Overview of the CO_2 Capture Project (CCP) Phase 2 Storage, Monitoring and Verification Program

CCP1 (2000-2004) Accomplishments

- The CCP2 - SMV program is building on the success of CCP1
- CCP1 identified and developed technologies applicable to the:
  - ***Integrity*** of geological and engineered systems
  - ***Optimization*** of processes and economic assets
  - ***Monitoring*** for performance and leakage
  - ***Risk assessment***

Integrity

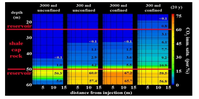
Natural and Engineered Analogs
- CO_2 Reservoirs (ARI)
- Leaky Systems (Utah State)
- Natural Gas Storage Experience (GTI)

Reservoir and Cap Rock Competence
- CO_2/Rock Changes at Reservoir P&T (GFZ-Potsdam)
- Reactive Transport Modeling (LLNL)

Well Materials
- Cement/Steel Corrosion/ Erosion (SINTEF)

Natural geyser system in East-Central Utah

Geochemical and geomechanical response to CO_2 injection



Conclusion: 3D geologic models combined with fluid history models address geological integrity, although geomechanical effects remain a concern. Well Integrity is more of a concern than geologic integrity.

Optimization

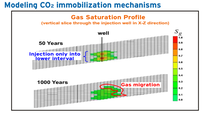
Hydrocarbon Reservoirs
- CO_2 EOR Record (NMT)
- Gas and Condensate Compatibility (TTU)

Coal Reservoirs
- CBM Potential and CO_2 Capacity (INEL)

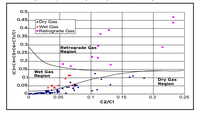
Saline Aquifer Reservoirs
- CO_2 Movement and Immobilization (UT)

Transportation
- Corrosion and Materials Selection (IFE/Reinertsen)
- CO_2 Impurities (Battelle)

Modeling CO_2 immobilization mechanisms



Assessing compatibility of hydrocarbon gases and CO_2



Conclusion: Simulation method development that tests avoidance of excessive CO_2 exposure to vulnerable features requires further work. New methods for CO_2 enhanced recovery are necessary to take advantage of economic offsets.

Monitoring

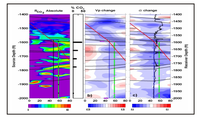
Geophysical
- Seismic Resolution and Modeling (TNO)
- Seismic Resolution and Costs (LBNL)
- Novel Non-Seismic (LBNL)

Geochemical
- Noble Gas Tracers and Costs (LLNL)

Satellite and Aerial
- InSAR Resolution (Stanford)
- Hyperspectral Geobotanical (LLNL)

Near Surface and Atmosphere
- State-of-the-Art and Strategies (Caltech)
- Eddy Covariance (Penn State)

Image Enhancement Using EM



Aerial hyperspectral image of Rangely CO_2 EOR Field, Colorado

Conclusion: Technology exists to monitor CO_2 flood performance and leakage but there are opportunities to reduce costs and improve resolution.

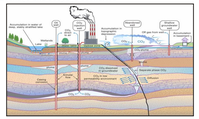
Risk Assessment

Comprehensive Methodologies
- Tools, Scenarios, Models (TNO, INEL)
- Testing On and Offshore Aquifers (TNO)
- Leakage Risk and Failure Scenarios (INEL)

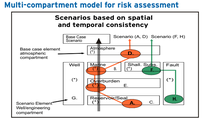
Mitigation and Remediation
- Leak Scenarios and Response (LBNL)

NGO/Regulatory/Public Perception
- HSE Review (LBNL)
- Effect on Subsurface Ecosystems (LBNL)
- Lessons on Honesty and Transparency (MSCI)

Leakage and seepage scenarios



Multi-compartment model for risk assessment



Conclusion: Methodology development should be simplified and benchmarked while incorporating input from stakeholders. A link needs to be established between the technical assessment of risk and regulatory/policy development.

CCP2 (2005-2008) Objectives

- CCP2 - SMV projects aim to:
  - Ready potentially cost effective technologies for deployment
  - Systematize site assessment and protocols
  - Address emerging issues in CO_2 storage

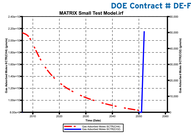
Operational Parameters

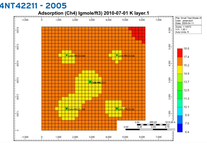
Operability of ECBM

Coal bed methane (CBM) recovery might be enhanced by CO_2 via desorption of methane and adsorption of CO_2 (~2X). The low permeability and reactivity of coal, however, introduce injectivity and conformance complications.

Simulation of CO_2 flooding using data from the Blue Creek Field (Alabama) is applied to optimize injection-production rate while avoiding formation damage and cap rock breaching.

DOE Contract # DE-FC26-04NT42211 - 2005



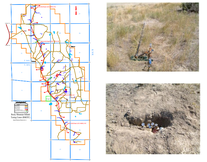


Monitoring

Remote (Aerial) Detection of CO_2 and Methane

Monitoring CO_2 leakage to the surface over field-scale areas will introduce considerable operating and post-closure expenses to CO_2 storage projects.

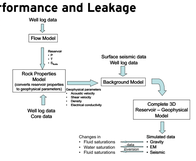
Remote (satellite and aerial) sensing of CO_2 and methane will be a potential solution if sensors capable of directly detecting both gases are developed. This project will test such a modified sensor using aerial field surveys over controlled leaks.



Novel Geophysical Monitoring of ECBM Performance and Leakage

Seismic monitoring might add significant expense to low margin operations such as CO2 ECBM and may not be applicable in some settings.

The resolution of low cost novel non-seismic geophysical techniques (EM and SP) will be simulated using data from the Blue Creek Field (Alabama).

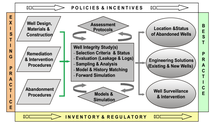


Well Integrity

Well Integrity has become the premier containment issue in geological storage of CO_2. A comprehensive well field study is proposed to evaluate well condition, predict survivability and identify engineering solutions.

- Selection (production/workover records, operational status)
- Characterization (logging tools)
- Fluids and solids sampling (casing, cement and country rock)
- Materials alteration (petrographic and geochemical analysis)
- Chemical kinetics (exposure experiments)
- Chemical modeling (fluid proxy inference of cement condition)
- 3D model of well with reconstruction of alteration history
- Simulation of well fate over an extended amount of time
- Recommendations on well design or materials and new approaches to remediation and intervention

Comprehensive Well Integrity Program

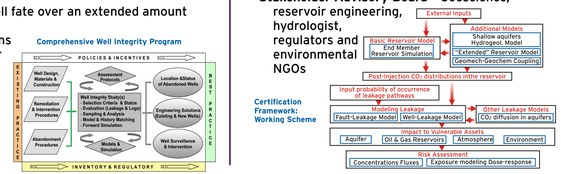


Certification Framework

At present, site selection criteria, reservoir simulation approaches and risk assessment methodologies are fragmented and vary in complexity. The "Certification Framework" is a streamlined, life-cycle approach to project certification (pre-operation, operation and decommissioning) aimed at meeting regulatory expectations.

External Inputs - Basic reservoir and additional model components
Post-injection CO_2 Distribution - Reservoir simulation
Leakage Model - Scenarios with probabilities
Impact - Effect of CO_2 on assets
Risk Assessment - Flux models and dose effects
Stakeholder Advisory Board - Geoscience, reservoir engineering, hydrologist, regulators and environmental NGOs

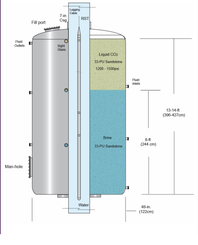
Certification Framework: Working Scheme



Well-based In-situ Detection of CO_2

A novel well design that allows subsurface CO_2 accumulation, using conventional logging tools (e.g., RST) for detection. A pressurized vessel containing water-saturated sand will be injected with supercritical and vapor phase CO_2.

Custom Tank Experimental Setup



Coupled Geochemical-Geomechanical Simulation

Injection of CO_2 in reservoirs results in pressure increases which can fracture reservoir rock or breach cap rocks.

The coupled geochemical-geomechanical simulation tests the extent to which the aperture opening effect (permeability increase) of pressure can be counteracted by geochemical reactions that act to reduce pressure increase.

CCP2 Path Forward

- The CCP2 - SMV team has developed a slate of projects to:
  - Develop key operational and monitoring strategies specific to coal beds.
  - Address CO_2 containment issues for wells and reservoir seals.
  - Develop a simplified tool for lifecycle monitoring and decommissioning schemes.
- Protocols and developed technologies will be tested through appropriate collaborative pilot or demonstration projects
- The CCP2 - SMV Policies & Incentives team and stakeholders will continue to be engaged to ensure that technology development remains relevant through the project timeframe

CCP2 Member Companies

bp, Chevron, ConocoPhillips, Eni, Hydro, Petrobras, Shell, Suncor

Support received from

US Department Of Energy, European Union, Norgesforskningsråd

Technical Providers

- Certification Framework
  - Lawrence Berkeley
  - UT Austin
- Coupled Geochemical-Geomechanical Simulation
  - U of Bergen
- ECBM Simulations
  - Sproule Associates
- Novel geophysical detection methods
  - Lawrence Berkeley
- Aerial Hyperspectral Detection
  - UC Santa Cruz
- Well-based in-situ Detection of CO_2
  - Schlumberger

Overview of the CO_2 Capture Project (CCP) Phase 2 Storage, Monitoring, and Verification Program (Paper O61)

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Petrobras - Rodolfo Dino
Shell - Nigel Jenvey
ConocoPhillips - Alan Rezigh
Hydro - Lars Ingolf Eide

Technologies

CO_2 Capture Project

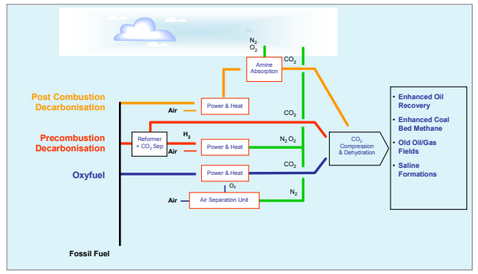
The CO_2 Capture Project – Capture Technology Program for Phase 2

FIFTH ANNUAL CONFERENCE ON
Carbon Capture & Sequestration
Taking Steps Toward Deployment
May 8 - 11, 2006 | Hilton Alexandria Mark Center | Alexandria, VA

Cooperating for a Better Environment The CO_2 Capture Project:

- Is an international industry/government partnership, including 8 of the world's leading energy companies and 3 governments.
- Develops BREAKTHROUGH TECHNOLOGIES to reduce the cost of CO_2 capture.
- Is a 3-phase program, just beginning Phase 2 (2005-2008), developing technology performance with $25mm in funding.
- Working to demonstrate storage is safe, measurable and verifiable.
- Involving other interested parties in the NGO community.

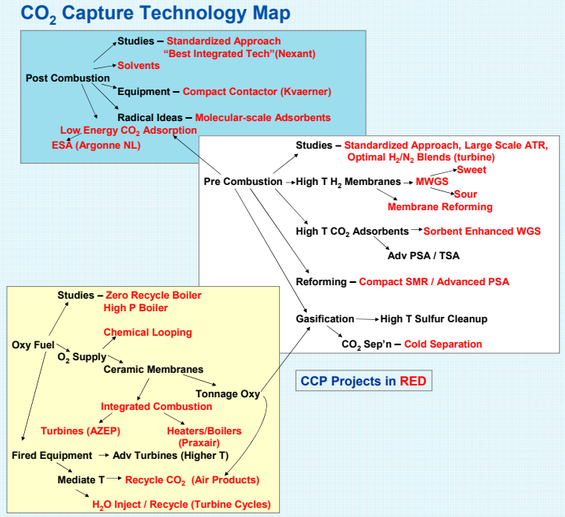
There are Three Broad Approaches to CO_2 Capture



Phase 1 Accomplishments (2000–2004)

More than 100 technology ideas screened

CO_2 Capture Technology Map

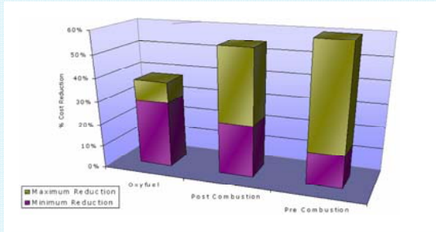


Phase 1 Results: Progress in Reducing Capture Costs

CCP has progressed the development of a range of technologies for Capture of CO_2

1. Capture of CO_2 in exhaust gases from combustion sources, such as power plants. This technology can be retrofitted to existing equipment. **(Post-combustion)**
   - **Membrane Contactor**
   - **Gas Turbines with Flue Gas Recycle**
2. Conversion of natural gas to hydrogen and burning of hydrogen, generating nitrogen and water with CO_2 captured for storage. **(Pre-combustion)**
   - **Advanced Syngas Regeneration**
   - **Thermal Reforming**
   - **Hydrogen Membranes**
   - **Adsorbents**
3. Separation of oxygen from air and pure oxygen used to burn fuels, resulting in CO_2 for storage. **(Oxy-fuel combustion)**
   - **High T Membrane Separation**
   - **Chemical Looping / Metal Oxide Redox Cycles**

Cost Reduction Achieved Relative to Status in Year 2000

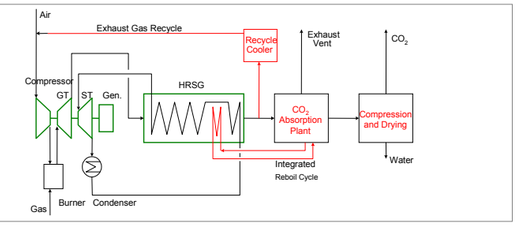


CCP Phase 2 Plans (2005–2008): Building on the Success of Phase 1

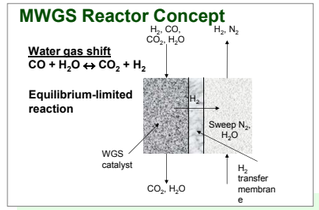
Project Objectives for Phase 2

- Undertake additional research, development and pilot testing to reduce cost of CO_2 capture from large fixed sources.
- Reduce technology and cost uncertainty associated with those technologies and deliver low-cost CO_2 capture technologies to demonstration stage by 2009.
- Demonstrate that the geological storage of CO_2 is secure and can represent a viable Greenhouse Gas mitigation technique. Further develop technology, best practice and industry standards for storage site evaluation, risk assessment, well integrity, monitoring and verification.
- Establish an extended network for CO_2 storage demonstrations to share learning and best practice.

Best Integrated Technology for Power Gen or "BIT"



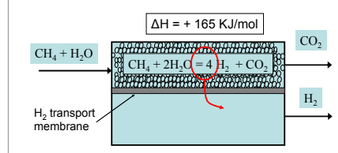
MWGS Reactor Concept



SEWGS Concept

- Uses high temperature CO_2 adsorbent in presence of WGS catalyst
- Drives equilibrium by "removing" CO_2
- Regenerated by heating
- Cyclic bed concept

H_2 Membrane Reformer Concept



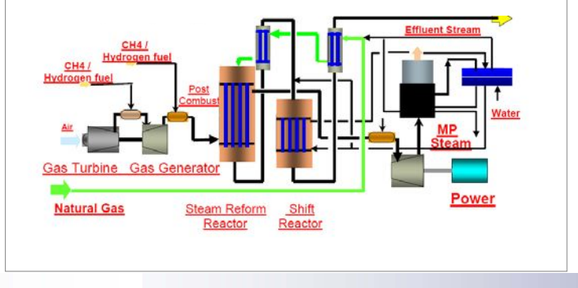
- Combination of reforming reactor and separation
- Extract product gas (H_2) from reactor, no traditional CO_2 removal system required
- **Drive equilibrium limited reactions** towards completion
- Expand allowed range of temperatures and pressures

Phase 2 Capture Goal:

Further reducing costs of capture technologies to be ready for demonstration in 2009 with broad applications

Priority	Technology
Near Term	Sorption Enhanced Water Gas Shift Best Integrated Technology
Mid-term Priority	Chemical Looping
Long-term Priority	Hydrogen Membrane Reactor Novel Technologies

Integrated SMR and Power Generation

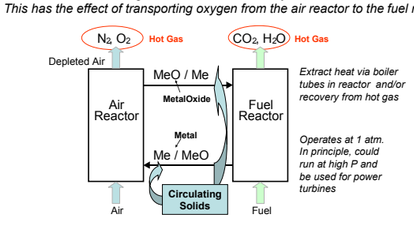


Chemical Looping Reforming or H_2 Production

- Extends the Chemical Looping concept to production of syngas or hydrogen
- One concept looks like CLC, but achieves partial oxidation to make syngas in the "fuel reactor"
- Another concept uses metal oxide that can be oxidized with steam, in order to produce H_2 directly

Chemical Looping Combustion

BASIC IDEA: Circulating solids that are alternately reduced and oxidized. This has the effect of transporting oxygen from the air reactor to the fuel reactor.



- CCP-funded work in Europe, led by Chalmers University (Sweden) and Altom Power, confirmed workability of chemical looping combustion
- Operated as an integrated pilot unit with NiO carrier at 30KW scale

Private/public project partners and co-funders:

bp, ConocoPhillips, Chevron, Eni, Hydro, Petrobras, Shell, Suncor, European Union, Norges forskningsrad, U.S. Department of Energy

Poster Authors:
Karl Gerdes, presenter – Chevron • Ivano Miracca – Snamprogetti SpA • Linda Curran – BP • Cliff Lowe – Chevron •
Gustavo Moure – Petrobras • Jan Assink – Shell • Cal Coulter – Suncor • Steven Schlasner – ConocoPhillips • Torgeir Melien – Hydro

For more information, visit web site at www.CO2captureproject.org
Or contact Linda M. Curran, CCP Program Manager
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Modeling CO2 plume evolution in oil reservoirs using parallel computing

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Abstract

CO2 sequestration (capture, separation, and long term storage) in various geologic media (such as depleted oil reservoirs, saline aquifers, oceanic sediments) is a possible solution to reduce green house gas emissions. In this study we utilize the PFLOTRAN simulator to investigate geologic sequestration of CO2. PFLOTRAN is a massively parallel 3-D reservoir simulator for modeling subsurface multiphase (CO2, H2O), and multicomponent reactive flow and transport based on continuum scale mass and energy conservation equations. PFLOTRAN has an efficient and modular mechanism to handle variable switching during multiphase transitions, bringing great flexibility in choosing the set of primary variables, addition of new EoS, mixing rules, etc. The multiphase flow equations are sequentially coupled to reactive transport equations describing multi-component chemical reactions within the formation. These reactions consist of aqueous speciation, and precipitation and dissolution of minerals including CO2-bearing phases to describe aqueous and mineral CO2 sequestration. The effect of the injected CO2 on pH, CO2 concentration within the aqueous phase, mineral stability, and other factors can be evaluated with this model. This work is focused on complex density driven flow patterns within both CO2-rich and aqueous phases, and their effect on the long-term containment of injected supercritical CO2. The efficiency of sequestration processes could be affected by many factors, including variations in fluid properties caused by CO2 dissolution and reservoir salinity, changes in geochemical and geophysical properties caused by mineral dissolution and precipitation, etc. This investigation will help provide criteria for site selection and to investigate leakage rates of CO2 to the surface.

PFLOTRAN: Parallel Flow and Reactive Transport

Mathematical Formulation

PFLOTRAN consists of two distinct modules: a mass and energy flow code (PFLOW) and a reactive transport code (PTRAN). The module PFLOW solves mass conservation equations for water and other fluids and an energy balance equation. The module PTRAN solves mass conservation equations for a multicomponent geochemical system. The reactions included in PTRAN involve aqueous species and minerals which can be written in the general form:

$$\sum_i \nu_{ji} A_i \Leftrightarrow A_j \qquad \text{and} \qquad \sum_i \nu_{jm} A_i \Leftrightarrow M_m$$

respectively, where the set of species $\{A_i\}$ refer to a set of primary or basis species in terms of which all other species are written, A_j denotes an aqueous complex referred to as a secondary species, M_m refers to a mineral, and ν_{ji} and ν_{jm} are reaction stoichiometric coefficients derived from an extensive database. The architecture is shown in the right figure.

Mass Conservation: Flow Equations

$$\frac{\partial}{\partial t}\left(\phi s_\alpha \rho_\alpha X_i^\alpha\right) + \nabla\cdot\left[q_\alpha \rho_\alpha X_i^\alpha - \phi s_\alpha D_i^\alpha \rho_\alpha \nabla X_i^\alpha\right] = Q_i^\alpha$$

$$q_\alpha = -\frac{kk_{r\alpha}}{\mu_\alpha}\nabla(p_\alpha - W_\alpha \rho_\alpha g z) \qquad p_\alpha = p_\beta - p_{c,\alpha\beta}$$

Energy Conservation Equation

$$\frac{\partial}{\partial t}\left[\phi\sum_\alpha s_\alpha \rho_\alpha U_\alpha + (1-\phi)\rho_r c_r T\right] + \nabla\cdot\left[\sum_\alpha q_\alpha \rho_\alpha H_\alpha - \kappa\nabla T\right] = Q_e$$

Multicomponent Reactive Transport Equations

$$\frac{\partial}{\partial t}\left[\phi\sum_\alpha S_\alpha \Psi_j^\alpha\right] + \nabla\cdot\left[\sum_\alpha \Omega_{j\alpha}\right] = -\sum_m \nu_{jm} I_m + Q_j$$

Total Concentration

$$\Psi_j^\alpha = \delta_{j\alpha} C_j^\alpha + \sum_i \nu_{ji} C_i^\alpha$$

Total Solute Flux

$$\Omega_j^\alpha = \left(-\tau\phi s_\alpha D_\alpha \nabla + q_\alpha\right)\Psi_j^\alpha$$

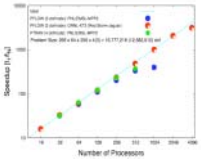
Mineral Mass Transfer Equation

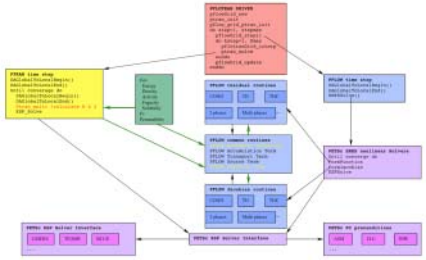
$$\frac{\partial \phi_m}{\partial t} = V_m I_m \qquad \phi + \sum_m \phi_m = 1$$

System closure is accomplished by combining these equations with other auxiliary equations and EoS of phases. Most current EoS, solubility and relative permeability formula were implemented to ensure accuracy, such as Span-Wanger formula for supercritical CO2 phase properties, etc.

Performance and scalability

PFLOTRAN been designed from scratch with parallel scalability in mind, and it displays excellent scaling characteristics on modern supercomputers. The figure at right shows the performance of PFLOW running a one phase thermohydrologic bench mark problem on a 256 x 64 x 256 grid with three degrees of freedom per node (approximately 12.6 million degrees of freedom total). The bench mark was run on both the MPP2 cluster at PNNL/EMSL, a cluster of 1960 1.5 GHz Itanium 2 processors with Quadrics QsNe tII interconnect, and Jaguar, the 5200 Opteron processor Cray XT3 at ORNL/NCCS. PFLOW scales quite well on both machines, bottoming out at around 1024 processors on MPP2, and scaling exceptionally well on Jaguar, displaying linear speedup all the way up to 2048 processors, and still displaying modest speedup when going from there to 4096 processors.





Architecture of PFLOTRAN

Variable switching and phase transition

PFLOW assumes all components exist in system are partly miscible, The solubility is governed by a modified Henry's Law. It employs the commonly used variable switching method to choose certain numbers of primary variables according to Gibbs phase law, resulting in $n_{dof} = n_{comp} + 1$. With this method, the set of primary variables varies for every possible phase combinations in 2^{Np}-1 cases, as listed in the table below. Other thermodynamic properties are derived from the primary variables through constraints and equilibrium relations.
Phase transition rules are one of the crucial aspects for implementing the variable switching method. A generic rule to determine if a new phase p forms is that the summation of all mole fractions in the new phase exceeds one, as evaluated from existing phases by pseudo equilibrium, $\sum X_p^i > 1$; a phase disappears if its saturation is less than zero, $S_p < 0$.

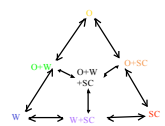
In the numerical implementation, a relaxation method is needed to reduce oscillations and improve performance. Examples below show phase transition diagrams for 3 and 4 phase systems and the selection of primary variables for a 3-phase 3-component system.

Example: 3 components (H2O, CO2, C10H22), 3 phases (Water, Supercritical CO2, oil) system

Primary variable set

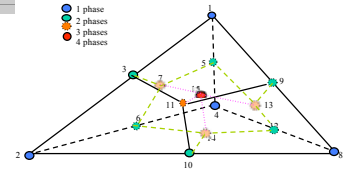
Case	Phase condition	Primary Variables
1	W	$P, T, X_G^{CO2}, X_G^{C10}$
2	G	$P, T, X_W^{CO2}, X_G^{C10}$
3	W+G	P, T, S_W, X_G^{CO2}
4	O	$P, T, X_W^{CO2}, X_W^{C10}$
5	O+W	P, T, S_W, X_W^{CO2}
6	O+G	P, T, S_G, X_G^{CO2}
7	O+W+G	P, T, S_W, S_G

Phase transition diagram



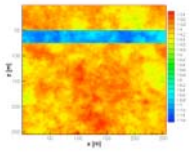
Example: 4 phase system(P1, P2, P3, P4), phase transition diagram

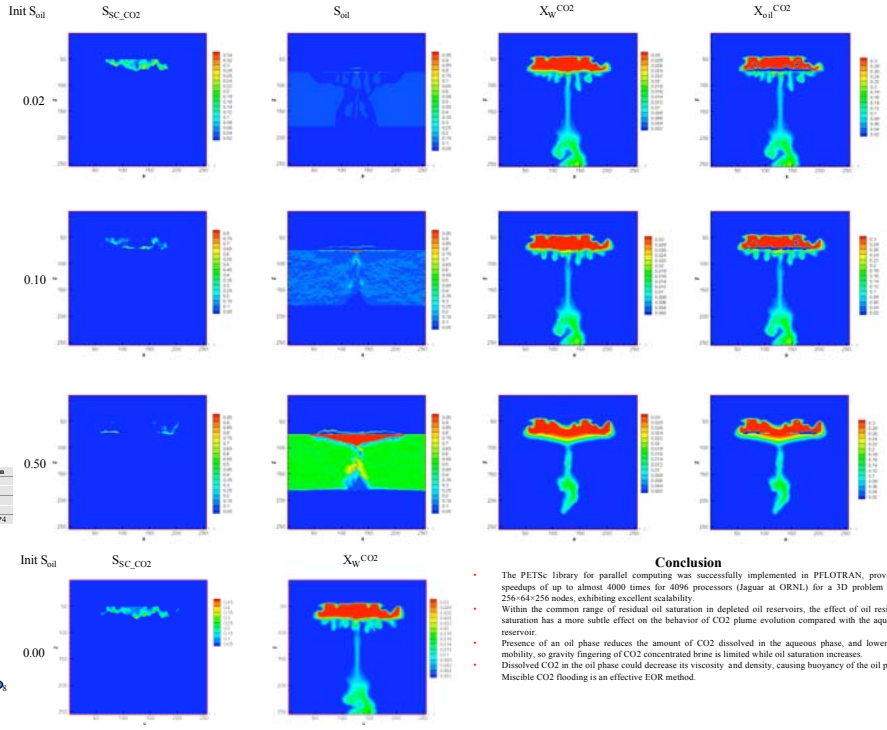
Case	Phase Condition	Case	Phase Condition	Case	Phase Condition
1	P1	6	P2 + P3	11	P1 + P2 +P4
2	P2	7	P1 + P2 + P3	12	P3 + P4
3	P1 + P2	8	P4	13	P1 + P3 + P4
4	P3	9	P1 + P4	14	P2 + P3 + P4
5	P1 + P3	10	P2 + P4	15	P1 + P2 + P3 + P4

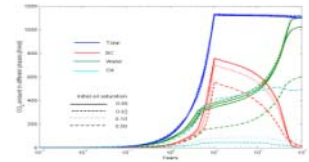


Numerical Simulation

The simulation was conducted for a 2D domain with dimensions 256 x 256m on a uniform grid with 1 x 1m spacing using a random permeability field containing 3 uncorrelated layers with 50m, 25m and 181m thickness, from top to bottom. The log-normal distributed random field is generated by the sequential Gaussian random field generator sgsim from GSLIB, with correlation length 20 m, zero mean and variance 0.25. The values are scaled with the mean permeability of each layer with 10-2, 10-5, 10-2 Darcy, as shown on the right panel. CO2 is injected for 10 years with the rate 1.6x10-4 kg/s at the center of the domain at a depth of 140m.
The initial residual oil is located at depths ranging from 75m to 180m, horizontally across the whole domain. Four cases with different initial oil saturation (0, 0.02, 0.10 ,0.50) are investigated. Outside the dominant oil region, the oil saturation is set to a small value (1x10-4), except for the first case, in which the oil residual is zero everywhere.The relative permeability is determined by linear interpolation. No capillary effect is considered.
Snapshots of saturation and concentration at 400 years are shown in the right panel.







Distribution of CO2 in phases

Conclusion

- The PETSc library for parallel computing was successfully implemented in PFLOTRAN, providing speedups of up to almost 4000 times for 4096 processors (Jaguar at ORNL) for a 3D problem with 256×64×256 nodes, exhibiting excellent scalability.
- Within the common range of residual oil saturation in depleted oil reservoirs, the effect of oil residual saturation has a more subtle effect on the behavior of CO2 plume evolution compared with the aqueous reservoir.
- Presence of an oil phase reduces the amount of CO2 dissolved in the aqueous phase, and lowers its mobility, so gravity fingering of CO2 concentrated brine is limited while oil saturation increases.
- Dissolved CO2 in the oil phase could decrease its viscosity and density, causing buoyancy of the oil phase. Miscible CO2 flooding is an effective EOR method.

Acknowledgements

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