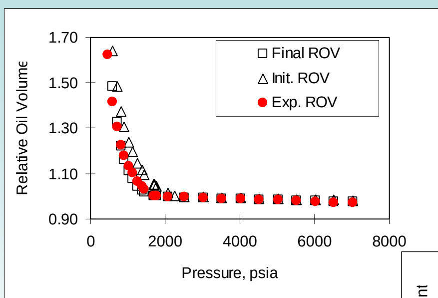
Rank (R_i) of the ANS Oil Pools

Pool	T, ºF	Φ,%	k, md	S_o, %	h, ft	º API	P/ MMP	R_i
Pt. McIntyre	180	22	200	60	156	27	1.27	1
Meltwater	140	20	10	60	95	36	1.5	2
Lisburne	183	10	1.5	70	125	27	1.03	3
Tarn	142	20	9	60	40	37	1.64	4
Prudhoe	200	22	265	70	222	28	0.94	5
Alpine	160	19	15	80	48	40	1.81	6
Kupurak -Milne	160	20	150	90	100	24	0.79	7
Kupurak River	165	23	40	70	35	22	0.76	8
Sag River	234	18	4	60	30	37	1.86	9
North Prudhoe	206	20	590	60	20	35	2.07	10
West Sak	75	30	1007	70	70	19	0.41	11
Schrader Bluff	80	28	505	70	70	17.5	0.4	12
Hemlock	180	10.5	53	70	290	33.1	2.34	13
Ivishak	254	15	200	50	125	44	4.11	14

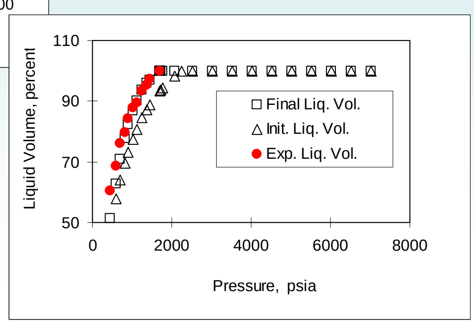
Phase Behavior Study

- The phase behavior of any reservoir fluid in CO_2 injection involves mass transfer and changes in composition.
- Any compositional simulator can predict the phase behavior of gas flooding, provided the Equation-of-State (EOS) is tuned.
- In the case of West Sak oil, the phase behavior during CO_2 injection was used to estimate the miscibility condition

Results after Regression



Better match of ROV and % liquid volume after Regression

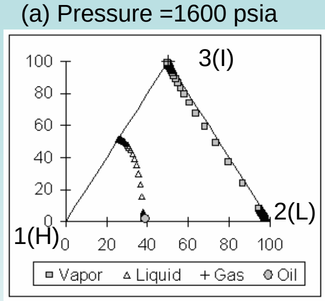


Multiple Contact Miscibility—CO_2 Injection

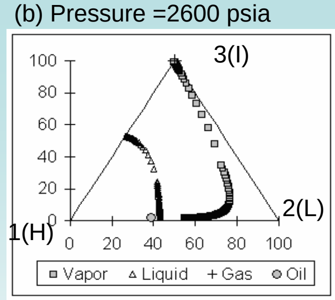
- To investigate the miscibility condition for the mixture of West Sak crude and 100% CO_2, the miscibility prediction were obtained by using tuned PR-EOS
- Pseudo-ternary diagrams are used to describe for West Sak crude in CO_2 injection process

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP 13

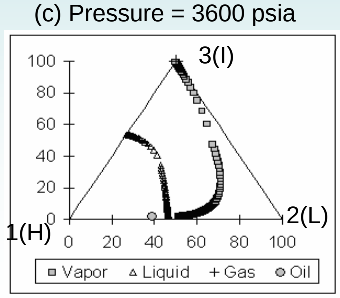
(a) Pressure =1600 psia



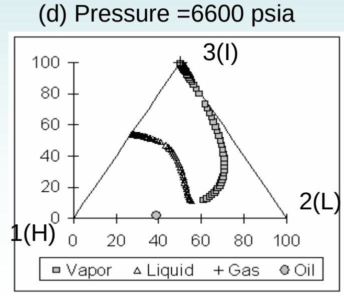
(b) Pressure =2600 psia



(c) Pressure = 3600 psia



(d) Pressure =6600 psia



Component 1: C7+ as the heavy fraction (H)
Component 2: N2,C1 as the light fraction (L)
Component 3 : C2,C3,C4,C5,C6,CO2 as the intermediate fraction (I)

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP 14

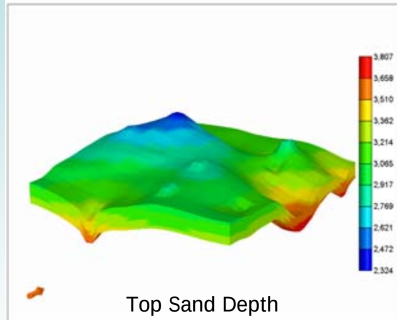
West Sak Reservoir and Properties

Area around 260 sq. miles

Oil gravity 14–22.5 API

Porosity up to 38%

Permeability 10–140 md



Drawn using well log data by Panda et al. (1988) and geostatistical tool

Due to the vast nature of the West Sak Pool, only small portion of the reservoir was selected for the simulation study

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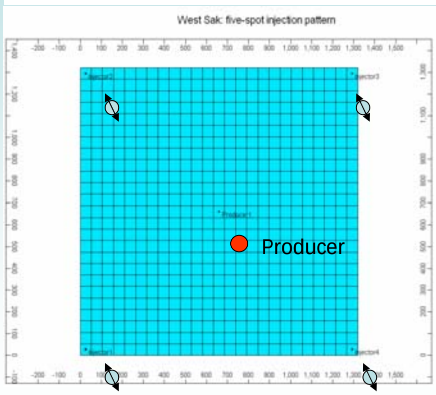
Injection Pattern in CMG's GEM (Compositional Model)

West Sak five-spot CO_2 injection pattern



- Five sand layers separated by shale layers
- Avg. petrophysical properties were obtained from Bakshi (1991)
- Previously tuned equation-of-state was put into the model
- CO_2 was continuously injected into the reservoir for 24 years

25 x 25 x 9 Cartesian model: 40 acre area

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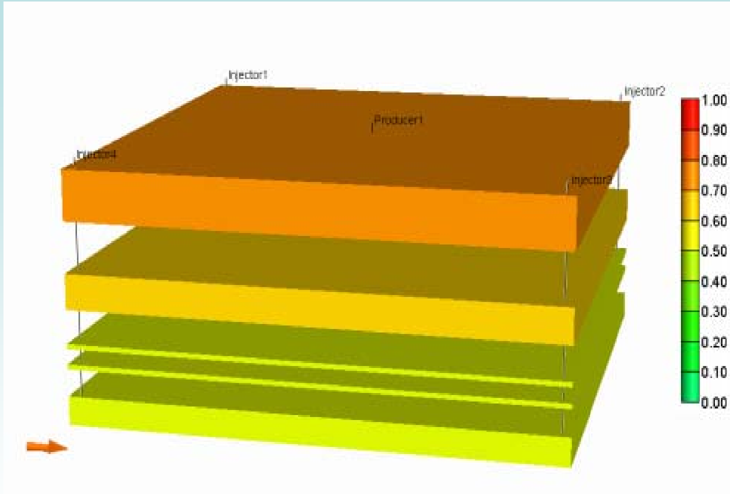
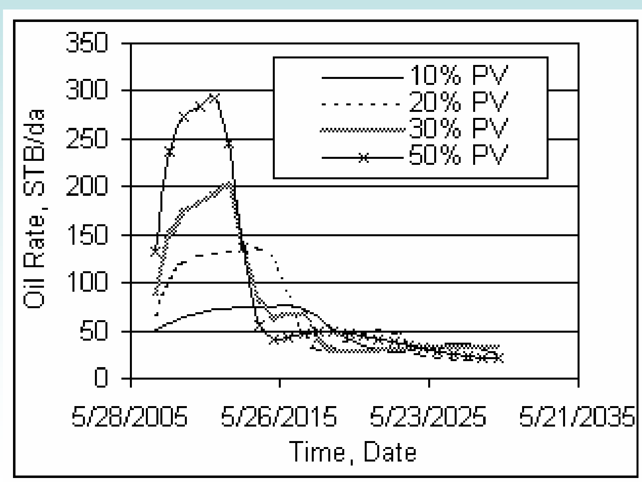
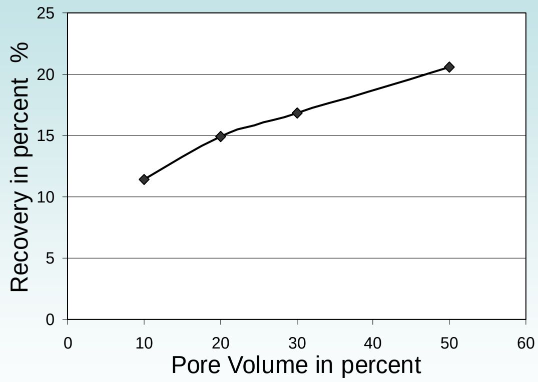


Changes in oil saturation for 0.2 PV

Pore Volume and Oil Rate



Pore Volume and Oil Recovery for 24-Year CO_2 Injection



Increase in injection pore volume increased the oil rate and % recovery (OOIP= 4.015MM STB), but it led to early onset of breakthrough

Summary of Injection at 24-Year Period

% PV	% Recovery	CO_2 Injected, million standard cubic ft	CO_2 Produced, million standard cubic ft	CO_2 Storage Ratio
10	11.40	1.598	0.075	0.95
20	14.93	3.196	1.009	0.68
30	16.82	4.841	2.327	0.52
50	20.62	8.040	4.981	0.38

For 50% pore volume of CO_2 injection was found to be 9.709 Mscf/STB of oil produced

Oil production and corresponding CO_2 storage for 0.5 PV was considered for economical modeling for CO_2-EOR

Economic Model

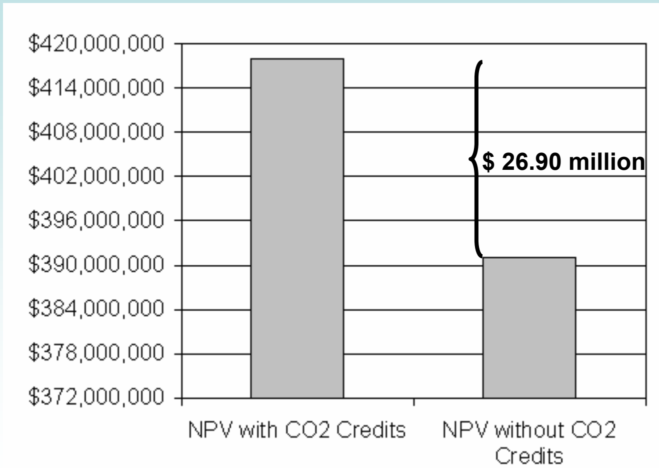
- To evaluate the feasibility of the CO_2 sequestration with EOR
- Costs for each stage of the CO_2-EOR project includes
  - CAPEX: Capital Expenditures
  - OPEX: Operating Expenditures
- Annual net cash flow (NCF), as given by Gasper et al. (2005), was used to calculate the net present value (NPV) of the EOR project
- NCF= (Gross Revenue+ CO_2 credits- Royalty-OPEX-Annual drilling or completion cost (if any)-Depreciation)*(1-Corporate tax) + Depreciation-CAPEX

Economic Model

- 40 X 75 (3000) acre area to justify the construction of pipeline as well as CO_2 compression unit and other facilities
- Stored CO_2 will be 75 times the 40 acre flood pattern = 1.37 million tons per year for 50% PV scenario

Parameter	Assumed Value for NPV
Oil Price (US $/bbl)	50
Project Life (years)	25
Royalty	12.50%
Corporate Tax	35%
Discount Rate	12%
Rent	$12/acre
Storage Ratio	38 %
CO_2 Credits (US $/ton CO_2)	10
Capture Cost (US $/ton CO_2)	3
Compression Cost (US $/ton$CO_2$)	7.5
Transportation Cost (US $/ton CO_2)	8
Storage Cost (US $/ton CO_2)	3

Comparison of NPV



Increasing with CO_2 in terms of PV can lead to more NPV with CO_2 credits as long as no leakage conditions are present

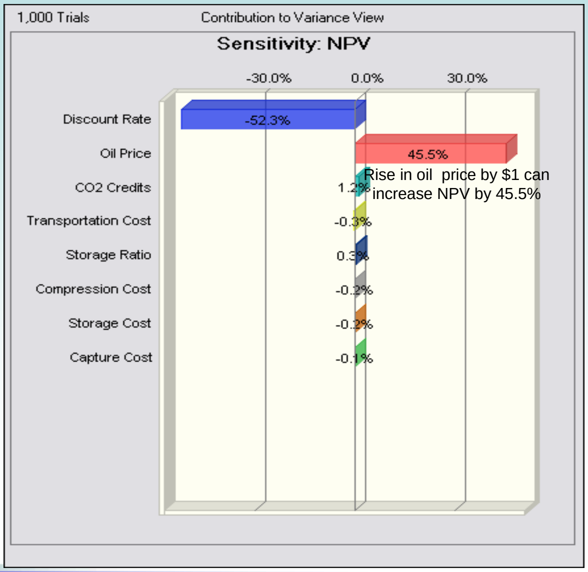
Economic Model

Parameters for Sensitivity Analysis

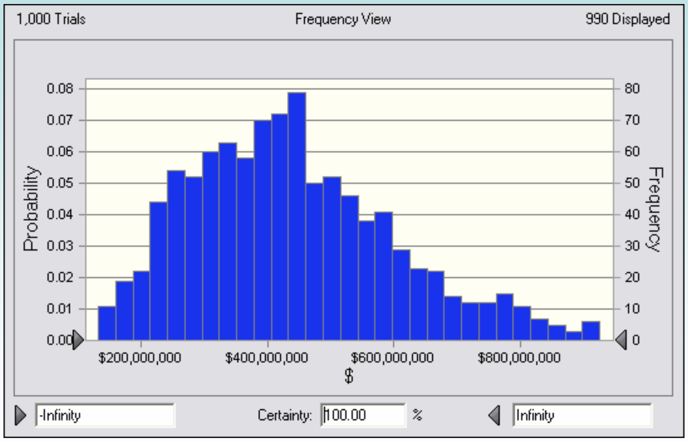
Variable	Distribution	Parameter Values
Discount Rate	lognormal	Mean = 12%; standard deviation =4%
Oil Price	lognormal	Mean = 50; standard deviation =10
CO_2 Credits	lognormal	Mean = 10;standard deviation =5
Storage Cost	triangular	1.5; 3; 4.5
Capture Cost	triangular	1.5; 3; 4.5
Compression Cost	triangular	6; 7.5; 9
Storage Ratio	normal	Mean = 37%; standard deviation = 10%
Transportation Cost	triangular	6; 8; 10

Source: Gaspar et al. (2005)

Sensitivity Analysis of NPV Using Monte Carlo Simulation



Probability Distribution



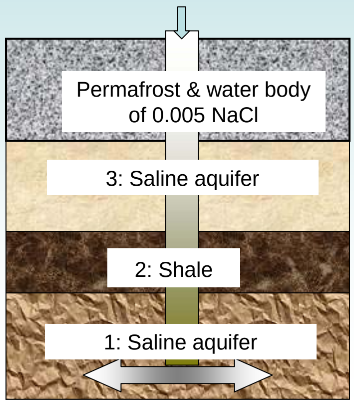
Probability distribution shows mean of the NPV would be around US$0.44 billion

Use of STOMP-WCSE

CO_2 injected was injected in the bottom layer for 10 years (3650 days): 4.4 lb/s

Purpose: To study temperature profile and its impact on CO_2 solubility

2-d 42 by 28 radial model

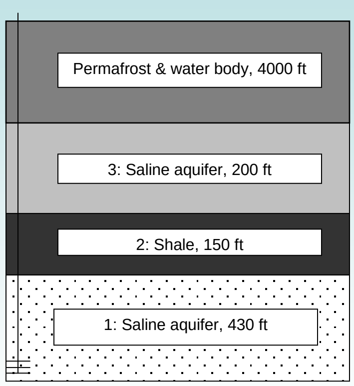


Properties of CO_2 at 45°C

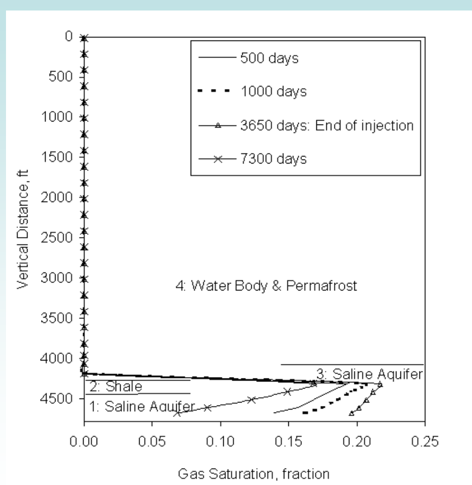
P (bar) / fluid phase	120	160
pure water		
density (kg/m3)	994.768	996.292
viscosity (Pa s)	5.97778e-4	5.98341e-4
water with CO2		
density (kg/m3)	994.768	996.292
viscosity (Pa s)	5.97778e-4	5.98341e-4
CO2 mass fraction	5.22541e-2	5.70921e-2
gas		
density (kg/m3)	658.574	760.891
viscosity (Pa s)	5.16820e-5	6.56320e-5
water mass fraction	9.93985e-5	8.60323e-5

Source: PNNL

Results of CO_2 Injection Studies

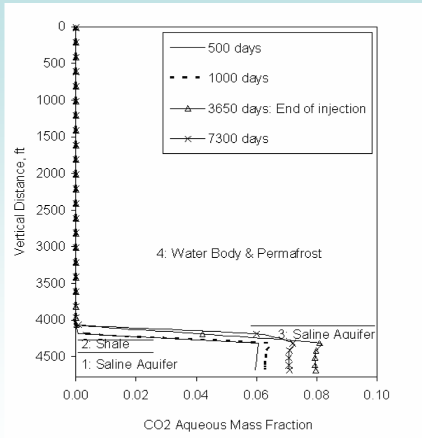


Two-dimensional cylindrical model used in Subsurface Transport Over Multiple Phases®-Water-CO_2-NaCl-Energy (STOMP®-WCSE).

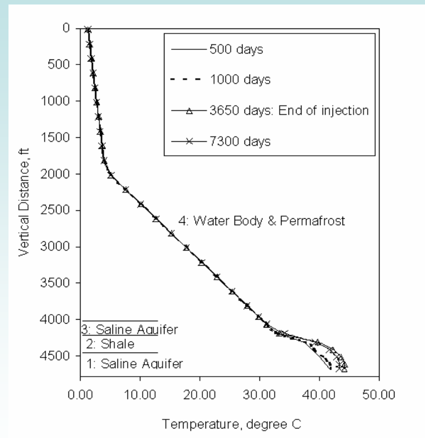


Gas saturation at a horizontal distance of 280 ft from the injection well.

Results of CO_2 Injection Studies (cont'd.)



CO_2 aqueous fraction at a horizontal distance of 280 ft from an injection well



Temperature profile at a horizontal distance of 280 ft from an injection well

Conclusions

- Weight-assigned parameters such as temperature, pressure, and average petrophysical properties of the oil pools are important in carrying out rudimentary screening of potential oil pools on the ANS with respect to their amenability to CO_2-EOR.
- At the reservoir pressures typical of the West Sak oil pool, the presence of partial miscibility can be determined through phase-behavior study.
- Oil recovery by continuous CO_2 injection for 25 years predicted 20.62% oil recovery when 50% PV of CO_2 was injected. An increase in PV led to a decrease in CO_2 storage ratio.
- Economic analysis of CO_2-EOR proved to be important in estimating the time value of the project. The NPV of the project with CO_2 credits was found to be higher by US$26.90 million than NPV without CO_2 credits.
- At a rate of 4.40 lb/sec, a saline aquifer can successfully sequester CO_2 with no leakage. Changes in the temperature profile were negligible when supercritical CO_2 was injected in a saline formation with a NaCl mass fraction of 0.05.