Technical Session 2:

UCG technology update, and panel, well design & engineering for future projects

Marc Mostade, Managing Director
Underground Coal Gasification (UCG) - Introduction

UCG (or In-situ Coal Gasification (ISCG)) is a combination of:

(i) a mining process  
(with its own efficiency & environmental impact), and  
(ii) a solid => gas energy conversion process  
(with its own efficiency & environmental impact).

Modern UCG is fully based on drilling & well completion, and is essentially surface gasification transplanted directly to the natural environment.

All UCG processes are similar in that they require a minimum of two process points linked in-seam:

(i) one to inject the gasifying agents and start ignition, and  
(ii) the other to recover the syngas produced.
Technology Update (well configurations)

**Linked Vertical Well (LVW)**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)

**Controlled Retracting Injection Point (CRIP)**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)

**Steeply Dipping Bed (SDB)**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)

**Standard**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)

**Linear**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)

**Enhanced**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)

**Parallel**
- **Injection Point** (oxidant: air, enriched air or oxygen, and water)
- **Production Point** (low range: $H_2$, $CO$, $CH_4$, $H_2S$, $CO_2$, steam, coal liquids and particulates)
Technology Update (gasification mode)

Linked Vertical Well (LVW)

Controlled Retracting Injection Point (CRIP)

Steeply Dipping Bed (SDB)

Standard

Linear

Enhanced

Parallel
Technology Update (best & optimum configuration)

Linear Controlled Retracting Injection Point (L-CRIP) is applicable to all depths, dip-angles and types of coal; Highest efficiency, highest productivity, lowest environmental impact.
Technology Update (reactor sections)

1. Central Rubble:
   ✓ Syngas re-combustion,
   ✓ Very high temperature (> 1300 °C),
   ✓ Important heat & mass transfers, and
   ✓ Rubble formation & compaction.

2. Coal Face:
   ✓ In-situ coal drying & char formation,
   ✓ Char gasification – solid-gas heterogeneous reactions (Boudouard & Water-gas reactions), and
   ✓ Development by conduction/erosion/convection.

3. Reactor Roof:
   ✓ Radiation, conduction & convection heat transfer,
   ✓ Overburden drying & spalling, and
   ✓ Roof collapsing.

4. Outflow Channel:
   ✓ Main pyrolysis area,
   ✓ Gas shift & methanation readjustment (< 800 °C), and
   ✓ V-shape development (risk of channel clogging for swelling coal?)
# Technology Update

(Most significant and remarkable “proof-of-concept” UCG pilot trials)

<table>
<thead>
<tr>
<th>Name</th>
<th>Thulin</th>
<th>Rocky Mountain 1</th>
<th>Rawlins CCUCG</th>
<th>El Tremedal</th>
<th>Linc Generators 4 &amp; 5</th>
<th>Carbon Energy Generators 1 &amp; 2</th>
<th>Swan Hills Synfuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funded</td>
<td>Germany, Belgium &amp; EU</td>
<td>US Government</td>
<td>Private</td>
<td>Spain, Belgium, UK &amp; EU</td>
<td>Private</td>
<td>Private</td>
<td>Alberta Innovates &amp; private</td>
</tr>
<tr>
<td>Place</td>
<td>Hainaut, Belgium</td>
<td>Wyoming, USA</td>
<td>Wyoming, USA</td>
<td>Teruel, Spain</td>
<td>Queensland, AU</td>
<td>Queensland, AU</td>
<td>Alberta, CA</td>
</tr>
<tr>
<td>Rank ASTM</td>
<td>Anthracite</td>
<td>Sub-bituminous</td>
<td>Sub-bituminous</td>
<td>Lignite (sub-bit.)</td>
<td>Sub-bituminous</td>
<td>Sub-bituminous</td>
<td>Bituminous</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Deep (&gt; 800)</td>
<td>Shallow (&lt;300)</td>
<td>Intermediate</td>
<td>Intermediate</td>
<td>Shallow (&lt;300)</td>
<td>Shallow (&lt;300)</td>
<td>Deep (&gt;800)</td>
</tr>
<tr>
<td>Dipping (°)</td>
<td>Shallow (&lt; 30)</td>
<td>Shallow (&lt;30)</td>
<td>Steeply (&gt; 60)</td>
<td>Intermediate</td>
<td>Shallow (&lt; 30)</td>
<td>Shallow (&lt;30)</td>
<td>Shallow (&lt;30)</td>
</tr>
<tr>
<td>Configuration</td>
<td>1) LVW (stopped)</td>
<td>1) ELW (E-LVW)</td>
<td>SDB</td>
<td>L-CRIP</td>
<td>4) P-CRIP</td>
<td>1) P-CRIP</td>
<td>L-CRIP</td>
</tr>
<tr>
<td></td>
<td>2) L-CRIP</td>
<td>2) L-CRIP – P-CRIP</td>
<td></td>
<td></td>
<td>5) L-CRIP</td>
<td>2) P-CRIP</td>
<td></td>
</tr>
<tr>
<td>Linking</td>
<td>1) Reverse comb.</td>
<td>In-seam drilling</td>
<td>In-seam drilling</td>
<td>In-seam drilling</td>
<td>In-seam drilling</td>
<td>In-seam drilling</td>
<td>In-seam drilling</td>
</tr>
<tr>
<td></td>
<td>2) In-seam drilling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasification agents</td>
<td>O₂/ liquid water</td>
<td>O₂/ steam</td>
<td>O₂/ steam</td>
<td>O₂/ liquid water</td>
<td>N.A. (proprietary)</td>
<td>1) Air &amp;O₂/ steam 2) Air</td>
<td>O₂/ liquid water</td>
</tr>
<tr>
<td>Tonnes gasified</td>
<td>1) N.A.</td>
<td>1) 4,150</td>
<td>N.A. (proprietary)</td>
<td>375</td>
<td>N.A. (proprietary)</td>
<td>N.A. (proprietary)</td>
<td>N.A. (proprietary)</td>
</tr>
<tr>
<td></td>
<td>2) 40</td>
<td>2) 9,870</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Gas losses (%)</td>
<td>High (&gt; 10)</td>
<td>1) High (&gt; 10)</td>
<td>Low (&lt;5)</td>
<td>High (&gt; 10)</td>
<td>N.A. (proprietary)</td>
<td>N.A. (proprietary)</td>
<td>N.A. (proprietary)</td>
</tr>
<tr>
<td></td>
<td>2) Low (&lt;5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasification efficiency (%)</td>
<td>Low (&lt; 75)</td>
<td>1) Low (&lt; 75)</td>
<td>High (&gt; 85)</td>
<td>Intermediate</td>
<td>N.A. (proprietary)</td>
<td>O₂: High (&gt; 85)</td>
<td>High (&gt; 85)</td>
</tr>
<tr>
<td></td>
<td>2) High (&gt; 85)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Air: Low (&lt; 7)</td>
<td></td>
</tr>
<tr>
<td>Dry syngas HHV (MJ/Nm³)</td>
<td>High (&gt; 12)</td>
<td>1) Intermediate</td>
<td>High (&gt; 12)</td>
<td>High (&gt; 12)</td>
<td>N.A. (proprietary)</td>
<td>O₂: High (&gt; 12)</td>
<td>High (&gt; 12)</td>
</tr>
<tr>
<td></td>
<td>2) High (&gt;12)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Technology Update (dry-N$_2$-free syngas composition)

Optimum range of syngas quality with depth (pressure)

- Swan Hills (100-120 bar)
- Bloodworth Creek (15-20 bar)
Technology update (Lessons learned from the El Tremedal project)

As an introduction to the guidelines of projects in the future, on a worldwide basis, MCE has summarised/integrated in a document:

✓ The lessons learned from the first trial in a framework of a community collaboration (THERMIE funded: SF/369/91; (1991-1997)). The in-situ coal conversion experiment at El Tremedal (Spain) demonstrated the technical feasibility of carrying out in-situ coal conversion process at an intermediate depth (500 to 600m) from Sub-bituminous C (ASTM) coal and established the potential viability of using the linear CRIP technique. The coal gasified in El Tremedal is very similar to the Oltenia coal (Lignite B coal) and the Velenje coal (Lignite A coal) analysed in the COAL2GAS project. The geological/hydrogeological conditions of the overburden at El Tremedal site are also similar (at the exception of the depth) to the conditions encountered at the Oltenia site.
Main issues:

- The down-dip in-seam section of deviated injection well and the high permeability and low strength of the sandstone overburden resulted in large quantities of water flowing and re-cycling into/around the in-situ georeactor, reducing the efficiency of gasification and creating consequently large volumes of steam/water to be produced; and
- The high gasification pressure and high permeability of the overburden allowed approximately 17% of the product gases to escape into the surrounding strata (with recycling water added to the bottom of the production well).
Improvements for future UCG projects:

- **Maintain all time** (during and after gasification operations) the underground reactor **pressure at significantly less (15-20%)** than the minimum water pressure of the surrounding underground system, thereby creating a positive pressure gradient on each in-situ reactor;
- **Drill and complete** the in-seam section of the deviated injection well **up-dip**; and
- **Manage/optimise the rate of gasification** in function of the important moisture content of soft coals and water influx present in and surrounding the targeted coal seam (the optimisation of the gasification rate will be **site-specific**: e.g. different gasification rate conditions will be drawn for Oltenia site in regard to the Velenje site conditions (geology and hydrogeology)).
A number of essential lessons learned for future UCG trials regarding directional drilling, detailed engineering design of the underground components and the gasification operations.

The problems identified during the Spanish trial are relatively easy to solve, especially given advances in drilling, completion and exploration technologies.

The El Tremedal trial (1996-1997) was seen as laying the foundations for subsequent CRIP-based UCG trials in Europe and worldwide (=> Swan Hills Trial, Canada).
Technology Update (comparison with surface gasifiers)
## Technology Update (comparison with surface gasifiers)

<table>
<thead>
<tr>
<th>(=&gt; Power, SNG, GTL, ...)</th>
<th>UCG</th>
<th>Surface Gasification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal mining, transport, washing &amp; storage</td>
<td><strong>Included</strong> in underground process</td>
<td>In addition to surface process</td>
</tr>
<tr>
<td>Slag control &amp; disposal</td>
<td><strong>Included</strong> in underground process</td>
<td>Part of surface process; Following constructors</td>
</tr>
<tr>
<td>Fly ash control &amp; disposal</td>
<td>Very reduced production; Part of surface process</td>
<td>Part of surface process; Following constructors</td>
</tr>
<tr>
<td>Reactor type &amp; size</td>
<td>CRIP-module based reactor; Mining panel configuration</td>
<td>Following constructors</td>
</tr>
<tr>
<td>Reaction residence time</td>
<td><strong>Minutes</strong></td>
<td><strong>Seconds</strong></td>
</tr>
<tr>
<td>Cold gas gasification efficiency</td>
<td>&gt; 80%</td>
<td>Following constructors</td>
</tr>
<tr>
<td>Syngas quality</td>
<td><strong>High CH₄ content</strong>; Increasing with depth/pressure</td>
<td>Following constructors</td>
</tr>
<tr>
<td>CAPEX</td>
<td>About 1/3 of surface gasification (mining &amp; transport excluded)</td>
<td>-</td>
</tr>
</tbody>
</table>

Your Partner in Non-conventional Deep Coal Engineering
UCG is a combination of environment, technology, operations and economy. Environmental impact mitigation will dictate minimum depth. Operations and cost will dictate maximum depth.
## Technology Update (comparison with coal supply chain)

**Your Partner in Non-conventional Deep Coal Engineering**

<table>
<thead>
<tr>
<th>Stage</th>
<th>EXW</th>
<th>FOB</th>
<th>CIF</th>
<th>DAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td>50-80 USD/t</td>
<td>56-106 USD/t</td>
<td>61-121 USD/t</td>
<td>67-147 USD/t</td>
</tr>
<tr>
<td>Preparation</td>
<td>50-70 USD/t</td>
<td>0-10 USD/t</td>
<td>4-6 USD/t</td>
<td>4-6 USD/t</td>
</tr>
<tr>
<td>Transport</td>
<td>2-20 USD/t</td>
<td>5-15 USD/t</td>
<td>4-6 USD/t</td>
<td>2-20 USD/t</td>
</tr>
<tr>
<td>Export Terminal</td>
<td>4-6 USD/t</td>
<td>2.1-4.2 USD/GJ</td>
<td>2.3-5.1 USD/GJ</td>
<td></td>
</tr>
<tr>
<td>Import Terminal</td>
<td>4-6 USD/t</td>
<td>2.1-4.2 USD/GJ</td>
<td>2.3-5.1 USD/GJ</td>
<td></td>
</tr>
<tr>
<td>Sea Freight</td>
<td>4-6 USD/t</td>
<td>2.1-4.2 USD/GJ</td>
<td>2.3-5.1 USD/GJ</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>2-20 USD/t</td>
<td>2-20 USD/t</td>
<td>2-20 USD/t</td>
<td>2-20 USD/t</td>
</tr>
<tr>
<td>Surface Plant</td>
<td>4-6 USD/t</td>
<td>2-20 USD/t</td>
<td>2-20 USD/t</td>
<td>2-20 USD/t</td>
</tr>
</tbody>
</table>

USD/t refers to USD per ton, USD/GJ refers to USD per gigajoule.
Your Partner in Non-conventional Deep Coal Engineering

Technology Update (raw syngas costs)

Conversion factors
1 GJ = 0.9478 mmBtu
1 GJ = 0.2778 MWh (thermal)

At 1,000 depth

- 120 GJ/m² => 5.3 m thickness
  25%-ash Anthracite & Bituminous
- 120 GJ/m² => 7.0 m thickness
  25%-ash Sub-bituminous
- 120 GJ/m² => 8.3 m thickness
  25%-ash Lignite

UCG becomes economic when the value of the amount of energy that can be drained from a UCG module exceeds the cost of installing a running module.
Technology Update (general lessons learnt)

The main findings and lessons learnt in UCG are:

(i) Gasify in-situ coal with pure oxygen and liquid water at great depth and high pressure: the counter-pressure of the underground reactor(s) will also be maintained continuously at significantly less than the minimum water pressure existing in the underground system;

(ii) Design the gasification module/reactor configuration in order to control/manage continuously the injection point low in the coal seam related to the production point (up-dip in-seam injection sections and “cavity gasification” mode);

(iii) Have an integrated sub-surface instrumentation and monitoring strategy to optimise both processes (mining and solid-to-gas conversion);

(iv) Commercialise progressively the technology: expanding from 2 reactors in parallel (“early-commercial”) to, perhaps 10 or more (“full-commercial”);

(v) Apply, from inception to commercial deployment of the project, a risk assessment strategy (technical, operational, environmental & financial) based on successive layers of protection: site selection & mining plans, sub-surface design & control, critical alarms & safety systems, and emergency plans; and

(vi) Foresee, from project inception, the mining plans that includes the sub-surface exploring, commissioning, operating, and decommissioning plans.

Your Partner in Non-conventional Deep Coal Engineering
Engineering (module concept & modelling)

Model calculates mass & energy (syngas) flow rates of an UCG module (defined as a pair of linked injection & production points/wells).

Key inputs:
✓ Coal seam thickness
✓ Coal seam depth & dip angle
✓ Coal quality (energy density)
✓ Energy (cold gas gasification efficiency)
✓ Geometrical (mining sweep efficiency)

Key outputs:
✓ Syngas & energy flow rates
✓ Syngas composition
✓ Oxygen & water consumption rates
✓ Underground gasification and deposition rates (coal, ash and char)
✓ Energy Return On Energy Investment EROEI (oxygen & drilling energy)

Your Partner in Non-conventional Deep Coal Engineering
Engineering (basic well configuration and design)
# Engineering (integrated risk assessment)

Risk assessment based first on the Layers of Protection Analysis (LOPA) methodology:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Site and Technology Selection &amp; Mining Plans</td>
</tr>
<tr>
<td>2.</td>
<td>Sub-surface Process Design, Monitoring and Control</td>
</tr>
<tr>
<td>3.</td>
<td>Critical Alarms and Safety Systems</td>
</tr>
<tr>
<td>4.</td>
<td>Emergency Plans</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Design, installation, commissioning &amp; integrity of UCG module (injection &amp; production wells)</td>
</tr>
<tr>
<td>2.</td>
<td>Design, installation, commissioning &amp; integrity of monitoring wells</td>
</tr>
<tr>
<td>3.</td>
<td>Ignition and relocation process</td>
</tr>
<tr>
<td>4.</td>
<td>Single-module operations</td>
</tr>
<tr>
<td>5.</td>
<td>Multi-modules operations</td>
</tr>
<tr>
<td>6.</td>
<td>Decommissioning</td>
</tr>
<tr>
<td>7.</td>
<td>Rehabilitation</td>
</tr>
</tbody>
</table>
The Features, Events and Processes Risk Assessment (FEP-RA) methodology developed by TNO is integrated to the previous:

<table>
<thead>
<tr>
<th>Likelihood / Probability</th>
<th>Impact / Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td>Possible</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Likely</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>High</td>
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<tr>
<td></td>
<td>High</td>
</tr>
</tbody>
</table>

(Green = low risk, acceptable; yellow = moderate risk, possibly acceptable; red = high risk, not acceptable)
The Phase Gate Management (PGM) methodology is added:
The essential operational stages of a module (panel) are:

- Module (panel) commissioning (water communication, water => nitrogen exchange, and nitrogen communication);
- Module (panel) operating (including ignition/start, temporary shutdowns for maintenance and subsequent re-starts);
- Module (panel) venting with nitrogen and cooling with water; and
- Module (panel) decommissioning (including well cementing and abandonment)
Process optimisation has the following objectives, namely to:

- Produce a sustainable high quality syngas with minimal compositional variation;
- Maximise the energy conversion (gasification) efficiency;
- Maximise the geometrical (mining sweep) efficiency;
- Minimise the pyrolysis (char/coal ratio indicator); and
- Minimise gas and heat losses.
Engineering (mining plans)

- Future expansion area: topography, seismic, access roads, ...
- Drilling, well completion & commissioning: exploration & process wells,
- Gasification operations & controls,
- Venting & cooling operations for safe decommissioning, and
- Activities of (i) subsidence & underground water monitoring, and (ii) well abandonment.
Engineering (commercial deployment)

ASU & Gas Compressor Plant (early commercial)

ASU & Gas Compressor Plant (full commercial)

Process Water Pumping Units (2 + N units)

Supply H2O

UCG Well Field

Losses

Char

N modules

2 modules

Raw Syngas

Pre-end-use Processing Plant (early commercial)

Cleaned/refined Syngas

End-use Plant (early commercial)

Pre-end-use Processing Plant (full commercial)

Cleaned/refined Syngas

End-use Plant (full commercial)

Water Treatment Plant (full commercial)

Water Treatment Plant (early commercial)

Coal

Water influx

Sparging Water Pumping Units (2 + N units)

© Most Coal Engineering Sprl
Engineering (processing routes & CCS)

UCG Raw Syngas
HHV: +1/4 NG;
CO₂ footprint ≈ 2xNG

UCG Dry Syngas
HHV: +1/3 NG;
CO₂ footprint ≈ 2xNG

UCG Refined Syngas
HHV: +1/2 NG;
CO₂ footprint ≈ NG

Reforming

Multi-step Shift

Acid Gas Removal

Gas Separation

SNG

CO + H₂

Hydrogen & Fertilisers

HHV: ≈ 1/3 NG

Sour Shift

SNG

H₂/CO=3

Acid Gas Removal

Multi-step Methanation

Liquids

HHV: > NG; CO₂ footprint > NG

Gas To Liquid

(F-T, methanol, ...)

Water Removal

Acid Gas Removal

Sour Shift

H₂/CO=n

Water Removal

Acid Gas Removal

Sour Shift

H₂/CO=3

Acid Gas Removal

Water Removal

Acid Gas Removal

Acid Gas Removal

Acid Gas Removal

CO₂

CO₂

CO₂

CO₂

CO₂
Engineering (poly-generation hub concept – early commercial)

- Power
- Nitrogen
- Argon
- SNG
- CO$_2$
- Water
- Liquids/Tars
- Chemicals
Engineering (oxy-combustion & CCS)

UCG Raw Syngas
HHV: +1/4 NG; CO₂ footprint ≈ 2xNG

Oxy-combustion

Power Generation

Condensation

High pressure/temperature steam/CO₂ stream
H₂O > 80%; CO₂ < 20%

UCG to oxy-combustion power generation => self-sufficient in water

Particularly suitable for area with water shortage
Technology Update (dry-$N_2$-free syngas composition)

Optimum range of syngas quality with depth (pressure)

- Swan Hills (100-120 bar)
- Bloodworth Creek (15-20 bar)
Potential of UCG Coal Resources

Every 100 millions tonnes equivalent (29.4 GJ/t) of coal in place have the potential to produce approx. 1,100 PJ of high quality (> 12 MJ/Nm³) syngas (CH₄, CO, H₂, CO₂) that could be, in turn, converted/processed in

(1PJ = 1 million GJ = 1 billion US MJ)

(i) => 20-25 billions cubic metres of synthetic natural gas (SNG); or

(i) => 120-140 millions barrels of synthetic liquids (diesel, naphtha, ...).