Underground Coal Gasification in the “Deep Coals” of the Powder River Basin and Preliminary Implications for EOR

May 29 and 30, 2008
Wyoming Enhanced Oil Recovery Institute

GasTech, Inc.
Casper, Wyoming
“Our world is fast becoming energy-starved. And yet, in the United States alone, there are vast resources lying just beyond our reach – oil bound in the shales of Colorado, natural gas locked in the “tight” sandstones and shales of the Rockies and Appalachia, and unbelievable quantities of coal, too deep to mine in the usual ways.”

US Department of Energy
June 1978
Powder River Basin (PRB)
UCG Program

- Why Coal, Why UCG?
- PRB Coal Resources
- UCG Selection Criteria
- PRB UCG Economics
- UCG Pilot Project
- Commercial UCG – Electricity and Liquid Fuels
- UCG as a source of CO2 for EOR
- Conclusions and Recommendations
Why Coal?

2006 World Energy Consumption

- Oil: 37%
- Natural Gas (NG): 23%
- Coal: 27%
- Nuclear (Nucl): 6%
- Hydro (Hyd): 6%
- Renewable (Renew): 1%

USEIA, 2007
Why Coal?
2007 Fossil Energy Reserves

Source: BP, 2007

- Oil: 17%
- NG: 16%
- Coal: 67%
Why Coal?

2007 Fossil Energy {Reserves + Resources}

96% Oil
2% NG
2% Coal

Source: AAPG and BP, 2007
World Coal Reserves/Resources

- Proven *world coal reserves* (economic) of 909 billion tons (BP, 2007). Cover Wyoming in 8 feet of coal.
- Estimated total *world coal resources* (identified, not necessarily economic) of up to 18 trillion tons (AAPG).
- Only 5% of resources are economically extractable as reserves.
- Most resources are simply too deep – known – but too deep.
- **Underground Coal Gasification (UCG)** converts coal Resources to coal Reserves.
Coal Combustion vs Gasification

- **Combustion (Excess oxygen)**
  - Carbon + O₂ → CO₂
  - Sulfur → SOx
  - Nitrogen → NOx
  - H₂ → H₂O
  - Water → Water Vapor

- **Gasification (25% to 50% of oxygen for Combustion)**
  - Carbon + ½ O₂ → CO
  - H₂O + C → H₂ + CO
  - C + CO₂ → 2 CO

Red are combustible gases
Combustion vs. Gasification

The diagram illustrates the composition of gases produced during combustion and gasification as a function of the oxygen to MAF coal feed ratio. The x-axis represents the oxygen to MAF coal feed ratio, and the y-axis shows the mole percent of various gases, including CH₄, H₂S, H₂, H₂O, SO₂, C, CO, and CO₂. The chart highlights the transition from combustion to gasification, with specific zones defined by the presence of different gases.
What is UCG?

- Underground Coal Gasification – a mining method utilizing linked well bores
- Inject air (air-blown) or O₂ and steam (oxygen-blown) through boreholes, ignite the coal in situ
- Same processes as surface gasification but done in the deep coal seam, a “geo-reactor”
- Process water from coal seam (and injection)
- Produces combustible hot syngas with H₂, CH₄, CO, CO₂ and H₂O; 150 to 300 BTU/scf; energy is combustible gas, temperature, and pressure
UCG is like surface gasification, with two major advantages -
1) No surface gasifier; 2) CO2 sequestration
History of UCG

- Conceived by William Siemens, 1868
- Russians developed commercial UCG starting in 1928, 9 large sites; 2 still operating
- US Trials started in 1946; 33 trials; peaked with Hanna trials 1972-79 and Rocky Mountain 1 1986-88
- Trials in Europe 1982-1999
- Australian test 1999 to 2002
Current UCG Activities

- Major Chinese (Xin Ao) commercial efforts underway in 2007 and 2008 ($100 MM)
- Eskom (South Africa) 2007. Proceeding to commercial. Pilot is 2.5 MMcfd, Commercial in 4 phases up to 4.4 Bcfd for 2,100 Mwe (2 million US homes)
- Virtually all tests gasified coal
- A few had operational problems
- *Much learned* from these efforts
- BP/ GasTech Demonstration Project
Cost/Logistical Advantages of UCG

- **Virtually unlimited reserves** – makes available most of the 95% of coals too deep to mine
- No exploration/delineation costs
- Manufacturing syngas, not depleting gas reservoir
- **Cap costs 25% to 30% lower** than surface gasification
- **Op costs lower** – no mining or coal/waste handling
- Lower energy costs - $1.50 to $2.00/million BTU
- Commercial project IRRs of 15% to 20%
Environmental Advantages of UCG

- No personnel underground → fewer industrial hazards → safe extraction technology
- **No (or little) surface water** required
- Limited ash or slag disposal
- Limited surface impacts (relative to mining)
- **Proper gasifier operation** produces organics as gases, not liquids in the cavern
- Immense UG heat storage → stable, robust gas supply
- **CO₂** capture economic; sequestration possible
Basics of UCG Gasifier Operation

- **Gasifier Depth ~ 1,000 feet**
  - Less likely coal is used as an aquifer
  - Higher P favors methane
  - Reduces surface subsidence
  - Operate gasifier P < hydrostatic P

- **I-P Well Linkage before ignition**
  - Link must be the highest permeability channel
  - Linkage in base of coal seam avoids “by-pass”
  - Allows high volumes of low P gas

- **High Temperature – All phases are gas, no liquids**

- **65% +/- Recovery**
  - Controlled subsidence with pillars
  - Galleries direct gas flow

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The PRB

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GasTech UCG Program in the PRB
Powder River Basin Coal
Resource Facts

- **510 Billion tons** coal in-place (USGS, 1999)
- Seams up to **250 feet thick**
- Energy content equal to **20 times** the world’s total annual energy consumption
- One ton of PRB coal has **300 times** the energy content of the CBM gas in that same ton of coal
- **307 billion tons** amenable to UCG (this study)
  - Seams >500 ft deep to top of seam
  - Seams > 30 feet thick
Powder River Basin and Drill Hole Data Locations

49,000 records

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Example – Locations with 50 ft Coal Overlain by 100 ft Mudstone

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Typical PRB Cross Section

- Target coals encased in low permeability siltstone rocks
- Sandstones are scattered and lenticular

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## Factors for UCG Selection – PRB is Ideal

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Optimal</th>
<th>Powder River Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Seam Thickness</td>
<td>30 ft +</td>
<td>30 to 250 ft – 70 ft avg</td>
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<tr>
<td>Coal Seam Continuity</td>
<td>High</td>
<td>Extremely high - miles</td>
</tr>
<tr>
<td>Coal Rank</td>
<td>Sub Bit to Low Vol Bit</td>
<td>Sub Bituminous “B”</td>
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<tr>
<td>Ash Content</td>
<td>&lt; 40%</td>
<td>6.4% avg</td>
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<tr>
<td>Faulting</td>
<td>Rare</td>
<td>Rare to absent</td>
</tr>
<tr>
<td>Depth to Coal</td>
<td>&gt; 1,000 ft</td>
<td>500 to 2,500 ft</td>
</tr>
<tr>
<td>Dip</td>
<td>0 to 20 degrees</td>
<td>1 to 3 degrees</td>
</tr>
<tr>
<td>Intrusions</td>
<td>Minimal</td>
<td>None</td>
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<tr>
<td>Immediate Roof</td>
<td>Strong, stable</td>
<td>Low perm siltstone</td>
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<tr>
<td>Hydraulic Head</td>
<td>&gt; 600 ft</td>
<td>500 to 2,500 ft</td>
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<tr>
<td>Swelling Character</td>
<td>Non-swelling</td>
<td>Non-swelling</td>
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<tr>
<td>Coal Permeability</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Water Quality</td>
<td>Poor</td>
<td>Stock quality</td>
</tr>
<tr>
<td>NG Availability</td>
<td>Available, low cost</td>
<td>Very Low Cost</td>
</tr>
</tbody>
</table>

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PRB Hydrology and UCG

- Water is a necessary ingredient in UCG
- Excessive water influx lowers BTU value of syngas
- Site selection is key
  - No water wells in coal
  - Thick siltstone “seal” overlying coal
  - No faulting
  - Fully characterize, understand, and accommodate local hydrologic conditions
- Operate reactor “correctly”
PRB Infrastructure

Legend
- WY Counties
- WY Cities
- PRB Cities
- Major Roads
- Rail Lines
- NG Pipe Line
- Township-Range
- Powerline

Powder River Basin Infrastructure

Figure: By: Date:
Printed EB 9/06
Approved 9/06
Scale: As Noted
Drawing Completed In ArcGIS

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UCG and Oil and Gas Development

- Natural potential conflict of two mineral estates
- CBM value highest in best UCG coals, thick and deep
- Energy content of coal is 300X the energy in the CBM
- Sequential development most reasonable
- Deplete economic CBM, then UCG development
- Deep oil and gas well bores need to be avoided
- O&G infrastructure valuable to UCG development
- UCG can proceed for next 50+ years
Example of PRB UCG Site

Subsea Depth

4200 -
4100 -
4000 -
3900 -
3800 -
3700 -
3600 -
3500 -
3400 -
3300 -
3200 -
3100 -
3000 -
2900 -
2800 -
2700 -
2600 -

SHALLOW COAL
ANDERSON COAL
WALL COAL

Overlying Siltstone
Target UCG Coal
Deep Coal CO₂ Sink?

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UCG Demonstration Project
Coal Leases & Pipelines

345 KV powerline
Oil pipeline
NG pipelines

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Permitting UCG in the PRB

- Primarily by Wyoming Department of Environmental Quality
- Impacts to groundwater, subsidence, air quality are key issues
- *In Situ* regulations and Guidelines in place, used for UCG and uranium
- 24 to 36 months to permit Pilot
- Significant bonding will be required
Uses of UCG Gas in the PRB

- **Power generation** in Integrated Gasification Combined Cycle (IGCC); Wyoming power growth 5%/yr
- **Synthesis of clean fuels** and chemicals
- Replace coal and NG in power plants
- Replace NG as chemical feedstock
- **Hydrogen** production
- Produce **synthetic NG**
UCG Economic Model

- Based on Boysen and Gunn (1979, 2006)

- UCG Model incorporates
  - Process dynamics (mass and energy balances, process model)
  - Equipment design (LVW, UCG modules)
  - Cost of equipment, piping, facilities, labor
  - Economic analysis to optimize design
UCG Economic Model

- **Determines:** UCG module consumption rate, compression requirements, piping and equipment costs, operating costs

- **Calculates:** Raw Syngas selling price required to yield a defined Rate of Return on the investment; 15% used in base case

- **Optimizing:** Seam depth, seam thickness, well field design and well spacing, compression requirements, casing/piping sizes, oxidant choices
UCG Raw Syngas Economics
PRB Reference Case

- Well spacing 200 feet
- Air-blown ➔ Dry gas heating value 150 Btu/scf
- Resource recovered is 65% of coal-in-place
- Zero gas leakage
- Gasification thermal efficiency of 81%
- Depth to seam top 1054 ft, thickness 112 ft
- UCG facility sized to fuel 200 MWe combined cycle power generation plant with 45% generation efficiency
- Plant capacity factor 95%

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GasTech UCG Program in the PRB
UCG Raw Syngas Economics

PRB Reference Case

- Current US dollars
- 2006/7 vendor quotes
- 100% equity financing
- Hurdle rate is 15%
- 20 year life
- SL depreciation
- Zero plant salvage value

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GasTech UCG Program in the PRB
UCG Raw Syngas Economics
PRB Reference Case

- Total Capital $57.2 million
- Annual operating expenses $13.5 million
- Raw syngas production cost of $1.62/ MMBtu, including 15% ROI on UCG investment
UCG Raw Syngas Economics

PRB Sensitivities

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UCG Raw Syngas Economics

PRB Sensitivities

Coal Seam Thickness (ft)

UCG Syngas Cost ($/MMBTU)

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UCG Raw Syngas Economics

PRB Sensitivities

Well Spacing (ft) vs. UCG Syngas Cost ($/MMBtu)

May 2008  GasTech UCG Program in the PRB
UCG-I GCC 200 MW Power Plant
200 MW UCG-IGCC Power Plant Economics

- Total Capital Investment $263 million
- Annual Operating Expenses $20 million
- USFIT 35%
- Sales price electricity $62/MW-hr
- After all taxes and royalties, DCF-ROR 18.3%, NPV @ 15% of $44.3 million
- Returns 15% DCF-ROR at electricity price of $51.68/MW-hr
<table>
<thead>
<tr>
<th></th>
<th>IGCC</th>
<th>UCG IGCC</th>
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<tbody>
<tr>
<td>MEGAWATTS</td>
<td>550</td>
<td>200</td>
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<tr>
<td>CAPACITY FACTOR</td>
<td>85%</td>
<td>95%</td>
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<tr>
<td>TOTAL CAPITAL, $K</td>
<td>$849,310</td>
<td>$263,300</td>
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<tr>
<td>CAPITAL $/KW INSTALLED</td>
<td>$1,544</td>
<td>$1,180</td>
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<td>76.0%</td>
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<tr>
<td>OP COST K$/YR</td>
<td>$90,073</td>
<td>$19,916</td>
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<td>OP COST $/MWHR SOLD</td>
<td>$21.99</td>
<td>$11.96</td>
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<td>54.0%</td>
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<td>CONSTRUCTION, YRS</td>
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<td>OPERATION, YRS</td>
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<tr>
<td>DEBT/EQUITY</td>
<td>100% EQUITY</td>
<td>100% EQUITY</td>
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<tr>
<td>USFIT RATE</td>
<td>35%</td>
<td>35%</td>
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<tr>
<td>SALES PRICE FOR 15% ROI</td>
<td>$80.60</td>
<td>$51.68</td>
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<tr>
<td>DCF-ROR AT $62/MWHR</td>
<td>10.40%</td>
<td>18.30%</td>
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<tr>
<td>PAYBACK AT $62/MWHR, YRS</td>
<td>10.77</td>
<td>7.64</td>
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</table>
UCG FT Plant

Gas Turbine

Clean Gas

Exhaust Gas

Parasitic Loads

Gas Turbine

Air

Clean Gas

HRSG

Water Pump

Condensor

Steam Turbine

Generator

Electricity To Sales

To Stack

ASU

Sulfur Recovery

FT Synthesis and Product Upgrade

Diesel To Sales

Gas Cleanup and Conditioning

Recycle

Naptha To Sales

Ground Level

UCG Reactor

Watt treatment

Coal Liquid Recovery

Parasitic Loads

Electricity To Sales

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GasTech UCG Program in the PRB
UCG – FT Plant Economics

- 10,200 bpd (8,560 diesel, 1,640 naptha) FT plant fed with oxygen-fired UCG syngas
- Generates 104 MW export power
- Capital cost $622 million
- Annual Operating cost $53.2 million
- Diesel price $63/bbl, naptha $30/bbl, electricity $62/MW-hr
- Straight equity case, after taxes and royalties
- DCF-ROR of 18.0%, NPV @ 15% discount of $104 million
Pilot Project Objectives

- Improve upon earlier US UCG trials, produce stable, dependable gas flow and composition
- Maintain strict *environmental compliance*
- Provide *cost and operating data* for Commercial Project front-end engineering
- Provide basis for **Bankable Feasibility Study** for Commercial project
- Operate 1 year, 3 UCG modules, generate 5 MW electricity. CCS can be added.
- **BP plc** is operating partner with GasTech
Elements of Commercial Project

- Both air- and oxygen-blown UCG modules, poly-generation
- Air-blown for IGCC, providing electricity requirements for Atmospheric Separation Unit to produce oxygen, and for electricity sales
- Base case is 200 Mwe CC power generation
- Oxygen-blown syngas for clean diesel, synthetic natural gas formulation; local markets
- Base case plant capacity 10,000 bpd
CO$_2$ Sequestration Options for the Commercial Projects

- If CCS desired, use all oxygen-blown CCS in the PRB
- CCS in the PRB
  - Tertiary oil recovery, as Salt Creek, Hartzog Draw
  - "Extinct" UCG cavities as dense phase
  - Deep marine formations; PRB has numerous candidates for receiver formations: Mesa Verde, Sussex, Shannon, Frontier, Muddy, Morrison, Tensleep
- Possible carbon credits
- Energy penalty economically acceptable
UCG and EOR in the PRB

 لكل قوة كهربائية من cogeneration بناء على UCG ستنتج 1 مليون طن (Mt) CO2/سنة

 UCG syngas is 15% CO2 (air blown) to 30% CO2 (oxy blown)

 Rocky Mtn Area Transmission Study (2006) predicts 700 Mwe new generating capacity from coal in the PRB; if UCG, produces 3.5 Mt CO2/yr

 PRB demand for CO2 for 168 reservoirs is 236 to 354 Mt (Wo, 2007)

 UCG is viable source of CO2 for EOR
CO2 Removal from Syngas – Energy Penalty

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GasTech UCG Program in the PRB
Conclusions of LLNL on UCG, 2007

- UCG-CC costs less than PC.
- UCG-CC + partial CCS is less than PC without CCS.
- UCG-CC + full CCS is less than above-ground IGCC without CCS.
- UCG-CC uses less water than any surface equivalent coal application.
- Costs are changing rapidly. Costs are site specific.
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:

- Could exploit high P applications
  -- Cryogenic separation
  -- Pressure Swing Adsorption (e.g., Rectisol)
- Could improve WGS/separations in subsurface or well
UCG Implementation in the PRB

- Site selection and characterization
- Permitting for Pilot
- Pilot plant program
- Commercial 200 MW UCG IGCC power project; CCS possible
- Develop FT liquids project on power project
- Multiple Commercial projects possible
UCG In the PRB
The Opportunity

- UCG is **clean coal technology**
- Environmental challenges can be met
- **Lowest cost syngas** for power generation and chemical feed-stocks
- **Pilot project sites selected**; complete Pilot project in 2 to 3 years
- **Commercial Projects** for GTL and electricity
- Use UCG-derived CO$_2$ in EOR projects