Carbon Management and Underground Coal Gasification

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Conclusions regarding UCG and CCS

Important synergies between UCG and CCS

Low-cost syngas provides cost-competitive opportunities for CO$_2$ capture & separation

Siting, monitoring, and key hazard assessment requirements for UCG support CCS and visa versa

Commercial-scale demos possible

CO$_2$ storage in the cavity is not commercially ready

Best Practices in Underground Coal Gasification: Pending DOE-FE Report

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344
Underground coal gasification produces syngas with low capital and low operating cost.

Gasification occurs in situ. The technology is well tested >40 years.

Environmental benefits
- No mining
- Much less pollution (no SO$_x$, NO$_x$; less mercury, particulates)
- Low-cost H$_2$ production

Economic benefits
- No gasifier purchase, operation
- No coal purchase or transport
- Low-cost power generation

Carbon Management
- Lower cost CO$_2$ separation
- Good coincidence between UCG and sequestration sites
DOE/LLNL has been active in UCG for over three decades

- Invented the CRIP (controlled retractable injection point) process (1974-1985)
- Conducted a number of field tests (Hoe Creek, Hanna, Centralia)
- Developed cavity growth models (Thorseness and Britten, 1989)
- Developed a CFD-based model of the UCG process and integrated it with Aspen Plus (Wallman 2004)
- Currently expanding the CFD model to include additional phenomenology
- Developed a large suite of tools for environmental assessment
- Developed methodologies for process control monitoring
- Applied carbon management and CO₂ sequestration expertise to UCG (Blinderman & Friedmann, 2006)
Carbon dioxide can be stored in geological targets, usually as a supercritical phase.

Carbon capture and storage (CCS) has emerged as a new field aimed at reducing greenhouse gas emissions, chiefly CO$_2$, through geological sequestration.

Saline Aquifers
Depleted Oil & Gas fields (w/ or w/o EOR and EGR)
Unmineable Coal Seams (w/ or w/o ECBM)

These formations are likely to be found near coal seams chosen for UCG.

Competitive carbon-capture economics and coincidence of storage targets make UCG + CCS an attractive carbon management package.
CO₂ Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions

- A key portfolio component
- Cost competitive to other carbon-free options
- Uses proven technology
- Applies to existing and new plants
- Room for cost reductions (50-80%)

Pacala & Socolow, 2004
Carbon management requires both CO$_2$ capture (separation) and CO$_2$ storage

LLNL’s capture program combines conventional & unconventional approaches:

- **Conventional**: ASPEN analysis of surface processes
  - (e.g., Selexol, PSA, water-gas shift)
- **Unconventional**: Advanced membranes, novel engineering concepts (e.g., down-hole water-gas shift)

Our current CO$_2$ storage program focuses on four components:

- **Advanced simulation**: Integrated hydrological, geochemical & geomechanical processes
- **Monitoring and verification**: Technology to detect CO$_2$ and to integrate many monitoring data streams
- **Site characterization**: Capacity estimation, hazard identification and assessment.
- **Risk quantification**: Source-term definition, GIS-based risk screening, constraint of operational protocols
There’s a high coincidence of prospective and highly prospective CO\textsubscript{2} storage sites and UCG sites

Over 33 US, 66 FSU projects, and 20 other international pilots
There’s a high coincidence of prospective and highly prospective CO₂ storage sites and UCG sites

Prior test sites
Announced/planned
Sites of note


By Capacity (MW)

- 0 - 250
- 251 - 1000
- 1001 - 4000

Oil & Gas Fields
Saline Aquifers
Coalbeds

Prior test sites
Sites of note
Announced/planned
UCG provides unique new strategies for carbon capture and separation

Partial decarbonization: CO$_2$ Separation from raw syngas
- conventional (e.g. Selexol)
- downhole: LLNL Proprietary

Full carbon separation
- Pre-combustion (water-gas shift+Selexol)
- Post-combustion (e.g., MEA)
- Air Separation and oxyfiring

Separation Technology:
- Chemical sorption (e.g., amines, selexol, chilled ammonia)
- Cryogenic separation (incl. hydrate separation)
- Pressure Swing Adsorption (e.g., Rectisol)
- Adv. membrane separation (e.g., SLIP, ion-transfer)
Energetics of CO$_2$ removal from UCG syngas

Data from Halmann & Steinberg, 1999

Basis: 100 kg/mole syngas, at 10 atm, produced by oxygen gasification

\[
\begin{align*}
H_2 & \quad 36.1 \\
\text{CO} & \quad 18.5 \\
\text{CO}_2 & \quad 36.1 \\
\text{Other} & \quad 9.3
\end{align*}
\]

Energy content of syngas (@248 BTU/scft) = 57.2*100 = 5720 KWH

$O_2$ used = 27.3 kg moles; Energy needed for $O_2$ = 384 kWH (0.44 kWH/kg $O_2$)

Case 1: No shift, remove CO$_2$ from raw syngas

Removal of CO$_2$ by improved amines absorption (better w/ Selexol):

energy required = 0.11*2.2*36.1*44*.9 = 346 kWH

Total energy penalty for CO$_2$ removal: 346/5720 = 6%

Case 2: Syngas after complete shift: (H$_2$ = 54.6; CO$_2$ = 54.6; Other = 9.3)

Removal of CO$_2$ by improved amines absorption:

energy required = 0.11*2.2*54.6*44*.9 = 524 kWH

Total energy penalty for CO$_2$ removal: 524/5720 = 9%

Case 3: Oxyfired combustion of raw syngas (e.g., in CES power block)

Energy needed for $O_2$ = (0.44*18.1*36) + (0.44*9.25*36) = 438 kWH

$O_2$ required for stoichiometric conversion = 18.1 mole + 9.25 moles $O_2$

Total energy penalty for total $O_2$ production: 438/5720 = 8%
Storage mechanisms are reasonably well understood

Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)
The crust is well configured to trap large CO$_2$ volumes indefinitely.

Because of multiple storage mechanisms working at multiple length and time scale, the shallow crust should attenuate mobile free-phase CO$_2$ plumes, trap them residually, & ultimately dissolve them.

This means that over time risk decreases and permanence increases.

IPCC, 2005
What are the key issues with sequestration as relates to UCG?

- Sequestration resource: How much and where?
- Site selection: What does a specific site need?
  - Injectivity
  - Capacity
  - Effectiveness
- Monitoring & Verification
- Hazards and risks
- **THE MAIN ISSUE IS SCALE!!**
  - Need >1mT/yr injection for 50 – 70 yrs (200 mw power plant)
  - Mechanics– integrity (effectiveness)
  - Affect of heterogeneity – larger volume, more heterogeneities contacted --- performance (capacity, injectivity)
The drive to deployment has brought focus on the life-cycle of CCS operations and its key issues.

Regulators and decision makers will make decisions at key junctures, only some of which are well understood technically.

Operators have to make choices that affect capital deployment and actions on the ground.
Site selection due diligence requires characterization & validation of ICE

**Injectivity**
- Rate of volume injection
- Must be sustainable
  - (test for months – use for years)

**Capacity**
- Bulk (integrated) property
- Total volume estimate
- Sensitive to trapping mechanisms

**Effectiveness**
- Ability for a site to store CO₂
- Long beyond the lifetime of the project
- Most difficult to define or defend

Gasda et al., 2005
Many aspects of CCS site selection have special relevance to UCG site selection

Overlying coals:
- “Fail-safe” filters for CO₂ leaks
- Good UCG containment helps CCS
- Coincidence of thick, deep seams and EOR/Saline Form. units

Infrastructure and economics
- Share pipeline rights of way
- Partial/complete CO2 capture streams for EOR
- Shared monitoring network
- Potential for joint permitting
Once injection begins, monitoring and verification (M&V) is required

**MMV serves these key roles:**
- Understand key features, effects, & processes
- Injection management
- Delineate and identify leakage risk and leakage
- Provide early warnings of failure
- Verify storage for accounting and crediting

**Currently, there are abundant viable tools and methods; however, only a handful of parameters are key**
- Direct fluid sampling via monitoring wells (e.g., U-tube)
- T, P, pH at all wells (e.g., Bragg fiberoptic grating)
- CO$_2$ distribution in space: various proxy measures (Time-lapse seismic clear best in most cases)
- CO$_2$ saturation (eg Electrical Resistance Tomography)
- Surface CO$_2$ changes, direct or proxy (atmospheric eddy towers best direct; LIDAR may surpass)
- Stress changes (tri-axial tensiometers)
Many tools exist to monitor & verify CO₂ plumes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best tool</th>
<th>Other tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid composition</td>
<td>Direct sample</td>
<td>(Surface sampling + simulation)</td>
</tr>
<tr>
<td>T, P fieldwide</td>
<td>Thermocouples &amp; pres. sensors</td>
<td>Fiberoptic Bragg grating</td>
</tr>
<tr>
<td>Subsurface pH monitoring</td>
<td>pH sensors</td>
<td></td>
</tr>
<tr>
<td>CO₂ distribution</td>
<td>Time-lapse seismic</td>
<td>(microseismic, tilt, VSP, electrical methods)</td>
</tr>
<tr>
<td>CO₂ saturation</td>
<td>Electrical methods (ERT)</td>
<td>(advanced seismic)</td>
</tr>
<tr>
<td>Surface detection</td>
<td>Soil gas, PFC tracing</td>
<td>(Atmos. eddy towers, FTIRS, LIDAR, hyperspectral)</td>
</tr>
<tr>
<td>Stress/strain changes</td>
<td>(Tri-axial tensiometers)</td>
<td>Bragg grating, tilt, InSAR</td>
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Tools that could monitor UCG process could also be used to monitor CCS, and visa versa
Leakage risks remain a primary concern

1) High CO₂ concentrations (>15,000 ppm) can harm environment & human health.
2) There are other potential risks to groundwater, environment
3) Concern about the effectiveness & potential impact of widespread CO₂ injection
4) Economic risks flow from uncertainty in subsurface, liability, and regulations

Elements of risk can be prioritized
• Understanding high-permeability conduits (wells and faults)
• Predicting high-impact effects (asphyxiation, water poisoning)
• Characterizing improbable, high-impact events (potential catastrophic cases)
The focus for CO$_2$ storage operations should be HAZARDS first, RISKS second

HAZARDS are easily mapped & understood, providing a concrete basis for action

\[ \text{RISK} = \text{Probability} \times \text{consequence} \]

RISKS are often difficult to determine

- Hard to get probability or consequence from first principles
- Current dearth of large, well-studied projects prevents empirical constraint
Work remains to develop a hazard risk framework that can be regularly employed.

The hazards are a set of possible environments, mechanisms, and conditions leading to failure at some substantial scale with substantial impacts.

<table>
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<tr>
<th>Atmospheric release</th>
<th>Groundwater degradation</th>
<th>Crustal deformation</th>
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<td>Well leakage</td>
<td>Well leakage</td>
<td>Well failure</td>
</tr>
<tr>
<td>Fault leakage</td>
<td>Fault leakage</td>
<td>Fault slip/leakage</td>
</tr>
<tr>
<td>Caprock leakage</td>
<td>Caprock leakage</td>
<td>Caprock failure</td>
</tr>
<tr>
<td>Pipeline/ops leakage</td>
<td></td>
<td></td>
</tr>
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The hazards must be fully identified, their risks quantified, and their operational implications clarified.

Friedmann, 2007
Because of local nature of hazards, prioritization (triage) is possible for any case

Hypothetical Case: Texas GOM coast

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Pink = highest priority
Orange = high priority
Yellow = moderate priority

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases
Environmental Issues In UCG

- Migration of VOCs into potable groundwater
- Organic compounds derived from coal and solubilized metals from minerals migrating into groundwater
- Upward migration of contaminated groundwater due to:
  - Thermally-driven flow away from burn chamber
  - Buoyancy effects from fluid density gradients resulting from changes in dissolved solids and temperature
  - Changes in permeability of reservoir rock due to UCG.
LLNL has outlined criteria for site selection and planning with environmental concerns in mind.

- **Geological Assessments**
  - Structural
  - Stratigraphic
  - Hydrologic

- **Contaminant Transport Prediction**
  - Potential contaminant types from coal and rock mineral compositions
  - Contaminant behavior under UCG burn and post-burn conditions

<table>
<thead>
<tr>
<th>Stratigraphic category</th>
<th>Lateral Isolation</th>
<th>Overlying Unit Character</th>
<th>Relative Risk</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Sand-prone</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Shale-prone</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
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<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>Shale-prone</td>
<td>Moderate</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
<td>Sand-prone</td>
<td>High</td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>Sand-prone</td>
<td>High</td>
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UCG processes cause thermal, geomechanical, and geochemical changes to the reservoir:

- Heating/quenching effects on fractures and rock properties
- Enhanced permeability from acid leaching of ash, tars, char, coal, rock minerals
- Changes in fluid density from temperature and TDS
- Increased solubility of organic contaminants in CO$_2$
- Increased solubility of metals in acid groundwaters

These concerns are credible.

The scientific or empirical basis to quantify these risks has not yet been established.
The potential advantages & disadvantages suggest a targeted research program

*Key scientific concerns should be addressed in lab, simulation, and field-based investigations*

- T-P-D constraints for effective storage operation
- Geomechanical response
- Environmental risk from displaced UCG zone water
- Geochemical effects
- Long-term fate of CO₂

*These concerns can be addressed quickly and effectively with a research agenda involving experiments, coupled-process simulations, and field injections, monitoring, and verification*
The complexity of UCG systems requires use of hydrological, geochemical and geomechanical models to capture:

- generation and behavior of contaminants within the burn chamber,
- enhanced vertical hydraulic conductivity of the rock matrix above the burn chamber as a result of collapse and fracturing, and
- buoyancy-driven upward flow of groundwater in the vicinity of the burn chamber toward potable water resources at shallower depths

The CFD process models and the Aspen Plus models need to be integrated with the environmental models

- Balancing gasifier operational pressure against hydrologic pressure and other gradients in the field to prevent outward contaminant migration.
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