LLNL April 2011 TKI Meeting

Materials: Introduction to Underground Coal Gasification

N. C. Goldstein, D. W. Camp, J. Wagoner, R. Gok

May 10, 2011
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LLNL OUTGOING MEMO

TO: Şahika Yürek, TKI
DATE: May 9, 2011

FROM: Noah Goldstein, David Camp, Rengin Gok, Jeff Wagoner, LLNL

Subject: Presentation materials from April 2011 visit to TKI

Contact information:
Noah Goldstein  Goldstein8@llnl.gov  925-423-3046
David Camp  Camp2@llnl.gov  925-423-9228

This package of documents contains the contents of the April 13-15th, 2011 visit of LLNL staff to TKI’s offices in Ankara, Turkey. The LLNL team members were:

1. David Camp, Chemical Engineer, Project Director
2. Noah Goldstein, Spatial Scientist, Project Lead
3. Jeff Wagoner, Geologist
4. Rengin Gok, Seismologist

The following are the contents of this pack:

1) Revised Agenda of LLNL-TKI meeting
2) Overview of Underground Coal Gasification (UCG)
3) 3D Geological Visualization
4) Preliminary TKI UCG economic calculations
5) Site Selection Factors
6) UCG Sweet Spot analysis
7) Overview of a Turkish University Consortium on UCG
8) Next Steps by LLNL and TKI
<table>
<thead>
<tr>
<th>Event</th>
<th>Timing</th>
<th>Topic</th>
<th>Presenter</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
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<tr>
<td></td>
<td>Large Audience</td>
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<tr>
<td>1</td>
<td>11:00</td>
<td>Preliminary Introductions with core team, Review meeting agenda</td>
<td>LLNL/TKI</td>
<td>LLNL and TKI introduce key members, confirm agenda</td>
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<tr>
<td>2</td>
<td>12:00</td>
<td>Lunch</td>
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<td>3</td>
<td>13:00</td>
<td>Announcement of Project</td>
<td>TKI</td>
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<tr>
<td>4</td>
<td>13:30</td>
<td>Message from LLNL Management; Overview of LLNL; Overview of UCG</td>
<td>LLNL</td>
<td>Presentation</td>
</tr>
<tr>
<td>5</td>
<td>15:00</td>
<td>Turkey’s Energy Strategy, National and regional energy needs, Overview of Turkish coal resources, TKI’s Gasification Program, Greenhouse gas emissions policy</td>
<td>TKI</td>
<td>LLNL needs to understand these topics</td>
</tr>
<tr>
<td>6</td>
<td>16:00</td>
<td>Overview of TKI, including: mission, business model(s), organizational structure, activities, and relationships with universities and with industry</td>
<td>TKI</td>
<td>LLNL needs to understand these topics</td>
</tr>
<tr>
<td>7</td>
<td>17:00</td>
<td>Discussion of University-based research program in UCG</td>
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<td></td>
<td>Day 2</td>
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<td></td>
<td>Small Groups</td>
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</tr>
<tr>
<td>7</td>
<td>9:00</td>
<td>Discussion of TKI’s vision for Turkey’s UCG program; Components of a complete national UCG program:</td>
<td>LLNL/TKI</td>
<td>Small Management group discussion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>● Options for a UCG Program:</td>
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<tr>
<td></td>
<td></td>
<td>○ Manage Leases</td>
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<td></td>
<td>○ In-house Commercial Operations</td>
<td></td>
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<td></td>
<td></td>
<td>○ TKI become an International UCG Operator</td>
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<tr>
<td></td>
<td></td>
<td>● Creation of TKI UCG Vision Statement</td>
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</tr>
<tr>
<td>8</td>
<td>10:00</td>
<td>TKI’s expectations of LLNL.</td>
<td>LLNL/TKI</td>
<td>Small management group discussion</td>
</tr>
<tr>
<td>9</td>
<td>11:00</td>
<td>Overview of site and regional selection methodology and list of factors for Sweet Spot analysis</td>
<td>LLNL-led</td>
<td>TKI Technical Experts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>discussion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Activity</td>
<td>Organizer</td>
<td>Notes</td>
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<td>--------------------------------------------------------------------------</td>
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<tr>
<td>10:00</td>
<td>Presentation of LLNL Team</td>
<td>LLNL</td>
<td>Presentation</td>
<td></td>
</tr>
<tr>
<td>11:00</td>
<td>Lunch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td>Preliminary calculation of UCG gas from Turkish Lignite</td>
<td>LLNL</td>
<td>Presentation</td>
<td></td>
</tr>
</tbody>
</table>
| 13:00 | Overview discussion of Turkey’s lignite basins and geological formations: | TKI       | 1. Data needs for regional-scale UCG evaluation  
2. Data needs for basin-scale UCG evaluation  
3. Data needs for site-specific UCG evaluation  
See full list of requested data below |
| 14:30 | If possible, detailed discussion of most promising regions for UCG      | TKI       | Half-day discussion; LLNL to learn about lignite resources and formations |
| 15:00 | Discussion about how to proceed with data gathering (protocols, format, contacts, software, etc...) | TKI / LLNL | Small group discussion  
1. Geologic / Coal  
2. Geographic / Market |
| 16:00 | Revisit LLNL Project Plan (tasks, deliverables, timing)                 | LLNL      | Small management group discussion |
| 17:00 | Next Steps:  
1. Data Gathering  
2. LLNL work  
3. TKI work  
4. Next Meeting | LLNL/TKI  | Small group discussion |
| 12:30 | Break                                                                   |           |       |
Underground Coal Gasification

David Camp
Lawrence Livermore National Laboratory
P.O. Box 808, L-223, Livermore, CA 94550
contact David Camp, camp2@llnl.gov
Lawrence Livermore National Laboratory (LLNL)
Lawrence Livermore National Laboratory is a U.S. Department of Energy lab applying science and technology to missions of national and global importance

- Approximately 6,000 employees
- 6 decades of gov’t investment
- World class experimental and computational facilities, capabilities
- Multidisciplinary project approach

National Ignition Facility (laser fusion)

Terascale Computing Facility
LLNL has a broad, multidisciplinary workforce

Total S&T staff: 2275
A letter from our Director
LLNL has programs in National Defense, Counterterrorism, Advanced Science Computing and Engineering, Energy and Environment, and Others

Examples of Energy and Environment:
# Energy technology development for a clean energy future

<table>
<thead>
<tr>
<th>Biofuel</th>
<th>Hydrogen</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstrated cellulosic substrate deconstruction by enzymes in an automated micro-bioreactor</td>
<td>Assessed viability of high pressure hydrogen storage</td>
<td>Characterized breakthrough super-lattice structures for future solar cells and radiation detectors</td>
</tr>
</tbody>
</table>

**Underground Coal Combustion**
- Completed prototype simulation capability for underground coal gasification (UCG)

**CO₂ Capture**
- Identified LLNL technologies and strategies for advancing LLNL’s role in carbon dioxide separation technology
We have now set the record for miles driven on a single tank of hydrogen – over 500 miles! (triple previous record)
Our wind characterization and prediction applies multi-scale modeling

Global, $\Delta x \sim 10\text{km}$
Regional, $\Delta x \sim 1\text{km}$
Wind park, $\Delta x \sim 10\text{m}$
Turbine, $\Delta x < 1\text{m}$
Using climate analysis skill and large computing to predict regional climate change

Predicting the future

LLNL’s enormous computing capability allows climate simulations at unprecedented resolution capturing California’s regional climate phenomena

Target Resolutions
Global: 15 Km
Regional: 1 Km
How does the nation use its energy?
How does the nation use its water?

Source

Surface water 264,000

Ground water 76,400

Water

25,100 2,100

Public supply 40,200

Domestic/commercial 41,700

Industrial/mining 100 28,000 4,200

Cooling for Thermo-electric 132,000

Irrigation/livestock 139,000

Consumed or evaporated 100,000

Disposition

Return flow 241,000

33,700

23,900

8,000

4,700

5,100

500

87,600

51,400

84,500

54,700

3,300
Where is the carbon?
UCG INTRODUCTION

HOW DOES IT WORK?
UCG is an alternative to surface gasification

- Coal +O$_2$+H$_2$O $\rightarrow$ H$_2$, CO, CH$_4$, CO$_2$, H$_2$O ... (syngas)

- Syngas can be burned for electric power (IGCC) or converted to methane, liquid fuels, methanol, ammonia, or hydrogen

- Gasification is a leading approach for clean use of abundant coal
  - Well-suited to pollutant and CO$_2$ capture
  - 160 coal gasifiers in operation around the world
  - Large DOE program
  - Costs are an issue for surface gasification (subsidies)
UCG uses the coal seam as the gasification reactor to convert coal to syngas underground.
Many cavity and module configurations are possible

Linked Vertical Wells (next slides)

Continuous Retractable Injection Point (LLNL, early 1980’s)

Parallel CRIP (An extension of Rocky Mt 1 technology)

Linear CRIP

Hill and Thorsness, 1986

Courtesy Burl Davis, Carbon Energy
Schematic of Linked Vertical Well module
-- early time

Injection well

Production well

Rock

Coal

Rock
UCG Cavity: Medium-early time

Diagram showing an injection well and a production well in a coal bed, with rock layers surrounding the coal and char, ash, and rubble below.
Reaction Regions

- Injection well
- Production well

Coal

- Oxidation Region
- Reducing/Gasifying Region
- Pyrolysis Region
- Drying Region
Strongly coupled physics and chemistry in several domains drive the UCG

\[
\text{Coal (~C } H_{0.8} O_{0.2}) + O_2 + H_2O \rightarrow CO + H_2 + CH_4 + HC's + CO_2 + H_2O
\]
Environment

Adapted from Creedy & Garner (2004)
Underground coal gasification has less surface impact and safety risks, and fewer particulate and gas emissions

- Less surface impact than surface mining
- Safer than underground mining
- Less coal and rock dust; less ash
- Criteria pollutants removed efficiently from syngas
Cattle grazing at Bloodwood Creek operation

Product Well

Courtesy
Burl Davis
Carbon Energy
UCG environmental issues are real and must be understood and managed by careful site selection and operation

- **Subsidence**
  - Coal is being removed, as in long-wall underground mining
  - Similar issues and management strategy

- **Groundwater contamination**
  - Organics are produced by UCG
  - Must avoid contaminating potable/high-value aquifers
    - Was a problem in 2 of the 30+ US tests
  - Careful site selection, operation, and closure strategies have proven effective

- **Uncontrolled coal fire is not a credible issue**
  - UCG sites are chosen far below the water table
  - When you stop injecting air; the groundwater flows in, floods the cavity, and quenches everything
Overburden changes and subsidence can be managed through site selection, design, & operational choices

Some overburden changes will happen

- Extent and nature depends:
  - mechanical properties of strata
  - geometry

Managed through site selection:

- Coal and rock properties
- Coal seam thickness, depth

**AND** design/operational choices

- Cavity/module widths
- Pillar widths
The risk of groundwater contamination from UCG can be managed.

- **Site selection**
  - Deeper sites (>~200 m)
  - Prefer saline, nonpotable water
  - Characterization of overburden
  - Risk characterization

- **Pressure management**
  - Operate below hydrostatic pressure keeps fluid flow going inward

- **Regular monitoring**
  - Water chemistry, pressure
  - Passive geophysics

- **Clean shutdown**
  - Nitrogen venting and water flushing

- Validated at RM 1, Chinchilla, and others

*Courtesy of ErgoExergy*
Welcome to Turkey

(A little story)
ECONOMICS

Adapted from Creedy & Garner (2004)
Underground coal gasification is an alternative to surface gasification that eliminates several costly operations:

- The gasification is done underground
- No coal mining
- No coal pulverizing
- No coal washing
- No coal transportation
- No surface gasifier
- UCG costs may be much lower than surface gasification
GasTech commercial assessment of US Powder River Basin shows promising economics for UCG

All 3 UCG cases show lower cists than surface gasification equivalent

1. Syngas production
   • Raw syngas $1.6-2.6/MMBtu
   • Total capital $57.2 M
   • Annual OPEX $13.5 M
   • Includes 15% ROI

2. UCG-CC power plant
   • ~75% surface IGCC capex
   • ~55% surface IGCC opex
   • ~65% surface IGCC elec. price

3. UCG-FT plant
   • 10,000 BPD +100 MW
   • $622 M Capex
   • $53 M Opex
   • Diesel @ $63/bbl, naptha @ $30/bbl, $62/MW-hr
   • 18% ROI

<table>
<thead>
<tr>
<th>Morzenti, 2007</th>
<th>IGCC</th>
<th>UCG-CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megawatts</td>
<td>550</td>
<td>200</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>Total Capital ($M)</td>
<td>$850</td>
<td>$263</td>
</tr>
<tr>
<td>Capital, $/KW</td>
<td>$1544</td>
<td>$1180 76%</td>
</tr>
<tr>
<td>OPEX, $M/y</td>
<td>$90.1</td>
<td>$20</td>
</tr>
<tr>
<td>OPEX, $/MW-hr</td>
<td>$22.0</td>
<td>$12.0 54%</td>
</tr>
<tr>
<td>Construction</td>
<td>3 years</td>
<td>3 years</td>
</tr>
<tr>
<td>Operation</td>
<td>22 years</td>
<td>22 years</td>
</tr>
<tr>
<td>Debt/Equity</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>USFIT rate</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td>Sale price for 15% ROI</td>
<td>$80.6</td>
<td>$51.7 65%</td>
</tr>
<tr>
<td>ROR at $62/MW-hr</td>
<td>10.4%</td>
<td>18.3%</td>
</tr>
<tr>
<td>Payback at $62/MW-hr</td>
<td>10.8</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Report available upon request
Bottom line: What does UCG cost?

- Costs of raw syngas production (various estimates)
  - $1 to $4 / Mbtu; most cases < $2/Mbtu

- Cost of applications fueled by UCG syngas
  - Estimates 20-50% less than surface gasif. equivalent

- Costs w/ CO₂ capture and storage
  - Roughly 50% less than surface gasif. equivalent
  - Roughly 1/4 as much government incentive needed

These are estimates – no large scale commercial data yet
UCG IS REAL

Adapted from Creedy & Garner (2004)
UCG projects include over 33 US, 200 Former Soviet Union, and 40 other international pilots

The Soviets have a long history of projects
“... liberate the masses from the toils of mining” Lenin (1913)
More projects are being planned and evaluated

- Alaska, CIRI (Laurus(Ergo) and LLNL) announced
- WY, IN, IL, KY, ND, TX, AK projects being evaluated
- Alberta – large Province-supported project w/ CCS
- Alberta, Saskatchewan, Maritimes being evaluated
- India, Bangladesh, Pakistan: leases & plans
- Eastern Europe (most countries): plans & eval’s
- South Africa (Majuba growing; Sasol hold) Botswana
- UK offshore projects being evaluated; leases issued
- Vietnam, Brazil, Chile, others: projects under evaluation
- Turkey: private project plus TKI national program
All these projects do not mean it is easy

- Learning curve
- Operational and mechanical details
- Many choices
  - Inadequate data and models to guide
- Monitoring
Requirements for a UCG project today

- Rights to an appropriate resource and location
- Market/customer/plan for your product
- Financing
- Technical and project provider team
  - UCG “General contractor”
  - Regulatory/Permitting/Environmental provider(s)
  - Geological exploration/characterization contractor
  - Modeling and environmental analyses support
  - Process engineering contractor for gas processing
- A Champion!
LLNL’s
Underground Coal Gasification Program

Overview:
Old and New Program
LLNL was a UCG leader in 1970’s and 1980’s – Only US institution still active in UCG
Hoe Creek Field Test

- Hoe Creek I
  - Explosive fracture for linking
  - Extensive instrumentation
  - Electrical ignition

- Hoe Creek II
  - Reverse combustion linkage
  - High frequency Electromagnetic imaging of cavity
  - Coring to verify cavity dimensions

- Hoe Creek III
  - Directionally drilled linkage
  - Air vs. Oxygen / Steam comparison
Centralia Field Test

- First demonstration of CRIP technology
- LLNL Silane igniter successfully demonstrated
- Igniter maneuvers successfully demonstrated
- 30-day time limit reached
LLNL Silane Igniter System
LLNL has Excavated a UCG Cavity
Rocky Mountain 1 Field Test
Rocky Mountain 1 Field Test

- LLNL had technical lead for module design, data acquisition, operation (control)
- Side-by-site CRIP and ELW modules
- CRIP very successful: 100 day continuous burn, 4-cavity module
- Three igniter maneuvers successfully demonstrated
- Environmental monitoring showed no contamination
- Successfully demonstrated Clean Cavern Concept
Livermore experience and developments

- Linking
  - Fracturing, reverse combustion, directional drilling

- Module types
  - Linked vertical well, multiple vertical wells, horizontal-vertical, Controlled Retractable Injection Point (CRIP) – linear and parallel

- Scientific understanding
  - Field tests done to produce information (not to say we did it)
  - Extensive instrumentation, monitoring, drill-back, excavation, ...
  - Best UCG models & simulation tools
Livermore experience and developments

- Linking: Fracturing, reverse combustion, directional drilling
- Module types: Linked vertical well, multiple vertical wells, horizontal-vertical, Controlled Retractable Injection Point (CRIP) – linear and parallel
- Scientific understanding
  - Field tests done to produce information
  - Extensive instrument, monitoring, drill-back
  - Best UCG models & simulation tools
LLNL’s Current UCG Program: Practical support for UCG projects
LLNL’s Current UCG Program:
– UCG process engineering and economics

UCG gas to methanol flowsheet
LLNL’s Current UCG Program:
– Monitoring of the UCG process and cavity

Electrical Resistance Tomography to “see” the UCG Cavity
Building simulation tools and applying them to UCG engineering and project decisions

- Site screening and evaluation
- Module design
- Operating plans
- Environment
- Training
- Operations
- Monitoring
- Clean closure
LLNL’s current UCG program

Active projects

- UCG proj in N.Am.– site char., concept design, envir. , CO2,…
  - Coal resource owner/developer, contract
- UCG conceptual mine plan, gas processing, economics
  - Major international energy company, contract
- Assessment of UCG prospects in a region of the US
  - Nongovernmental environmental group, contract
- Development of UCG simulation tools, training
  - Major international energy company, contract
- Strategic program plan and site screening
  - A State-owned coal company, contract
- Compendium of data from old US field tests
  - Government-funded, grant approved
- Design of UCG mine plan and operations for project
  - Major North American coal company, contract in negotiations
- Interpretation of UCG field test monitoring data
  - Major foreign energy company, active cooperative MOU
- Development of next generation UCG simulator
  - Funded by LLNL Internal R&D program
- Improvement in UCG monitoring capabilities
  - Funded by LLNL Internal capability-building program

Staff

- Julio Friedmann – Program Leader, UCG business
- David Camp – Assoc Prog Leader, tech. oversight
- Jeff Wagoner – geology, geospatial modeling
- Steve Hunter – proj mgt., sensors, monitoring, test data
- Xianjin Yang – monitoring geophysics
- Ravi Upadhye – UCG and process engineering
- John Nitao – simulator development
- Tom Buscheck – hydrogeology, thermal flow transport
- Josh White – geomechanics
- Greg Burton – cavity fluid transport & reactions
- Tom McVey – process engineering, economics
- Rob Mellors – monitoring & survey geophysics
- Oleg Vorobiev - geomechanics
- Noah Goldstein – GIS, site selection
- Jerry Britten, George Metzger – historical consultant
- Zafer Demir, Hydrogeologist
- Rengin Gok – international relations
Conclusion

UCG is promising, challenging, and technically fun!

We are excited to help TKI build a world class UCG capability, in Turkey
3D Geological Visualization

Jeff Wagoner

Lawrence Livermore National Laboratory
3D geologic models are important tools to understand the subsurface geologic setting and to evaluate the potential for underground coal gasification.
The basin fill is stripped off to reveal geometry of the coal seams, as well as faulting and channeling. Both faulting and channeling can disrupt the lateral continuity of the coal seams.
Boreholes are important sources of stratigraphic data used to construct the geomodel. Seismic surveys are also invaluable to define the subsurface structure.
Geomodels can be sliced and rotated, helping to evaluate the variation in the stratigraphy, faulting, and channeling.
Geomodels are invaluable to evaluate possible UCG pilot project locations.
Results of Preliminary UCG-MEEE Calculations for TKI Lignites

Ravi Upadhye, David Camp
Lawrence Livermore National Laboratory
P.O. Box 808, L-223, Livermore, CA 94550
contact David Camp, camp2@llnl.gov
UCG-MEEE is our Excel Based Material and Energy Balance and Economics Estimator for UCG

- **Material and Energy Balance**
  - Given coal properties and injection gas, etc.
  - Assumes parameters: product gas temperature, water influx, heat loss, unconverted char, methane yield, shift delta T, etc.
  - Parameters calibrated (roughly) to past test results (HC 1,2,3)

- **Economic Estimator**
  - Must sell gas for $X/10^6$ Btu of raw, uncleaned product gas to make 15% return on investment
  - User inputs module size, coal lease cost, drilling cost, compression costs, etc.

- **Preliminary results this project**
  - Preliminary calibration on one Texas Lignite field test
  - Ran on four TKI cases using similar parameter assumptions
Caveats – these are preliminary draft calculations

- Model not calibrated for lignites
  - Preliminary calibration for one test with one lignite

- Many inputs guessed at, not properly estimated
  - Water influx
  - Heat loss
  - Char unconverted
  - Output temperature
  - Methane yield
  - Shift reaction temperature
  - Others

- Economics very approximate and likely low

***But relative dependence on coal CV is probably reliable***
### Inputs

- **As of 25-March 2011**
## Preliminary UCG-MEE TKI Results (as per 25-March data)

<table>
<thead>
<tr>
<th>Field</th>
<th>Caloric Value kcal/kg</th>
<th>Thickness (h) m</th>
<th>( CV^<em>p^</em> )</th>
<th>Depth m</th>
<th>Over-burden</th>
<th>Permeability</th>
<th>Air Blown Heating Value MMBTU/csf (+/- 50%)</th>
<th>$ per MMBTU (+/- 50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>&gt;2500</td>
<td>&gt;2</td>
<td></td>
<td></td>
<td>Strong</td>
<td>Low</td>
<td></td>
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</tr>
<tr>
<td>Soma-Eynez</td>
<td>4931</td>
<td>25.30</td>
<td>600-1200</td>
<td>30-177</td>
<td>150</td>
<td>3.6</td>
<td>90</td>
<td>5.4</td>
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<tr>
<td>Demirbilek</td>
<td>3525</td>
<td>5.55</td>
<td>87-191</td>
<td>54-169</td>
<td>-5</td>
<td>-38</td>
<td>Data delivered 4-14; to be evaluated in next assessment</td>
<td></td>
</tr>
<tr>
<td>Trakya</td>
<td>2334</td>
<td>1.90</td>
<td>20.70</td>
<td>54-169</td>
<td>50</td>
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<td>Tufanbeyli</td>
<td>1273</td>
<td>20.70</td>
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<td>Duvutlar</td>
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<td>2.14</td>
<td>5-132</td>
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<td>Turgut</td>
<td>2100*</td>
<td>5.6*</td>
<td>350</td>
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</table>
What does this mean?
Based on data from TKI sent 25 March:

- Soma-Eynez looks very promising
  - Learn more about it and move forward
  - Best pilot field if no show stoppers
- Demirbilek may be a viable second field
  - Need to refine model and learn more
- Do you have any more thick seams with as-received lower CV above 3,000?
- Trakya appears marginal
- Tufanbeyli does not appear promising
Recommendation

- Refine and adapt UCG-MEEE
- Soma-Eynez
  - Appears to be best choice for first pilot.
  - Gather more site- and seam-specific information
  - Refine estimates
- Demirbilek (model based on 25 March data)
  - Obtain accurate site information
  - Re-do calculations
- Find other fields with high $CV_{L,ar}$ and thick seams
- Seams with $CV_{L,ar} < 2,500$ kcal/kg may require oxygen injection, which increases costs
The following are a list of factors relevant to Underground Coal Gasification (UCG) Site Selection. This list includes factors of utmost importance, as well as less important factors. These factors are implicitly related to each other. The purpose of this document is to list these factors, in order to begin data collection for calculations and the identification of sites to be used as a pilot study. The list below is a preliminary list; this will be refined and expanded upon in the future.

*** - The more *'s, the more important.

**Coal Properties**

*****Heating Value
Perhaps the single most important commonly available coal parameter is its “As-Received Lower Heating Value”, as this most closely fits the energy balance of typical UCG operations.

**Definition of a “Seam”
Where there are multiple seams or interburdens, estimates need to made as to which seams will be gasified and which will remain isolated. In addition, which layers of rock will get dried and heated and which will not, also need to be identified. All the layers in each seam, as well as those surrounding it must be counted in the energy balance, either explicitly or by adjusting the as-received calorific value.

**Rank
Sub-bituminous best. Some bituminous good, but swelling and plastic phase are bad. Lignites are good except low heating values are less desirable than subbituminous.

**Proximate, Ultimate, Ash, and Trace Element Analyses**

**Proximate analysis
Necessary for calculations; The basis is important to know correctly.

**Ultimate analysis
Necessary for calculations; The basis is important to know correctly.
Ash analysis
Trace element analysis

Chemical Attributes of Coal and its Char
Reactivity and Chemical Behavior
Pyrolysis Products
No Relevant Gasification Assay Exists

Quality and Consistency of Analyses
Need to check TKI’s so far look good.

Small-Scale Physical Properties of Coal and Char

***Coal/Char Spalling Behavior
Important, but no assay for this yet

(Coal Geotechnical Properties are best considered along with the rock)

*** Rock and Ash Composition and Mineralogy (especially carbonates, other species that decompose at temperature, low-melting, ash catalysis)

Coal Resource Factors

****Seam Thickness

*** Seam Depth
Figure 1 illustrates the following tradeoffs;

- **Factors against shallow and/or for deep are mainly environmental**
  - UCG is not suitable above or close to the water table because of the risk of uncontrollable coal fires
  - Hazard of CO leak to surface
  - Hazard of cavity extending to surface, sinkholes
  - Greater vertical subsidence
  - Contamination from process will be left near surface – more likely to interfere with other beneficial uses (e.g. water use)
  - Deep UCG may favor higher methane yields (theoretically yes; surface gasifiers yes [??]; limited field data unsupportive)
  - Deeper rock may be stronger and lower water content
  - Deeper seams may be more mature with higher heating value and/or less moisture

- **Factors against deep and/or for shallow are mainly cost**
  - Higher drilling costs of process wells
  - Higher drilling costs of monitoring wells
  - More problems with drilling and completing
  - Greater thermal expansion, engineering issues, etc. of process wells
  - Monitoring is more difficult and expensive
  - Higher air compression costs (assume that pressure energy in product gas cannot be efficiently recovered)
  - Less experience base at deeper depths
  - More difficult and expensive to troubleshoot and fix problems
  - Higher costs of water pumping (sump/dewatering wells) and lifting of product water by product gas
In general:

1. Environmental factors favor deeper seams.
2. Cost factors favor shallower seams

**Dip**
Not steep; flat best

*Multiple Seams*
Take some credit for extra UCG-worthy seams, but not much credit.

**Combined Factors**

*****Areal As-Received Lower Heating Value (kcal per m$^2$, as received)

*Multiple Seams*

***Hydrological Properties of Coal and Rock***

*****Roof Rock Resistance is Very Important
Vertical cavity growth into overburden is bad
Mechanisms of Cavity Roof Growth
Possible Mitigation of Weak Roof Rock

***Spalling of Overburden Rock***
No good assay yet. But important, especially if roof rock is strong
Geomechanical Properties of Coal and Rock

“Strength” is Very Important

Models and Properties

When Strength Might Not Be Very Important

Where Strength and Spalling Resistance is Most Important
While strong surrounding coal and rock is better than weak, strength is more important in some locations than others. The following is an estimated ranking of where strength is most important. H is the coal seam height; W is the cavity width.

A. Overburden strength in the first one to two cavity widths above the coal seam
B. Overburden strength in the second to fourth cavity widths above the coal seam
B. Overburden spalling propensity (low) in the first one to two cavity widths above the seam
B. Coal strength (as a cavity sidewall or intercavity pillar)
C. Coal spalling propensity (medium?); (probably important but we don’t know what we want)
C. Underburden strength in the first cavity width below the seam
D. Overburden strength more than four cavity widths above the coal seam
E. Underburden strength more than one cavity width below the seam

Faults and Structure

***Faults

**Dip

Anticline and Syncline Structure

Coal Seam Lateral Continuity

Material and Energy Balance Framework for Assessing Technical Factors

A Framework for Valuing Selection Factors

System Definition
Figure sketch. Shows: Injected gas, produced gas, water influx, gas leakage, and “removed and accumulated material and energy” (pointing to void and rubble)
Material and Energy Balance

Balance equations for UCG must include all terms. The atoms (C, H, O, S, N, etc.) and the energy must balance. The energy balance is the most important.

The atoms and energy content of the clean fraction of the product gas (excludes H₂S energy, etc.)

\[
\text{mass and energy content of +inputs – outputs - accumulations:}
\]

+ coal consumed (combusted or gasified)
+ coal partially affected (dried or pyrolyzed)
+ Injected gas
+ rock affected
+ fluid advection in
+ any other net energy put into the system
- product gas contaminants (H₂S, NH₃, produced ash, etc.)
- condensed organics and water in the product
  (the organics may have either a negative value (disposal cost) or a positive value (fuel source and potential for upgrading to liquid transportation fuels))
- solid and liquid material left behind in the cavity
  (coal-derived: dry coal, char, ash, organic liquids and tars, etc.)
  (rock-derived: ash, rock, inorganic products, etc.)
- fluid loss to the formation (noncondensable gas and condensable liquids and tars)
- heat lost to the surroundings not counted above

A Financial Framework for Assessing UCG Site Selection Factors

A Factor-Weighting Algorithm for Assessing UCG Site Selection Factors (Sweet Spot)
LLNL “Sweet Spot” Analysis for UCG

- UCG is a promising technology
- Opportunities and challenges exist when developing a strategy for UCG.
- A UCG development program strategy balance:
  - Resource availability
  - Resource Quality
  - Economic Potential
  - Available Infrastructure
  - Environmental Risk
  - Social Impacts
The goal of a “Sweet Spot” analysis is to answer:
- How do you choose which region to pursue first?
- Which are the best places to investigate further?
- What are potential “roadblocks” to certain sites?

Analysis results can be spatial (mapped), aspatial, or both.
Analysis is both quantitative and qualitative.
The most important component is capturing expert, local knowledge.
- Capturing knowledge is a valuable process for documentation.
Methodology: Site Suitability

1. Unit of Analysis (UOA) and boundaries of region determined
   - <1-100 km², depending on data, regional choice
   - Nation, State, locale
Methodology: Site Suitability

1. Unit of Analysis (UOA) and boundaries of region determined
   • <1-100 km², depending on data, regional choice
   • Nation, State, locale

2. Framework for key parameters chosen
   • Resource availability
   • Infrastructure
   • Hazards
   • Market potential
Methodology: Site Suitability

1. Unit of Analysis (UOA) and boundaries of region determined
   • <1-100 km², depending on data, regional choice
   • Nation, State, locale

2. Framework for key parameters chosen
   • Resource availability
   • Infrastructure
   • Hazards
   • Market potential

3. Data compiled in GIS form
   Includes:
   - Geology
   - Hydrology
   - Seismology
   - Infrastructure analysis (distance)
   - Inhabited areas
   - Regional environmental regulations
Methodology: Site Suitability

1. Unit of Analysis (UOA) and boundaries of region determined
   • ~1-100 km², depending on data, regional choice
   • Nation, State, locale

2. Framework for key parameters chosen
   • Resource availability
   • Infrastructure
   • Hazards
   • Market potential

3. Data compiled in GIS form

4. Relative values of parameters determined (1-5 ranking)
   • E.g.: <10km to electric lines = “5”, 10-20km = “4”….

5. Calculate values for entire region
Methodology: Site Suitability

1. Unit of Analysis (UOA) and boundaries of region determined
   • ~1-100 km², depending on data, regional choice
   • Nation, State, locale

2. Framework for key parameters chosen
   • Resource availability
   • Infrastructure
   • Hazards
   • Market potential

3. Data compiled in GIS form

4. Relative values of parameters determined

5. Calculate values for entire region

6. Relative ranking map produced

7. Identification of regions of refined analysis, or Site Characterization
Methodology: Previous work for BP

- **Four different markets**
  - Synthetic NG
  - Electric power
  - Hydrogen
  - Liquid fuels

- **Four GIS inputs**
  - Geology/resource
  - Infrastructure
  - Market
  - Hazards

- **Final analysis**
  - Location of best opportunities
  - Ranking of sites by market opportunity
  - Understanding of future opportunities and contingencies
Methodology: Geological Resource

- Coal ranked on 4 factors
  - Seam thickness
  - Number of seams
  - Rank/energy content
  - Overburden characteristics
Methodology: Hazard assessment

- Ranked on multiple factors
  - Land-use; water-bodies
  - Sensitive areas
  - Populated areas
  - Active Seismic faults
  - Well density; mines
  - Aquifer status; overburden vulnerability
Methodology: Infrastructure

- Different foci for each market, but based on Euclidian distances
  - Transmission substations
  - Natural gas pipelines access points
  - Major roads for liquid transport
  - Railroad yards

Legend:
- Interstate Pipelines
- Intrastate Pipelines

Source:
Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System
Methodology 4: Market potential

- Electricity: keyed to state demand only
- Natural gas
  - Number of EIA regions receiving
  - Market of each region added
- Liquid fuels: local market only
  - Jet fuel: commercial & military airport
  - Diesel: Highways and railroad yards
- Hydrogen
  - In-state projections (Singh et al. 2005)
  - Did not map to merchant H$_2$ markets (e.g. refineries)
- EOR potential

*This section is highly dependent on TKI’s valuation*
The BP study focused on Wyoming, Illinois, & Texas

- Wyoming
  - PRB + Hanna: 300 km radius
  - Rock Springs, Green River pending
- Illinois
  - Illinois Basin + 300 km radius
- Texas
  - Lignite belt to Gulf Coast
WY coal resource varied considerably, while sequestration resource proved fairly uniform

- Screened out coals < 300 m depth
- High overall values
  - Coal > 3m thickness
  - Large area with >20m thickness
  - Good sequestration resource
- No variation in coal composition & energy content
There was a slightly higher density of hazards in the eastern PRB

- Many coal mines
- Extremely high density of CBM wells
- Higher population densities

The presence of hazards does not limit the deployment of UCG in these areas, but does affect comparisons with other areas.
Wyoming Market ranking

- Electricity market good
  - small population centers
  - proximity to transmission is key
  - Need to verify access and load limits
- Liquid fuels market deliberate underestimate
  - Wanted to illustrate methodology
  - Wanted to view heterogeneities
- Surprisingly good natural gas
  - Many connections
  - Increase western area
  - Limited by impact for sale (NE U.S. only)
- Hydrogen – simple estimate
  - Future work will forecast national H₂ demand
Wyoming statewide 2013 and 2028 ranking dominated by infrastructure and market factors

- Natural gas access, transmission hubs dominate high-end
- Resource size limited to >300m depth
- Power and liquid fuel demand centers play small role in resource estimation

These are relative rankings: the value of “low-ranked” prospects can still be very high
## Current analytical results: Wyoming

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<td>Electricity</td>
<td>4,549</td>
<td>21%</td>
<td>10,032</td>
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<td>Liquid Fuels</td>
<td>1,980</td>
<td>9%</td>
<td>9,607</td>
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<td>7%</td>
<td>8,169</td>
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<td>Hydrogen</td>
<td>2,626</td>
<td>12%</td>
<td>6,464</td>
<td>30%</td>
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<tr>
<td>All Products</td>
<td>2,626</td>
<td>12%</td>
<td>10,428</td>
<td>49%</td>
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Final points on Wyoming

- State is market export limited: the current Governor is changing this in real time, which will affect market size
- Current resource estimate is underestimated – will tie to digital top picks shortly.
- Current power market is probably underestimated (Denver, SLC)
- Changes in decisions regarding resource depth will affect resource suitability
- PRB and Hanna basin only: More to come as USGS, WOCC, and WGS publish materials

The potential of western basins is likely to prove good, but the resource considerably smaller
Next Steps:

1. Identify study areas / scale
   - How large is a basin?
2. Identify factors
   - Resource availability
   - Infrastructure
   - Hazards
   - Market potential
3. Locate data
   - Data Ownership, currency, scale
4. Process data
5. Explore preliminary results
6. Refine results
7. Final analysis and visualization
Discussion of Major Regional Factors

- Geology
  - Resource,
- Seismology
- Hydrology
- Infrastructure
- “Excluded Areas”
Thank You
Framework for a multi-University Underground Coal Gasification (UCG) Consortium

Draft April 14, 2011

Goal: to create a long-term capability for TKI in UCG in human capital. This will ensure that TKI can implement a long-term program in UCG

Method: The creation of a multi-university consortium of different departments and/or disciplines that dedicate expertise to UCG topics. Every year, 10 Masters and 3 PhDs will graduate with expertise in relevant fields, with an emphasis on UCG in their thesis. The consortium will balance a concentrated UCG program at a single Turkish university and distributed programs at multiple universities.

Consortium structure: The consortium will be led by a steering committee of university professors, as well as 1-2 TKI staff. The steering committee will:

1) Create a curriculum for their individual departments to include an emphasis in UCG
2) Advise students that are a part of the consortium
3) Lead study and research groups on UCG topics at their university
4) Perform research and publish papers on those findings
5) Participate in international conferences in UCG

The consortium will dedicate itself to collaborative advancement of UCG.

Consortium activities:

The collective consortium activities include:

- Hold periodic meetings to discuss research projects and UCG advancements.
- Host an international UCG conference and training workshop every alternate year
- Create a summer program in UCG. This program will encourage collaboration among researchers and students. The summer program consists of seminars, visiting UCG sites for intensive field experience, and collective academic research.

Each University in the consortium will:

- Recruit students to study UCG topics
- Identify and pursue funding for UCG research
- Be available for TKI as experts in the field
- Teach classes on the different components of UCG

Funding: This consortium will be funded by multiple methods.

- TÜBİTAK will provide funding for faculty and students, similar to its programs in other coal-related fields.
The consortium could have a privately funded mechanism; these private companies could sponsor conferences, students, field trips, etc...

TKI can provide support and coordination funding, a “center” or “unit” based in Ankara; TKI will also be a repository of relevant UCG data and academic papers and funding.

It is important to create a funding mechanism that promotes collaboration between consortium members.

**Academic departments / disciplines:**

The following areas of expertise are relevant to the UCG Consortium, and may be housed in different university programs:

- **Underground fossil energy technologies**
  - Underground coal gasification
  - Coal science and/or technology
  - Petroleum engineering
  - Enhanced oil recovery
  - Drilling and well completion technology
  - Coal bed methane technology
  - Shale gas technology
  - CO2 management/sequestration siting and engineering

- **Above ground fossil energy technologies and marketplace**
  - Coal gasification expertise
  - Pipeline marketplace and engineering
  - CO2 management/sequestration siting, marketplace, project planning, permitting
  - Fossil energy conversion technologies and marketplace
  - Energy/environmental project permitting/regulations
  - Energy process or chemical process project cost estimation

- **Subsurface science and engineering**
  - Geophysical logging technology,
  - Underground geophysical imaging technologies
  - Geotechnical/geomechanical engineering
  - Hydrogeology flow and transport,
  - Hydrological monitoring technologies
  - Geologic spatial modeling
  - Sedimentary geology

- **Chemical/mechanical engineering**
  - “Reaction Engineering” (a classic ChemE specialization)
  - Reactive flow, heat, and mass transfer cfd modeling or experiments
  - Energy process or chemical process engineering
  - Energy process or chemical process project cost estimation
LLNL OUTGOING MEMO

TO: Şahika Yürek, TKI  
DATE: May 9, 2011  

FROM: Noah Goldstein, David Camp, Rengin Gok, Jeff Wagoner, LLNL  

Subject: Next Steps by LLNL and TKI  

Contact information:  
Noah Goldstein  Goldstein8@llnl.gov  925-423-3046  
David Camp  Camp2@llnl.gov  925-423-9228  

The following are next steps to be performed by TKI and LLNL for the TKI UCG Program Project  

LLNL is currently packaging a number of products at LLNL for the TKI UCG team. These include:  

1) A compilation of the presentations and findings from LLNL  
2) A list of data sets for TKI to organize and send to LLNL  
3) A set of next steps for assisting TKI to generate a program in UCG.  
4) Suggested changes to the work LLNL can do to help TKI reach its goals, based on what is needed.  

LLNL is expecting the following products from TKI::  

1) The coal resource contour maps that identify the geology of the Turkish seams more completely  
2) A list of your coal fields that you believe are attractive candidates for UCG, based on the criteria we discussed during our visit  
3) The report describing the Slovakian block testing, in English if available  
4) An English version of Aysa’s MA thesis abstract and a copy of the thesis, so we can extract data (please send digital, not paper copies).
5) We would find it most helpful if you could create a high-level dictionary of UCG/geology/coal words from Turkish to English for better interpretive ability of documents we have received, and expect to receive so data documents will need less translating.

6) Let us know any progress towards the kiln heating experiments on blocks or cores of marl. Or results of any discussions with local experts in decomposition of the carbonates (or sulfates, bicarbonates, hydrates, etc.) in your marl.

7) We would appreciate it if you could send us a picture of the TKI staff members we met, along with their name, contact information, position / title, areas of expertise, and role within TKI’s UCG efforts. This will greatly help our joint collaboration.