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<thead>
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<th>Term</th>
<th>Definition</th>
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<tr>
<td>AI-EES</td>
<td>Alberta Innovates – Energy and Environment Solutions</td>
</tr>
<tr>
<td>bpd</td>
<td>Barrel per stream day</td>
</tr>
<tr>
<td>Btu</td>
<td>British Thermal Units</td>
</tr>
<tr>
<td>CCA</td>
<td>Coal Conservation Act</td>
</tr>
<tr>
<td>CCPC</td>
<td>Canadian Clean Power Coalition</td>
</tr>
<tr>
<td>CHOPS</td>
<td>Cold Heavy Oil Production with Sands</td>
</tr>
<tr>
<td>CAPRI</td>
<td>Catalytic upgrading Process In-situ</td>
</tr>
<tr>
<td>CPF</td>
<td>Central Processing Facility</td>
</tr>
<tr>
<td>CRIP</td>
<td>Continuous Retraction of the Injection Point</td>
</tr>
<tr>
<td>CWE</td>
<td>Cooling Water Equivalent</td>
</tr>
<tr>
<td>EIA</td>
<td>Environmental Impact Assessment</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>GJ</td>
<td>Gigajoule ($10^9$ Joules)</td>
</tr>
<tr>
<td>HHV</td>
<td>High Heating Value</td>
</tr>
<tr>
<td>IGCC</td>
<td>Integrated Gasification, Combined Cycle Power Plant</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>ISCG</td>
<td>In-Situ Coal Gasification</td>
</tr>
<tr>
<td>LVW</td>
<td>Linked Vertical Well</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt (electric)</td>
</tr>
<tr>
<td>MWth</td>
<td>Megawatt, thermal</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural Gas Combined Cycle Power Plant</td>
</tr>
</tbody>
</table>
Term Definition
OGCA Oil and Gas Conservation Act
OGCR Oil and Gas Conservation Regulation
OOIP Original Oil-In-Place
OTSG Once Through Steam Generator
SAGD Steam Assisted Gravity Drainage
SIR Supplementary Information Request
SOR Steam to Oil Ratio
TJ Terra Joule ($10^{12}$ J)
TOR Terms of Reference
$ Canadian dollars, unless otherwise noted (Q1/2013 basis)
THAI Toe to Heat Air Injection
VAPEX Vapor Extraction of Bitumen
WACC Weighted Average Cost of Capital
WTI West Texas Intermediate Crude Oil Used as a Price Benchmark

List of Definitions

Term Definition
Enhanced-LVW ISCG technology comprising a set of vertical, horizontal and/or slant wells.
Module The combination of a single injection well, production well and associated monitoring/logging wells hydraulically lined to produce Syngas.
ISCG Panel A number of individual ISCG Modules operating simultaneously to generate a target quantity of total Syngas.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Linear-CRIP</td>
<td>ISCG technology comprising a horizontal injection well and a vertical production well.</td>
</tr>
<tr>
<td>Parallel-CRIP</td>
<td>ISCG technology comprising a horizontal injection well, a horizontal production well and a vertical injection well.</td>
</tr>
<tr>
<td>Syngas</td>
<td>The product gas from gasification, comprising primarily of CH₄, CO, H₂, CO₂ and trace gases such as H₂S.</td>
</tr>
</tbody>
</table>
1.0 EXECUTIVE SUMMARY

In the in-situ coal gasification (ISCG) process, oxygen (or air) and steam are injected into a deep coal seam through an injection well. The oxidants react with the coal in-situ through a set of pyrolysis, gasification and oxidation reactions to produce synthesis gas (Syngas) comprising primarily of CH₄, CO, H₂, CO₂ and trace gases such as H₂S. Syngas, which is brought to the surface through a production well, can be used to produce a range of products including power, transportation fuels and petrochemicals.

The technical and economic value proposition of ISCG technology (described in Section 1.3) for deep Alberta coal seams is evaluated in this report. Key findings include:

- Alberta has vast quantities of geologically continuous, currently un-mineable deep coal resources that could potentially be recovered through in-situ coal gasification (1.5 trillion tonnes at depths of 250 – 3,600 m and with seam thicknesses of up to 12 m to support multiple commercial scale operations) within the Province;
- The well drilling and completions technologies required for in-situ coal gasification are relatively well established and commercially proven for in-situ bitumen extraction from the Oilsands, and could be readily adapted;
- The marginal cost of Syngas production from an integrated ISCG/FT liquids facility can be significantly lower than the current price of natural gas due to the high level of integration with the oxygen supply and ISCG process requirements.
- An ISCG Syngas plant once constructed could become a predictable, cost stable, low-cost supplier of energy for a base load fuel or Syngas processing application for:
  - the production of Fischer-Tropsch (FT) transportation fuels and essentially eliminate the natural gas price volatility impact on the economics of a conventional gas to liquids plant;
  - power generation while meeting new Federal regulations on greenhouse gas emissions from coal based power plants and cost competitive with natural gas fired combined cycles operating as base load units (95% capacity utilization) at projected natural gas prices; and
  - use as a boiler fuel for steam assisted gravity drainage operations, replacing for natural gas. The analysis indicates that there would be essentially no change to the boiler performance due to the fuel switch to Syngas and minimal retrofit costs. However, a 10 – 15% reduction in the greenhouse gas intensity (tonne of CO₂ per barrel produced) for bitumen production could be achieved.
- Surface processing facilities to treat the Syngas are based on commercially proven processes; and
• Environmental and regulatory permits for an ISCG facility can be obtained; the Alberta regulatory regime is one of the most advanced jurisdictions in the world with respect to ISCG permitting.

The Study finds that the ISCG technology and economics look promising. However the analysis assumes a long term, consistent Syngas quality and quantity, which must be tested through site specific field demonstration. A key limitation of the study is the reliance on computer simulations, using design conditions significantly beyond what is proven with existing operating experience, such as:

• Deeper coal seams (> 200 m depth); and
• Continuous operation at the required commercial scale Syngas production rates.

It is therefore recommended that commercialization of the technology is preceded by field demonstration of ISCG technology by a consortium of interested parties to generate the required performance and scale-up data to support commercialization, including:

• Investigating a strategy for commercialization of the ISCG technology as potentially a complementary, not primary feedstock source for an existing or new commercial scale facility where the Syngas can be gradually incorporated into commercially proven operations;
• Finalizing a strategy for field demonstration that stages promising ISCG Technologies, capital outlay, minimizes scale-up risk and maximizes scale-up data generation and results in an optimized ISCG Module configuration for a specific site;
• Conducting targeted screening level technical and regulatory work to define the requirements for a site-specific, scale-up and commercialization focused field demonstration of ISCG technology in Alberta; and
• Developing a better understanding of ISCG technology through controlled laboratory physical test work coupled with advanced computer modelling.

The remainder of this section reviews the study objectives and highlights the key findings from the study.

1.1 STUDY OBJECTIVE

The objectives of this study were:

• Technical: To understand the key operational attributes, technology options, and risks associated with ISCG technology.
• Economic: To evaluate the value proposition and business case for the ISCG technology for selected Alberta coal seams.
• **Pathway to Commercialization:** To identify follow-up activities to support the development of an industry/government consortium leading to ISCG field demonstration pilot test work and ultimately, commercialization.

### 1.2 ALBERTA HAS SIGNIFICANT DEEP COAL RESOURCES

Alberta’s coal resources, at depths greater than 150 m, are estimated by the Alberta Geological Survey to be in excess of two trillion tonnes, while the surface coal resource is estimated to be 33 billion tonnes. The energy value in these resources is greater than the energy value of all of Alberta’s oil and gas resources combined, including the oil sands. The major coal zones of the plains area of Alberta are the Ardley coal zone, the Drumheller coal zone, and the Mannville coal zone; the estimated tonnage in place, is summarized in Table 1 (based on publicly available data from over 350,000 oil and gas boreholes that have been drilled historically, and 15,000 – 20,000 boreholes that are added to the database annually).

**Table 1 - Summary of Major Alberta Coal Zones**

<table>
<thead>
<tr>
<th>Coal Zones</th>
<th>Area (km²)</th>
<th>Coal (Gt*)</th>
<th>Depth Range (m)</th>
<th>Seam thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ardley</td>
<td>59,000</td>
<td>596</td>
<td>0 – 1,000</td>
<td>up to 10 m</td>
</tr>
<tr>
<td>Drumheller</td>
<td>128,000</td>
<td>564</td>
<td>0 – 1,300</td>
<td>up to 5 m</td>
</tr>
<tr>
<td>Mannville</td>
<td>253,000</td>
<td>500</td>
<td>250 – 3,600</td>
<td>up to 12 m</td>
</tr>
</tbody>
</table>

* Gt (gigatonnes or billion tonnes)

### 1.3 IN-SITU COAL GASIFICATION - TECHNOLOGY OPTIONS

Alberta has the diverse technical know-how to commercialize ISCG technology because of significant expertise in drilling and completions technology, chemical processing, carbon capture and the extensive conventional and unconventional oil and gas industry in the province. Three ISCG technologies evaluated for this study are described next.

#### 1.3.1 Parallel-CRIP Technology

In the Parallel-CRIP (Controlled Retraction of the Injection Point) Module shown in Figure 1, two process wells (injection and production wells) are drilled in-seam parallel to each other. The two wells are deviated towards each other at the end of the in-seam section (horizontal reach) and converged towards a third vertical borehole which is used to ignite the surrounding coal. Once the coal is ignited, the ignition point is continually retracted as the coal continues to gasify. Multiple Modules operating simultaneously would be expected to generate the Syngas required for a commercial scale operation.
1.3.2 Linear-CRIP Technology

The Linear-CRIP Module comprises a deviated in-seam injection linked to a vertical production well as shown in Figure 2. Coal ignition around the injection point gasifies the surrounding coal, to the point in time where the quality and quantity of the Syngas is not acceptable. The injection point is then retracted into fresh coal and re-ignited.

Figure 1 - Schematic of the Parallel-CRIP Configuration Showing the Location of the Process Points (Graphic Courtesy of Carbon Energy Limited)

Figure 2 - CRIP Maneuvers and New Reaction Zone Ignition in Linear-CRIP
1.3.3 **Enhanced Linked Vertical Well (Enhanced-LVW) Technology**

In this technology, modules comprise of at least two vertical wells per panel (Figure 3). Linkage between the wells is achieved by enhancing permeability of the seam by additional means such as coiled tube or horizontal drilling. The exact configuration of wells required to extract energy from a Panel is considered proprietary.

![Figure 3 - The Enhanced-LVW Configuration](image)

1.4 **KEY FINDINGS**

1.4.1 **Key Assumptions**

The key assumptions in the analysis are as follows:

- The Syngas production rate is sufficient to provide feedstock over a 30 year commercial project life (1,100 MWth for the Power generation case and 1,500 MWth for the Fischer-Tropsch transportation fuel analysis);
- Capital and operating costs for CO₂ capture, compression and pipeline delivery at the ISCG Syngas plant battery limits (at 145 bara) are included for all the in-situ coal gasification cases; and
- Credits for pipeline ready CO₂ are taken at $15/tonne.

1.4.2 **ISCG Technology Performance Comparison**

The overall coal utilization is the overall percentage of coal gasified to Syngas in the prospect area, and is the product of the following three utilization metrics (30 – 70 %):
• Prospect area utilization by modules (or panels) is the fraction of the overall coal resource that can be accessed by modules (or panels) to produce Syngas. The prospect area utilization is reported to be 70 – 80% based on the need to maintain sufficient support structures between modules (or panels) to minimize subsidence;

• Per Module (or Panel) coal utilization is the actual amount of coal gasified compared to the theoretically accessible coal within that module. The Per Module coal utilization is reported to be 65% - 95%, based on the seam thickness, seam depth, coal quality, water ingress, ISCG technology and heat loss from the reaction zone. High levels of coal utilization are achieved for thicker seams; and

• The cold gas efficiency is the fraction of energy in the gasified coal contained in the produced Syngas. Cold gas efficiency is reported to be comparable to those achievable in surface gasification facilities (70 – 90%).

1.4.3 Drilling Requirements for a Commercial Scale Project

The number of Modules (injection, production and ignition well combinations) required to supply a commercial scale facility (two F-Class Syngas turbines) over a 30 year project life was calculated. The key findings are as follows:

• The required number of Modules over the project life is significantly more sensitive to coal seam thickness than coal seam depth.

• Thinner seams require an increased number of Modules to access the same quantity of coal, which leads to significantly higher drilling costs.

• The number of Modules appears to be less sensitive to seam thickness for the Parallel-CRIP technology than the Linear-CRIP technology due to the ability to control the lateral extent of the reaction zone in the former; the Parallel-CRIP technology may be more suitable for Syngas production from thinner seams.

• For the deeper, thicker coal seams of economic interest, the drilling costs become a small part (<10%) of the overall cost of Syngas production.

1.4.4 Power Generation from ISCG Syngas

The key performance metrics for power generation from the technology options evaluated are summarized in Table 2.
Table 2 - Summary of Major Performance Metrics

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>In-situ Syngas (ISCG)</th>
<th>Surface gasification (IGCC)</th>
<th>Natural gas combined cycle (NGCC)</th>
<th>Pulverized Coal (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Natural gas combined cycle (NGCC)</td>
<td>Pulverized Coal (PC)</td>
<td></td>
</tr>
<tr>
<td>Net power production</td>
<td>MW</td>
<td>492</td>
<td>444</td>
<td>535</td>
<td>450</td>
</tr>
<tr>
<td>Design life</td>
<td>years</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>%</td>
<td>95%</td>
<td>85%</td>
<td>50%</td>
<td>93%</td>
</tr>
<tr>
<td>Relative capital intensity</td>
<td>$/$</td>
<td>2.29</td>
<td>5.45</td>
<td>1.0</td>
<td>1.99</td>
</tr>
<tr>
<td>CO₂ Captured</td>
<td>%</td>
<td>89</td>
<td>97</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Carbon Captured</td>
<td>%</td>
<td>51</td>
<td>97</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GHG intensity</td>
<td>Tonne CO₂/MWh</td>
<td>0.42</td>
<td>0.08</td>
<td>0.35</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The ISCG case has been designed to capture enough CO₂ to meet the new Canadian Federal Regulations stipulating an emission limit of 0.42 tonne CO₂/MWh for coal based power generation facilities. Compression costs for the captured CO₂ are included for all ISCG cases. There is a significant methane content in the ISCG Syngas, and thus while 89% of the CO₂ in the Syngas is captured prior to combustion, this corresponds to a lower 51% carbon capture prior to combustion. The CAPEX intensity for the ISCG Syngas case is nearly 60% lower than for the surface gasifier based combined cycle power generation unit; the ISCG Syngas CAPEX is nearly 40% lower than a pulverized coal power plant with post combustion CO₂ capture. Approximately 50% of the ISCG Syngas CAPEX is required for raw Syngas clean-up, processing and CO₂ capture and compression.

The required first year selling price for power for the ISCG Syngas case is approximately 1/3 of the price required for a similar IGCC facility, comparable to that required for a traditional pulverized coal power plant, and significantly lower than for a pulverized coal power plant that is retrofitted with carbon capture and sequestration technology at a similar capture level.
The first year price of power required for an NGCC unit is very sensitive to changes in the price of natural gas (high commodity price risk). On the other hand, ISCG Syngas will provide the power producer a cost stable fuel over the long term.

1.4.5 ISCG Syngas Interchangeable with Natural Gas for Steam Assisted Gravity Drainage Steam Generation

Steam assisted gravity drainage (SAGD) is a rapidly growing means of bitumen production in Alberta and is expected to almost triple from the current production of just under one million barrels per day to 2.8 million barrels per day by 2025. Potential operational issues and CO₂ emissions from the use of ISCG Syngas as boiler fuel for steam generation in SAGD operations were investigated. For the ISCG Syngas composition evaluated, the key findings are:

- ISCG Syngas and natural gas can be used interchangeably as steam generation boiler fuel - no significant operational issues or operating or capital cost differences were identified within the accuracy of the estimate; and

- Use of the ISCG Syngas with CO₂ capture resulted in a 10 – 15% reduction in greenhouse gas intensity compared to natural gas; the level of reduction will depend on the actual composition of the ISCG Syngas produced.

1.4.6 ISCG Syngas for Fischer-Tropsch (FT) Fuel Production

The Study evaluated the economics of producing approximately 14,000 bpd of Fischer-Tropsch transportation fuel from different mixtures of ISCG Syngas and natural gas. Historically, the volatility of natural gas prices has presented a barrier to the commercial development of gas to liquids (GTL) facilities. Natural gas commodity risk could continue to challenge the commercialization of GTL technology. The production of transportation fuels from ISCG Syngas provides an excellent opportunity to reduce, if not fully eliminate, the natural gas commodity price risk, as compared to the production of transportation fuels from natural gas alone.

This study finds that a Syngas to Fischer-Tropsch fuel conversion facility can be built to use either Syngas or natural gas, providing a valuable, low marginal cost back-up feedstock to a conventional GTL plant to ensure maximum capital utilization and long term sustainable low cost production of FT transportation fuels. The largest component in the selling price for all three cases is the capital recovery of the surface facilities. Operations and maintenance are the next highest cost component for both of the ISCG cases. For the GTL case, the second largest cost component is natural gas feedstock cost.
The greatest challenges to overcome in the development of ISCG to FT facilities appear to be the high up-front capital costs, and the technological risk of ensuring a stable quantity and composition of ISCG Syngas.

1.4.7 Environmental and Regulatory Permitting of ISCG

Permits for an ISCG facility can be obtained; the Alberta regulatory regime with respect to ISCG is more advanced than most jurisdictions in the world. The regulatory process is well laid out for the orderly development of energy related resources, including for ISCG technology demonstration and commercialization. The potential environmental impacts of ISCG are well known and technology exists to mitigate potential issues:

- Proper site selection is the most important mitigating factor for environmental effects;
- Surface subsidence is mitigated by appropriate site selection; and
- Surface and groundwater protection is achievable through proper site selection, monitoring, and control of in-situ gasification operations.

1.5 RECOMMENDATIONS

The Study finds that the ISCG technology and economics look promising. However the analysis assumes a long term, consistent Syngas quality and quantity, which must be tested through site specific field demonstration. Recommendations for further evaluation are listed below.

1.5.1 Further Evaluate Syngas End Use Options and Flowsheets

- The specificity of ISCG technologies for end use applications should be further investigated. It appears that certain ISCG technologies could be better suited to producing Syngas for fuel applications (boiler fuel, gas turbine fuel, etc.), while other technologies with a higher CO and H₂ content might be more suitable for petrochemical and transportation fuel production which require H₂ and CO rich syngas. Further investigation is recommended.
- New above ground plant configurations to produce Syngas with minimal pre-combustion processing should be investigated as a method to reduce the cost incurred by the operation of surface facilities for power generation. The following flowsheet should be evaluated for the end use raw Syngas:
  - post combustion capture on the power block;
  - an evaluation of oxy-firing technology to facilitate post combustion capture; and
  - use of oxygen in one or more of the gas turbines to generate a high CO₂ concentration flue gas (with steam as the other component). A post combustion condensing heat exchanger could be used to separate the CO₂ from the condensed
steam, potentially reducing the CO₂ capture costs. It should be noted that oxygen fired gas turbines are currently under development.

- Alternate flowsheet options to further reduce the capital cost and greenhouse gas emission intensity of an ISCG based Fischer-Tropsch plant should be evaluated.

### 1.5.2 Further Evaluation of ISCG Technology

It is recommended to investigate the variability of the Syngas composition and production rates due to the inherent variability of the target coal composition, seam conditions and operating conditions through controlled laboratory experiments:

- Reaction fundamentals need to be better understood through experimental test work to support predictive computer model development – the predicted Syngas compositions vary significantly between ISCG technology developers indicating a lack of a full understanding of the underlying physical and chemical phenomena.

- Physical test work is required to calibrate and validate on-going computer modelling efforts. Modelling ISCG operations is at an early stage, particularly for the deeper coal seam operations which are of greater economic interest. Deriving the physical and chemical data to support computer modelling efforts is required to produce a reliable model for ISCG performance predictions.

### 1.5.3 Field Demonstrate Promising ISCG Technologies in Alberta

It is recommended to investigate ISCG demonstration on a suitable Alberta coal seam to evaluate the Syngas quality and quantity achievable:

- Finalize selection of a demonstration site that could ultimately support a commercial scale operation;

- Finalize a field demonstration strategy that stages capital outlay, minimizes scale-up risk and maximizes scale-up data generation. The final, optimized Module configuration would be replicated for commercial scale operations;

- Complete selected Front End Engineering Design (FEED) studies:
  - drilling and well completion technology specification;
  - feasibility engineering and FEED study for the required surface facilities; and
  - identification of long delivery materials and equipment.

- Initiate selected environmental assessments and regulatory permitting processes:
  - clarify all regulatory policy requirements;
  - finalize permitting process and requirements; and
  - initiate collection of permitting data.
Future ISCG technology demonstration (outside the scope of this study) would use the most promising ISCG technology (or sequence of technologies) for a selected site, and Syngas end use, and provide adequate field data to:

- Refine the technology value proposition;
- Evaluate ISCG technology and commercialization strategy in a chosen coal seam;
- Evaluate, control and model the propagation of the reaction zone over time;
- Optimize Module operation and provide data to support computer modelling activities;
- Demonstrate greenhouse gas reduction opportunities and associated costs;
- Support policy development; and
- Ultimately lead to several commercial ISCG operations in Alberta.

### 1.5.4 Further Evaluate a Commercialization Strategy

It is recommended to investigate a commercialization strategy for ISCG technology comprising the following elements:

- A strategy to effectively demonstrate the most appropriate ISCG technology at a target site; capable of supporting a commercial scale operation (discussed in Section 1.5.3);
- A strategy to effectively manage the captured CO₂; and
- A strategy for the use of the produced ISCG Syngas.

Traditional approaches to commercialization have been centered on the stand-alone commercial scale production and use of Syngas. An alternative approach to be considered is the implementation of ISCG as a complementary feedstock for an existing (or new) commercial scale facility where the produced Syngas can be gradually integrated into a pre-existing process such as NGCC power, pulverized coal power plants, refineries, petrochemical complexes and GTL facilities.
2.0 BACKGROUND

In situ coal gasification (ISCG) is an emerging, transformational clean energy technology with tremendous potential to support a long term sustainable Alberta economy by unlocking significant deep coal resources. ISCG is a method to extract energy from deep, currently un-mineable coal seams. Oxygen (or air) and steam are injected into a coal seam through an injection well. The oxidants react with the coal in-situ through a set of pyrolysis, gasification and oxidation reactions to produce synthesis gas (Syngas) comprising primarily CH₄, CO, H₂, CO₂ and trace gases such as H₂S. Syngas, which is brought to the surface through a production well can be used to produce a range of products including power and liquid fuels. In addition, some heavier hydrocarbons (tars, etc.) generated from coal pyrolysis and entrained solids report with the raw Syngas at the surface.

2.1 ALBERTA’S COAL RESOURCES

Alberta is sited on a large foreland basin in which coal bearing formations underlie approximately 46% of the entire area of the province. A large publically available geological database exists in Alberta primarily because of extensive oil and gas exploration in the province. Over 350,000 oil and gas boreholes have been drilled historically, and 15 - 20 thousand boreholes are added to the database annually. Information from these boreholes has been used to quantify Alberta’s coal resources. Alberta’s coal resources, at depths greater than 150 m are estimated to be in excess of two trillion tonnes, while the surface coal resource is estimated to be 33 billion tonnes. The energy value in these resources is greater than the energy value of all oil and gas resources combined, including the oil sands.

The major coal zones of the plains area of Alberta are the Ardley coal zone, the Drumheller coal zone, and the Mannville coal zone. A summary of the coals in these zones, including estimated tonnage in place, is summarized in Table 3.

**Table 3 - Summary of Major Alberta Coal Zones**

<table>
<thead>
<tr>
<th>Coal Zones</th>
<th>Area (Km²)</th>
<th>Coal (Gt*)</th>
<th>Depth Range (m)</th>
<th>Seam thickness (up to)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ardley</td>
<td>59,000</td>
<td>596</td>
<td>0 – 1,000</td>
<td>10 m</td>
<td>[1]</td>
</tr>
<tr>
<td>Drumheller</td>
<td>128,000</td>
<td>564</td>
<td>0 – 1,300</td>
<td>5 m</td>
<td>[1]</td>
</tr>
<tr>
<td>Mannville</td>
<td>253,000</td>
<td>500</td>
<td>250 – 3,600</td>
<td>12 m</td>
<td>[1,2]</td>
</tr>
</tbody>
</table>

*Gt (gigatonnes or billion tonnes)*
2.2 THE OPPORTUNITY FOR ALBERTA

Alberta has the diverse technical know-how to commercialize ISCG technology because of significant expertise in horizontal drilling and well completions technology, chemical processing, carbon capture and the conventional and non-conventional oil and gas resources in the province. It also has the infrastructure to transport the products to market.

Potentially, ISCG has several attractive economic and environmental benefits, including:

- **Unlocking Resources:** Alberta’s significant deep coal resources not currently accessible, could be accessed through the development of this technology.

- **Cost-Effective:** When compared with clean coal technologies designed with carbon capture technologies, such as surface gasification of coal, there is a potential for significant reduction in capital (CAPEX) and operating (OPEX) expenditures due to the elimination of surface coal handling and gasification facilities. This Study found the an in-situ gasification based operation may have CAPEX and OPEX reductions of more than 50% compared to similarly sized surface gasification based processes.

- **Stable Costs:** In-situ Syngas could be produced at a stable, predictable, long-term cost and it could economically supplement or replace natural gas:
  - for a combined cycle power generation facility with appropriate CO₂ capture;
  - as an energy source for steam assisted gravity drainage (SAGD) operations;
  - as a feedstock for plants that would convert Syngas gas to high value liquid fuels or petrochemicals (e.g. methanol, hydrogen, Fisher Tropsch liquids, etc.);
  - and
  - methane could be produced to replace declining natural gas reserves in the future.

- **Clean Power:** ISCG technology has the potential to produce clean electricity from coal in an environmentally sustainable and cost-effective manner.

- **Smaller Footprint:** The surface area coverage for an ISCG facility could be an order of magnitude smaller than a comparable surface mining facility with reduced dust, noise levels and mine safety costs.

- **Reduced Freshwater Usage:** Potential to use brackish water for deeper seams as well as to re-use process water.

- **CO₂ Capture & Storage:** The cost of CO₂ capture could be greatly reduced when compared to traditional, fossil-fueled power generation and the underground spent reaction zone remaining after ISGC could eventually be a potential site for CO₂ sequestration.

- **No Solid Wastes:** Coal ash management is eliminated, since ash is not extracted with the Syngas. Tailings ponds or ash fines ponds could be eliminated.
However, there are considerable challenges to the successful commercialization of ISCG technology, including the lack of credible field data in the public domain. In that respect, ISCG could be compared to the status of in situ oil sands in the 1970’s, when the Government of Alberta initiated, and industry actively collaborated on, a significant initiative to develop and deploy novel recovery technologies, which have since been commercialized and make a significant contribution to Alberta’s prosperity today. A similar ISCG initiative could ensure sustainable prosperity in Alberta’s energy industry throughout the 21st century.

Alberta has already initiated work to support the deployment of ISCG technology. Alberta Innovates – Energy & Environment Solutions (AI-EES) provided financial support for the Swan Hills Synfuels ISGC field pilot and initiated ISCG modelling work at the University of Calgary. An application for a field pilot submitted by Laurus Energy has recently also been approved.

2.3 STUDY PARTICIPANTS

Broad participation by industry, academia and government is important to bring an understanding of the value proposition of unlocking Alberta’s deep coal resources, for the benefit of all Albertans. An overall objective of the White Paper was to generate sufficient technical and economic data to demonstrate the value proposition and importance of developing Alberta’s deep coal resources to senior decision-makers in industry and government.

Sherritt, Alberta Innovates – Energy and Environment Solutions, and the Canadian Clean Coal Power Coalition have jointly funded this Study. The participants provided overall direction to the final scope and execution of the work. Another objective of the White Paper is to provide the required background information on ISCG to accelerate the development and deployment of ISCG in Alberta.

Sherritt International Corporation (Sherritt) has conducted considerable work over the past four years on identifying ISCG-compatible coal resources, evaluating ISCG technology options, as well as assessing the economic viability and identifying potential barriers to deployment.

Alberta Innovates - Energy and Environment Solutions (AI-EES) is the lead agency for energy and environmental research in Alberta. AI-EES is a catalyst for the development of innovative, integrated ways to convert Alberta’s natural resources into market-ready, environmentally responsible energy and the sustainable management of Alberta’s water resources. AI-EES brings together decision makers from government, industry and the resource community, as well as research and technology organizations, to develop solutions for the biggest challenges facing Alberta's energy and environment sectors.
The Canadian Clean Power Coalition (CCPC) is an association of responsible, leading Canadian electricity producers. The CCPC believes that coal, along with a diverse mix of fuels like hydro, natural gas, wind, solar and nuclear, will play an important role in meeting the energy needs of the future. The CCPC's mandate is to research technologies with the goal of developing and advancing commercially viable solutions that lower coal power plant emissions. Our objective is to demonstrate that coal-fired electricity generation can effectively and economically address environmental issues - including CO₂ emissions - and move us forward to a cleaner energy future.

2.4 TECHNOLOGY COMMERCIALIZATION STATUS

There have been over 50 significant field trials of ISCG in the past century (e.g. see Burton et al. 2006). Some of the more recent US trials were well monitored and the data made publicly available, whereas older Russian trials were less well recorded and published in the open literature. The results from several historical ISCG projects are summarized in Table 4.
Table 4 - Summary of Results from Major Historical ISCG Projects from Around the World. Light blue [5]; Dark blue [6]; Purple [7]; Green [8]; Yellow [9].

<table>
<thead>
<tr>
<th>Text</th>
<th>Year</th>
<th>Coal Type</th>
<th>Technique</th>
<th>Seam Thickness (m)</th>
<th>Seam Depth, m</th>
<th>Clastic</th>
<th>Spez. SD, MJ/m³</th>
<th>System Processors (bars)</th>
<th>Thermal efficiency (%)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krutova (Russia)</td>
<td>1923-35</td>
<td>brown chamber</td>
<td>2.5</td>
<td>15</td>
<td>air</td>
<td>14.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shakhovye (Russia)</td>
<td>1933-34</td>
<td>Anthracite</td>
<td>0.38</td>
<td>n/a</td>
<td>air</td>
<td>3.87</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Krutova (Russia)</td>
<td>1923-35</td>
<td>brown chamber</td>
<td>1.75</td>
<td>20</td>
<td>air</td>
<td>14.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Leninsk-Kuznetsk</td>
<td>1924-26</td>
<td>coal mine</td>
<td>4.85</td>
<td>28</td>
<td>air</td>
<td>10.04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lisichansk (Ukraine)</td>
<td>1924-26</td>
<td>MV: bit/steam</td>
<td>0.4</td>
<td>60 oxygen</td>
<td>3.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lisichansk (Ukraine)</td>
<td>1924-26</td>
<td>bit/steam</td>
<td>0.75</td>
<td>24</td>
<td>air</td>
<td>3.78</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lisichansk (Ukraine)</td>
<td>1924-26</td>
<td>single MV</td>
<td>0.75</td>
<td>24</td>
<td>air</td>
<td>2.77</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lisichansk (Ukraine)</td>
<td>1924-26</td>
<td>bit/steam</td>
<td>0.75</td>
<td>24</td>
<td>air</td>
<td>10.45</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gorlovka (Ukraine)</td>
<td>1918-41</td>
<td>n/a SD</td>
<td>2.1</td>
<td>40 oxygen</td>
<td>3.68</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gorlovka (Ukraine)</td>
<td>1927-29</td>
<td>n/a SD</td>
<td>1.84</td>
<td>40 oxygen</td>
<td>5.82-10.34</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Podmoskovye/Tula (Russia)</td>
<td>1940-66</td>
<td>brown (HA)</td>
<td>0.3</td>
<td>9.11</td>
<td>8.4-8.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lisichansk (Ukraine)</td>
<td>1940-66</td>
<td>bit/steam</td>
<td>2.7</td>
<td>188</td>
<td>air</td>
<td>2.57</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yuzhno-Binsk (Siberia)</td>
<td>1955-69</td>
<td>LV: bit/steam</td>
<td>2</td>
<td>n/a</td>
<td>air</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Angron (Lebanon)</td>
<td>1965-69</td>
<td>brown (LA)</td>
<td>4</td>
<td>110</td>
<td>8.3-11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shatsky (Ukraine)</td>
<td>1965-69</td>
<td>brown (HA)</td>
<td>0.3</td>
<td>11</td>
<td>air</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Belgium               |       |             |            |                    |               |         |                |                         |                       |                  |
| Bolle-De-Gane (Belgium) | 1945  | Anthracite | 6          | air                | n/a           | -       | -              | -                       | -                     | -                |
| Newman Johnsey (UK)   | 1949-59 | sub bit. | 1.2        | 7.5                 | air           | 2.6     | -              | -                       | -                     | -                |
| Browne-Michot (France) | 1951  | Anthracite | 0.5       | 1200               | air           | -       | -              | -                       | -                     | -                |
| Trilin (Belgium)      | 1965-66 | Anthracite | 2         | 680                | air           | -       | -              | -                       | -                     | -                |
| Heute-Deule (France)  | 1965-66 | anthracite | 5         | 800                | air           | -       | -              | -                       | -                     | -                |
| Trilin (Belgium)      | 1965-66 | anthracite | 6         | 800                | air           | -       | -              | -                       | -                     | -                |
| El Tresmedal, Spain   | 1957-63 | Sub bit.  | 0.7       | 900                | air           | -       | -              | -                       | -                     | -                |

| United States of America |       |             |            |                    |               |         |                |                         |                       |                  |
| Hanna, WY (I)          | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (II)         | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (III)        | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (IV)         | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (V)          | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (VI)         | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (VII)        | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (VIII)       | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (IX)         | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Hanna, WY (X)          | 1975-76 | Sub bit.  | 0.7       | 700                | air           | -       | -              | -                       | -                     | -                |
| Pricedown, WV          | 1975-79 | Bit/steam | 0.7       | 800                | air           | -       | -              | -                       | -                     | -                |
| Rawlins, WY (I)        | 1975-79 | Sub bit.  | 0.7       | 720-200             | air           | -       | -              | -                       | -                     | -                |
| Rawlins, WY (II)       | 1975-79 | Sub bit.  | 0.7       | 720-200             | air           | -       | -              | -                       | -                     | -                |
| Rawlins, WY (III)      | 1975-79 | Sub bit.  | 0.7       | 720-200             | air           | -       | -              | -                       | -                     | -                |
| Centralia, WA (LBK)   | 1981-82 | Sub bit.  | 6-8       | 20-50               | air           | -       | -              | -                       | -                     | -                |
| Centralia, WA (LBK)   | 1981-82 | Sub bit.  | 6-8       | 20-50               | air           | -       | -              | -                       | -                     | -                |
| Centralia, WA (CRP)   | 1982-87 | Sub bit.  | 6-8-10    | 20-52               | air           | -       | -              | -                       | -                     | -                |
| Rocky Mountain (Hanna) | 1965-93 | Sub bit.  | 0.7       | 75                  | 02/steam      | 9.7     | -              | -                       | -                     | -                |
| Rocky Mountain (Hanna) | 1965-93 | Sub bit.  | 0.7       | 75                  | 02/steam      | 10.7    | -              | -                       | -                     | -                |
| College Station, Texas | 1977-78 | Lignite   | 7         | 75                  | 02/steam      | 9.7     | -              | -                       | -                     | -                |
| Bostport County, Texas | 1978-79 | -         | -         | -                  | -             | -       | -              | -                       | -                     | -                |
| Tennessee Colony, TX   | 1978-79 | Lignite   | 7         | 75                  | 02/steam      | 9.7     | -              | -                       | -                     | -                |
| Rocky Hill, UT         | 1978-79 | Sub bit.  | 0.7       | 75                  | 02/steam      | 10.7    | -              | -                       | -                     | -                |

| Canada                 |       |             |            |                    |               |         |                |                         |                       |                  |
| Swan Hills, Alberta    | 2005-11 | HV 8 bit.  | 7.9       | 1400                | O2            | -       | -              | -                       | -                     | -                |

* Canadian Clean Power Coalition
  * sherritt
  * Alberta Innovates and Energy Environment Solutions
3.0 STUDY SCOPE AND OBJECTIVES

3.1 OBJECTIVE

The objective of this study is to provide sufficient background information on in-situ coal gasification to a group of diverse stake holders to set the foundation for the development of an industry/government consortium leading to ISCG field demonstration pilot test work to support commercialization. The future demonstration pilot test (outside the scope of this Study) would use the most promising ISCG technology for the selected site, Syngas use and provide adequate field data to evaluate the value proposition, demonstrate greenhouse gas reduction opportunities and associated costs, support policy development and ultimately lead to several commercial ISCG operations in Alberta.

The study has the following broad objectives:

- **Technical:** To accelerate the deployment of ISCG technology in Alberta. Screening level data was compiled to educate participants on the key operational attributes, technology options, and risks associated with ISCG technology.
- **Economic:** To use the technical data generated to evaluate the value proposition and business case for the ISCG technology for selected Alberta coal seams.

The information generated could be used as part of an overall package to demonstrate the importance of developing Alberta’s deep coal resources. However, the development of a demonstration pilot plant is outside the scope of this study.

3.2 SCOPE OF STUDY

The overall work scope is described in the following sections.

3.2.1 Technical

- **ISCG Technology Comparison:** An evaluation of the most promising ISCG technologies (Parallel-CRIP (controlled retraction of the injection point), Linear-CRIP and linked vertical wells (or a combination thereof)).
- **Technical/Operational Challenges:** A brief review of the operational and technical challenges that may have historically limited the wide spread commercial adaptation of the ISCG technology.
- **Enabling Technologies:** A review of recent advances in key technologies (e.g. horizontal drilling) which may enable the cost effective commercialization of ISCG technologies.
• **Complementary Technologies:** A high level comparison with partial combustion based bitumen extraction technology and steam assisted gravity drainage (SAGD) operations.

• **Drilling Costs:** To the extent possible, indicative costs associated with in-situ drilling requirements for each technology option and indicative cost savings from optimizing the scale-up from single Modules to multiple Modules for each technology.

• **Computer Modelling of ISCG:** A review of applicable ISCG modelling techniques and a preliminary performance comparison between ISCG technologies to the extent possible.

### 3.2.2 Environmental

- Environmental Monitoring Requirements: A high level review of environmental and process monitoring requirements for selected coal seams; and
- Review of Environmental Factors:
  - **GHG Footprint:** A proof of concept level evaluation of the GHG reduction options from ISCG relative to regulatory requirements to reduce GHG;
  - **Groundwater:** The considerations required in the plant design to avoid groundwater problems will be addressed; and
  - **Ground subsidence:** The considerations required in the plant design to avoid surface subsidence problems will be addressed.

### 3.2.3 Economics

- **Expected CAPEX/OPEX Reductions:** Screening level engineering studies to further quantify the Alberta-specific value proposition for ISCG Syngas to selected final products was conducted. A comparison of the expected reduction in CAPEX/OPEX and economics for the use of ISCG technology compared to the current/expected reference (base) cases for each end product identified below (power, FT-liquids, SAGD steam) was conducted.

### 3.2.4 Regulatory/Permitting

- **Roadmap for Environmental/Regulatory Permitting:** An overview of the environmental and regulatory permitting requirements in the province of Alberta, based on a review of the applications for ISCG pilot plants recently approved under the experimental provisions by the province. Determine the environmental and regulatory permitting requirements for both a field demonstration facility and an eventual commercial facility.
3.2.5 Commercialization Roadmap

- A high level road map and progressive activity list for a stage gated pathway towards the commercial application of ISCG in Alberta was developed.
4.0 ISCG TECHNOLOGY OVERVIEW

A number of ISCG technologies exist, which are similar to the extent that they require a minimum of two process points linked within the coal seam: (1) one to inject the gasifying agents; and (2) the other to recover the Syngas produced (Figure 4). Typically, injection points are located at some point along an injection borehole (well) and production points at some point along a production borehole (well). A competent gas circuit between the ignition and production points must be constructed by increasing the coal permeability between both wells where ignition and subsequent gasification reactions can proceed. Numerous techniques are available to form a competent gas circuit between the process wells. The configuration of a linked injection well and production well is known as an ISCG “Module” (Figure 4).
There are three generic categories of Module configurations currently used in ISCG:

- The Controlled Retracting Injection Point (CRIP) concept;
- The Linked Vertical Well (LVW) concept; and
- The Steeply Dipping Bed (SDB) concept.

The reactions involved in coal gasification are well understood as coal gasification has been a common industrial process for over 150 years. The reliability of in-situ processes depends on the ability of the reactor to operate despite the variations in natural ground conditions. Reliability is therefore critically dependent on site selection processes ensuring that any known risks are avoided and ISCG panel design ensuring that the reaction zone maintains a consistent and continuous retraction across the entire width of the panel.

A requirement for any ISCG design is that the gas in the gasification reactor is contained by the surrounding strata. With this in mind, for any ISCG opportunity, it must be established that there is an impervious gas seal overlying the target coal, and that the water pressure in the target seam is high enough to limit gas loss through the seam. Apart from these generic gas flow issues, there are specific requirements for different ISCG technologies. Three promising ISCG technologies are discussed next.

### 4.1 PARALLEL-CRIP TECHNOLOGY

In the Parallel-CRIP (Controlled Retraction of the Injection Point) configuration, both process wells are deviated and drilled in-seam parallel to each other. Once the in-seam section has reached a pre-determined length within the coal seam (typically >500 m), the two process wells are deviated again and drilled towards each other to converge into a third borehole. The third borehole, known as the ignition well, is drilled conventionally (i.e. vertically) and used to ignite the coal at the start of operations and provide a target for the directionally drilled process wells (Figure 5).

This configuration was first tested at the partial seam CRIP test, in Centralia, Washington State, USA and has since been used during the Rocky Mountain 1 (RM-1) trial, Wyoming USA and by Carbon Energy Limited (CEL) at their Bloodwood Creek (Bloodwood Creek) facility in Queensland, Australia. The Parallel-CRIP configuration tested by Carbon Energy Limited is now recognized as a trademark under the name Keyseam®.

In the Keyseam® Parallel-CRIP design, methane is first pumped down the vertical ignition well, mixed with oxidant that has been injected down the injection well and ignited to initiate gasification. After ignition, oxidant is continuously pumped down the deviated injection well
and a new injection point develops at the end of the deviated injection well. Oxygen and steam pass from the injection point across the coal face to the production well.

**Figure 5 - Schematic of the Parallel-CRIP Configuration Showing the Location of the Process Points (Graphic Courtesy of Carbon Energy Limited)**

The Parallel-CRIP method uses a streaming reactor model for the gasification face. In this configuration, gasification occurs between two horizontal boreholes, one for oxidant injection, and one for product removal as shown in Figure 6. This flow path between the horizontal boreholes creates a single gasification face that advances evenly along the coal seam as coal is extracted during gasification.

The hot gases are held against a fresh coal face by the pressure differential between the boreholes, and maintain a constant gasification profile for the duration of a panel’s extraction. Parallel-CRIP maintains a continuously retracting injection point and thus maintains continuous exposure of fresh coal to oxidant; this is essential to sustain consistent high quality Syngas production. It also ensures a constant flow path for the streaming gasification face. The streaming gasification face provides high conversion efficiency as hot gases are held against fresh coal, and a consistent Syngas quality is maintained throughout the life of the panel. The in-seam section of the production well itself is lined with a perforated liner and forms a long outflow channel within the virgin coal seam. These
constant gasification conditions allow for a consistent Syngas quality to be maintained. The height, width and length of the horizontal boreholes define the panel of coal to be extracted, and the horizontal bore hole can be over 1 km in length within the coal seam. The width of the panel is determined by the distance between the parallel injection and production wells. A panel width of 30 m has been tested successfully at Carbon Energy’s Bloodwood Creek trials.

Figure 6 - Illustration of a Streaming Reactor in Parallel-CRIP In-Situ Coal Gasification

The Parallel-CRIP method is a continuous extractive ISCG process, in contrast to the “batch” processes used by other ISCG technologies. Once ignited, a Parallel-CRIP panel can operate for 5 to 10+ years in a consistent manner.

A major benefit of this flow path is the reduced risk to disruptions of the gas flow. The injection and production boreholes are within virgin coal, not affected by the disruptions of strata associated with the high temperature reaction zone formation, improving the reliability of Syngas extraction and delivery processes. In contrast, vertical extraction boreholes with the hot reaction zone situated directly at the base of the production borehole are vulnerable to high temperature impact on borehole integrity.

4.2 LINEAR-CRIP TECHNOLOGY

The Linear-CRIP module comprises a deviated in-seam injection well linked to a vertical production well (Figure 7). The injection well is either drilled along the coal seam, no more than 1 m from the base, to link the previously drilled production well, or the production well is drilled to intersect an injection well already in place. The optimum sequence of
drilling/completion of a Linear-CRIP module is defined by a contingency strategy in case of a failure of the planned drilling and completion program.

Figure 7 - (A) Schematic of the Linear-CRIP Configuration with the Injection Point, Production Point and Linkage Concepts. (B) Linear-CRIP Schematic Showing two CRIP Cavities within a Coal Seam

For the CRIP and ignition system (coiled tubing based), a “coil-in-coil” configuration is used for ignition, where tubing to introduce combustible gases and/or pyrophoric liquids is placed within the main coiled tubing that transports the gasification agents. An igniter/burner controlled remotely from surface is fixed at the tip of the coiled tubing system. The remote control of the down-hole ignition is based on a sequence of pyrophoric liquid injections through the inner coil. Figure 7 shows schematically how CRIP maneuvers are operated at depth. At start-up or when an ISCG reaction zone has matured, a window at a new position is burned/opened through the in-seam liner. These CRIP/burning operations are repeated all along the in-seam section of the injection well.
The coiled tubing CRIP system is designed to be retracted during all injection and gasification conditions. When to undertake a retraction is dictated by the performance efficiency of the active reactor, which is monitored continuously. Previously, ignitions were mainly operated by injecting hot air in the coal seam, which initiated self-ignition of the coal. Different down-hole devices were experimented with, to inject the hot air and ignitions were either operated from the vertical process wells (injection or production) or from vertically drilled ignition wells (as in the Parallel-CRIP concept previously described).

During the in-situ coal gasification process, the volume of the reaction zone will be related to the volume of coal gasified minus the volume of ash and char left in the reaction zone. In the Linear-CRIP method, a small reaction zone is initially generated above the ignition point of the deviated injection well. As gasification proceeds and solid coal is gasified, the reaction zone grows within the coal seam and extends in three-dimensions around the injection point until it intersects the roof rock. The outflow channel of the active reactor develops from the initial in-seam link at the base of the coal seam up to the roof rock. The final size of the outflow channel will be proportional to the coal seam thickness and will form the connection (high permeability rubble connection) between the active reactor and the goaf area left behind from a previous reactor.

With continued gasification, the area of exposed roof rock increases and the roof rock itself begins to collapse. Such collapse is important as it aids the lateral growth of the reaction zone into the coal seam [10]. Greater amounts of heat energy will be lost from the reaction zone as a greater surface area of the roof is exposed. The quality of the Syngas will steadily decrease as this occurs because the energy lost to the surroundings will no longer be available to drive the reactions that produce the main combustible gases in Syngas (CH₄, H₂ and CO). It will be necessary to stop gasification in the active reaction zone at a point when the conversion efficiency becomes unacceptable, then retract the injection point and create another reaction zone. The point at which it becomes inefficient to continue to gasify will essentially define the maximum size or width of the reaction zone; consequently the Linear-CRIP method is designed to optimize the geometrical (sweep) and energy conversion (gasification) efficiencies of the combined underground processes.

4.3 VERTICAL WELL TECHNOLOGY

4.3.1 Linked Vertical Wells (LVW)

In this concept, the process wells comprise at least two vertical wells drilled into the coal seam. The injection point is located at the base of the injection well and the production point at the base of the production well (Figure 8). Linkage between the wells is typically achieved by enhancing natural permeability using a number of possible techniques, such as
reverse-combustion followed by forward-combustion [12], electro-linking, horizontal drilling and coiled tube drilling [5].

Figure 8 - The Linked Vertical Well Configuration

4.3.2 Enhanced Linked Vertical Wells [Enhanced-LVW]

The enhanced, or extended, vertical well configuration (Enhanced-LVW) is very similar to the linked vertical well technology but uses a deviated in-seam borehole to link the two vertical wells (Figure 9). This creates a reliable gas path between the vertical wells. Use of the deviated in-seam borehole allows for greater distances between the vertical wells, enabling a greater volume of coal to be converted per process well pair compared with a standard linked vertical well technique.

This technique was first used at the Hoe Creek III trial in the US and again during the Rocky Mountain-1 test, Wyoming, where it was compared directly with a CRIP module. The Enhanced-LVW may also have been used in the early phases of Australian and South African projects.
Figure 9 - The Enhanced-LVW Configuration

This technique was used extensively during the Russian ISCG experiments and early trials in the USA (e.g. Table 4). At least one currently operating ISCG company is understood to use the Enhanced-LVW configuration (or a variant thereof), but details are kept confidential. The LVW technique has been extensively tested, although the results have been variable [13], and it is thought that it has never been used in coal seams greater than about 200-300 m in depth. The following recent trials are reported:

- Chinchilla, Linc Energy, Australia – gasifying a 10 m thick seam at a depth of 140 m;
- Majuba, Eskom Holdings Ltd., South Africa - gasifying 3.5 m thick seam at 350 m depth; and
- Huntley West, Solid Energy Ltd., New Zealand - gasifying the top 5 m of a 25 m thick seam at 400 m depth.

4.4 ISCG IN STEEPLY DIPPING BEDS

The Steeply Dipping Bed configuration has been used in coal seams with high dip angle (>60°) and comprises two slanted boreholes (Figure 10). The production well is drilled in-seam to a predetermined distance above the base of the injection well, which is drilled initially beneath the coal seam until it intersects the coal seam. A second deeper injection well was, in some configurations, designed to continue the gasification process deeper in the coal seam.
This configuration was first used at Bois-la-Dame, Belgium in 1948. The most significant trials, however, were undertaken during trials at Rawlins, USA between 1979 and 1981 (e.g. Table 4), which demonstrated that the steeply dipping bed configuration can achieve the highest gasification efficiency of any ISCG technique.

4.5 KEY FINDINGS – OPERATING COMPARISON

Table 5 provides a qualitative comparison of the operating characteristics and potential risks associated with the various ISCG technologies, based on the operating information and process descriptions provided by respective ISCG technology vendors.
Table 5 - Comparative Operational Risk Factors for Different ISCG Technologies

<table>
<thead>
<tr>
<th>Risks/Variables</th>
<th>Linear-CRIP</th>
<th>Parallel-CRIP</th>
<th>Enhanced-LVW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth Tested to Date</td>
<td>Up to 1,400 m</td>
<td>&lt;300 m</td>
<td>&lt;300 m</td>
</tr>
<tr>
<td>Long term operation tested</td>
<td>Up to 2 years (demonstration plant). Only short term continuous operation demonstrated (&lt; 3 months).</td>
<td>Up to 5 years (demonstration plant) with over 20 months of continuous operation.</td>
<td>Several demonstration plants operated. Commercial operation reported in the Former Soviet Union.</td>
</tr>
<tr>
<td>Scalability – Single Modules</td>
<td>Limited design optimization possible - Performance dictated by specific coal seam geometry.</td>
<td>Significant opportunity - Module optimized for specific coal (horizontal spacing, coal face retraction rate, etc.).</td>
<td>Significant opportunity? - Panels optimized for specific coal seam.</td>
</tr>
<tr>
<td>Scalability – Multiple Modules</td>
<td>Repeatable geometry and modular design (comparable to room and pillar mining).</td>
<td>Repeatable geometry and modular design (comparable to longwall coal mining).</td>
<td>Panels, not modules comprising multiple vertical, horizontal, and slant wells are drilled as required. Multiple panels are operated to produce the required Syngas.</td>
</tr>
<tr>
<td>Module-module interaction</td>
<td>Module spacing selected to limit interaction</td>
<td>Module spacing selected to limit interaction.</td>
<td>Interactions are high (by design) to ensure high coal utilization within the project area. Hydraulic linkage between modules expected.</td>
</tr>
<tr>
<td>Risks/Variables</td>
<td>Linear-CRIP</td>
<td>Parallel-CRIP</td>
<td>Enhanced-LVW</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Syngas consistency</td>
<td>Average +/- 20% of HHV reported, but higher variability expected due to batch wise retraction of the injection point.</td>
<td>Operated to give consistent composition of Syngas with lower expected variability due to the continuous retraction of the injection point.</td>
<td>Information not provided.</td>
</tr>
<tr>
<td>Reliability of shutdown, retraction, re-ignition</td>
<td>Medium/high due to batch wise CRIP maneuvers</td>
<td>Low due to single ignition for each module.</td>
<td>Medium/Low due multiple ignitions required for each panel.</td>
</tr>
<tr>
<td>Control of reactor efficiency</td>
<td>Controlled through batch wise CRIP maneuvers, and other operating parameters (H₂O/O₂ ratios, etc.)</td>
<td>Dependent on seam thickness, depth and other operating parameters (H₂O/O₂ ratios, etc.).</td>
<td>Controlled through operating parameters</td>
</tr>
<tr>
<td>Reaction zone temperature control</td>
<td>Controlled through injection of water through production well (sparging); smaller production borehole required due to lower temperature Syngas at production well head.</td>
<td>Only control is reduction of oxidant flow (decreased production); larger production borehole required due to higher temperature Syngas at the production well head.</td>
<td>Information not provided.</td>
</tr>
<tr>
<td>Drilling complexity</td>
<td>Low (only one horizontal and one vertical well required)</td>
<td>Medium (two horizontal wells required)</td>
<td>High (a combination of vertical, horizontal and slant wells required)</td>
</tr>
<tr>
<td>Risks/Variables</td>
<td>Linear-CRIP</td>
<td>Parallel-CRIP</td>
<td>Enhanced-LVW</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Drilling contingency</td>
<td>If completion of full length horizontal well fails, vertical production well can be drilled to intersect well</td>
<td>Both wells must be completed successfully for production</td>
<td>Fewer risks associated due to the availability of multiple, hydraulically connected vertical, horizontal and slant wells.</td>
</tr>
<tr>
<td>Potential for and effect of premature reaction zone collapse</td>
<td>High impact – collapse could result in loss of Syngas pathway; production well could be re-drilled as contingency</td>
<td>Low impact - unlikely to affect the reactor significantly</td>
<td>High probability due to the claimed high utilization of the coal, but low impact; reaction zone collapse expected as part of operation.</td>
</tr>
<tr>
<td>Module contingency (due to plugging, etc.)</td>
<td>Vertical production well can be re-drilled as a contingency</td>
<td>Wells can be sealed and new horizontal wells drilled</td>
<td>Wells can be sealed and new wells drilled</td>
</tr>
<tr>
<td>Decommissioning methods</td>
<td>Some decommissioning work undertaken in the past (Rocky Mountain, Swan Hills, El Tremedal); no active development.</td>
<td>Decommissioning methodology under development</td>
<td>Developed and proven methods in the Former Soviet Union; transferability to western Canada unclear.</td>
</tr>
<tr>
<td>Ability to flush reactor to remove contaminants</td>
<td>High; link between ignition and production wells provide conduit for flushing</td>
<td>Limited due to configuration of injection and production wells</td>
<td>Difficult due to interconnectivity between reactors</td>
</tr>
</tbody>
</table>
5.0 SIMILARITIES WITH IN-SITU BITUMEN EXTRACTION TECHNOLOGIES

This section provides an overview of the in-situ thermal operations for bitumen extraction, which offer many parallels for the technologies required for ISCG Syngas extraction. An overview of in-situ heavy oil recovery technologies and a comparison to steam assisted gravity drainage (SAGD) well construction with those proposed for ISCG is also provided. The drilling technologies available in western Canada from related industries is described as well.

5.1 THERMAL IN-SITU HEAVY OIL RECOVERY TECHNOLOGIES

When considering in-situ coal gasification (ISCG), the lessons learnt in accessing deep heavy oil deposits and their in-situ recovery are relevant. In particular, the rapidly developing thermal methods of in-situ combustion and SAGD as well as the drilling technologies that are applied are comparable with the main methods of implementing ISCG; linked vertical wells, Linear-CRIP and Parallel-CRIP.

5.1.1 Enhanced Recovery of Heavy Oils

Conventional crude oil is normally recovered by drilling oil wells into a petroleum reservoir, from where the oil flows to the surface under natural reservoir pressure, although artificial lift and techniques such as water flooding and gas injection are usually required to maintain production as reservoir pressure drops toward the end of a reservoir’s life [14]. In the case of oil sands, which are considered as unconventional, the hydrocarbon resource is predominantly present as heavy oil and bitumen. Of the 170 billion barrels of bitumen estimated by the Alberta Energy Resources Conservation Board [15] to be recoverable from identified deposits, 34 billion barrels or 20% is accessible with current surface mining technology [16]. Bitumen must be recovered from the oilsands by strip mining or the oil must be made to flow into wells by in-situ methods due to the high viscosity of bitumen.

The principal obstacle to the in-situ recovery of heavy oil and bitumen from underground reservoirs is the high viscosity of these liquids. Practical enhanced oil recovery methods rely on reducing the viscosity of the oil to a point where it can be pumped to the surface.

In the in-situ extraction of heavy oil from oil sand formations, between 20 and 30 percent of the oil can be recovered by means of primary and secondary recovery methods (Table 6).
Table 6 - Primary and Secondary In-Situ Bitumen Recovery Techniques

<table>
<thead>
<tr>
<th>Recovery</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Pressure Pulse Technology (PPT)</td>
</tr>
<tr>
<td></td>
<td>Cold Heavy Oil Production with Sand (CHOPS)</td>
</tr>
<tr>
<td>Secondary</td>
<td>Inert Gas Drainage</td>
</tr>
<tr>
<td></td>
<td>Water Injection</td>
</tr>
</tbody>
</table>

After the conventional primary and secondary recovery methods have been exhausted, tertiary (enhanced oil recovery) methods are used to increase oil recovery. These methods can be divided into two broad categories; thermal and non-thermal. The most important of these methods are summarized according to their level of technological maturity in Table 7.

Table 7 - Enhanced Oil Recovery Technologies

<table>
<thead>
<tr>
<th>Maturity</th>
<th>Tertiary (Enhanced Oil Recovery) Method</th>
<th>Thermal</th>
<th>Non-thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed</td>
<td>Cyclic Steam Stimulation (CSS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steam Assisted Gravity Drainage (SAGD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emerging</td>
<td>Toe-to-Heel Air Injection (THAI)</td>
<td>Vapor Assisted Petroleum Extraction (VAPEX)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catalytic upgrading Process In-situ (CAPRI)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cyclic steam stimulation has largely been superseded by SAGD. Emerging technologies such as THAI and VAPEX could, in turn, compliment PPT, CHOPS and SAGD. Brief descriptions are given for the SAGD and THAI methods. Importantly, parallels may be drawn between in-situ heavy oil recovery (particularly the SAGD and THAI methods) and in-situ coal gasification.

5.1.2 Steam Assisted Gravity Drainage

In the SAGD process, two parallel horizontal oil wells are drilled in the formation, one about 4 to 10 metres above the other. During steady state operation, the upper well injects steam, and the lower one collects the heated crude oil or bitumen that flows out of the formation, along with any water from the condensation of injected steam. The basis of the process is that the injected steam forms a "steam chamber" that grows vertically and horizontally in the formation. The ideal steam chamber is shown in Figure 11. The heat from the steam reduces the viscosity of the heavy crude oil or bitumen which allows it to flow down into the lower
wellbore [17]. A well configuration and stream flows for a typical SAGD implementation is shown in Figure 11.

![Figure 11 - A Representation of a SAGD Steam Chamber [20]](image)

### 5.1.3 Toe-to-Heel Air Injection

Toe-to-Heel Air Injection (THAI) is an integration of injection and production wells and combustion processes with a target to recover about 70-80% of heavy oil from unconventional reservoirs. Essentially, THAI consists of a vertical injection well located at the ‘toe’ of the horizontal well and a lateral producer that frames the heel to thermally recover the mobilized oil. During the process a combustion front is created where part of the oil in the reservoir is burned, generating heat which reduces the viscosity of the oil allowing it to flow by gravity to the horizontal production well. The combustion front sweeps the oil from the toe to the heel of the horizontal producing well recovering an estimated 80% of the Original Oil-In-Place (OOIP) while partially upgrading the crude oil in-situ [19]. A schematic showing the process is shown in Figure 12.
**Figure 12 - Toe-to-Heel Air Injection. Air or Oxygen is Injected and Part of the Resource is Ignited to Heat the Reservoir [21]**

5.1.4 Accessing the Oil Reservoirs

The main method of gaining access to the oil reservoir for in-situ recovery is by means of vertical and horizontal wells drilled into the reservoir. The required drilling technologies have been perfected to a large degree, allowing accurate and precise placement of multiple wells over large lateral distances and depths. The typical arrangement of SAGD wells in a field is shown in Figure 13. The wells are positioned in a way such that the entire payzone can be accessed.
5.2 KEY FINDINGS

A comparison of the drilling specifications for a typical SAGD operation with those stipulated for Parallel-CRIP and Linear-CRIP technology has shown that essentially all the drilling requirements for ISCG operations can be either directly applied from corresponding SAGD operations or adapted readily; no areas of major concern were noted upon review of the technical specifications, specifically:

- There have been significant recent advances in horizontal drilling technology, which can be expected to support the eventual commercialization of the ISCG technology, especially in western Canada with vast, contiguous coal seams.
- For this study, the maximum depth of coal was assumed to be 1,600 m, with a 1,600 m maximum horizontal reach within the coal seam which reflects coal seam characteristics in western Canada.
- Alberta has the required skill sets to achieve the drilling required for ISCG.
6.0 QUANTIFYING ISCG TECHNOLOGY PERFORMANCE

One of the key objectives of this Study was to generate to the maximum extent possible, a quantitative comparison of the currently available state-of-the-art ISCG technologies for potential commercial scale operation in Western Canada. This Section summarizes the results for selected western Canadian coal seams. The assumptions used for the seam thicknesses and depths for selected Alberta coals seams are indicated in Table 8.

Table 8 - Key Coal Seam Metrics for Alberta Coals Studied

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total seam thickness</td>
<td>m</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>(including partings)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parting thickness (maximum)</td>
<td>m</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Seam dip</td>
<td>Degrees</td>
<td>Assume flat (horizontal) seams</td>
<td></td>
</tr>
<tr>
<td>Seam depth (below surface)</td>
<td>m</td>
<td>200</td>
<td>1,500</td>
</tr>
<tr>
<td>In-seam horizontal reach</td>
<td>m</td>
<td>800</td>
<td>1,600</td>
</tr>
</tbody>
</table>

Note the following from Table 8:

- The seam thickness ranges were derived through a screening level evaluation of coal seams in Alberta by Sherritt as well as independent third parties such as the Alberta Geological Survey.
- The shallow seam depth of 200 m appears to be the minimum recommended to allow safe operation considering the base of ground water protection in Alberta is 600 m. Worldwide, several pilot tests have however been conducted at shallower depths.
- The proximate and ultimate analysis of the coal seams of interest are indicated in Appendix A. Note that detailed coal characterization work will be required for a specific site as only limited data is currently available; considerations for a specific site are outside the scope of this study.
- The horizontal reach is the in-seam length of the horizontal section of the horizontal well within the target coal seam. The horizontal wells are drilled within 1 m of the bottom of the coal seam to maximize resource utilization.
6.1 EFFICIENCY OF COAL UTILIZATION

There are three measures of efficiency in in-situ coal gasification (ISCG) technologies as follows:

- Prospect area utilization by modules (or panels) is the fraction of the overall coal resource that can be accessed by modules (or panels) to produce Syngas. The prospect area utilization is reported to be 70 – 80% based on the need to maintain sufficient support structures between modules (or panels) to minimize subsidence;
- Per Module (or Panel) coal utilization is the actual amount of coal gasified compared to the theoretically accessible coal within that module. The Per Module coal utilization is reported to be 65% - 95%, based on the seam thickness, seam depth, coal quality, water ingress, ISCG technology and heat loss from the reaction zone. High levels of coal utilization are achieved for thicker seams; and
- The cold gas efficiency is the fraction of energy in the gasified coal contained in the produced Syngas. Cold gas efficiency is reported to be comparable to those achievable in surface gasification facilities (70 – 90%).

The overall coal utilization is the overall percentage of coal gasified to Syngas in the prospect area, and is the product of the above three utilization metrics (30 – 70%).

6.2 SYNGAS COMPOSITION

The Syngas produced from different technologies may be suitable for different applications. The main categories for Syngas application are as a fuel gas and for the production of chemicals or petrochemicals. Table 9 compares the Syngas composition ranges reported for Mannville Coal.
**Table 9 - Dry and Dry, CO₂ Free Syngas Compositions for Selected ISCG Technologies for Mannville Coal**

<table>
<thead>
<tr>
<th>Syngas Components</th>
<th>Dry Syngas Composition (Vol.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>1.1 – 1.2</td>
</tr>
<tr>
<td>H₂</td>
<td>10.5 – 11.3</td>
</tr>
<tr>
<td>Methane</td>
<td>24.8 - 32.0</td>
</tr>
<tr>
<td>Ethylene</td>
<td>&lt; 0.15</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.8 – 2.6</td>
</tr>
<tr>
<td>Propylene</td>
<td>&lt; 0.14</td>
</tr>
<tr>
<td>Propane</td>
<td>&lt; 0.34</td>
</tr>
<tr>
<td>CO</td>
<td>10.7 – 22.0</td>
</tr>
<tr>
<td>CO₂</td>
<td>37.0 - 42.9</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.3 - 0.4</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.00</td>
</tr>
<tr>
<td>Argon</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td>HHV (MJ/Nm³)</td>
<td>15.0 - 16.4</td>
</tr>
</tbody>
</table>

### 6.3 DRILLING COST COMPARISON

The total number of modules required to supply a commercial scale facility (sufficient for two F-Class Syngas turbines) over a 30 year project life is shown in Figure 14.
Figure 14 – Total Number of Modules (or Panels) required for Different Coal Seam Depths and Thicknesses for Different ISCG Technologies

Note the following from Figure 14:

- The required number of Modules over the project life is significantly more sensitive to coal seam thickness than coal seam depth. Thinner seams require an increased number of Modules to access the same quantity of coal, which leads to significantly higher drilling costs to produce the same quantity of Syngas.

- The number of Modules is less sensitive to seam thickness for the Parallel-CRIP technology than the Linear-CRIP technology due to the ability to control the lateral extent of the reaction zone; the recovery of thinner seams may therefore be more attractive using the Parallel-CRIP technology.

- Drilling cost intensities ($/GJ) vary with the seam depth and seam thickness and are generally lower for deeper and thicker coal seams. This is due to the fact that a single module Syngas production rate increases at greater depths and thicker seams and fewer Modules are required to produce the same quantity of Syngas (Figure 14).
### 7.0 POWER GENERATION FROM ISCG SYNGAS

This Section summarizes the operational performance, capital and operating costs and economics for a plant to generate power from Syngas produced from an in-situ coal gasification (ISCG) facility in Alberta, Canada. The potential cases of interest are based on the choice of oxidant for the ISCG process and the required level of CO\textsubscript{2} capture:

- Air blown vs. oxygen (95 mol% or 99.5 mol%) blown in-situ gasification; and
- Sufficient CO\textsubscript{2} capture to meet Canadian Federal regulations for CO\textsubscript{2} emissions intensity for coal fired power generation (0.42 tonne/MWh).

#### 7.1 AIR VS. OXYGEN AS OXIDANT FOR SYNGAS PRODUCTION

The bulk of the parasitic power loads at the power generation facility to supply oxidant vary depending on the coal seam depth. These parasitic power loads consist of:

- The air separation unit (for oxygen blown ISCG) including oxygen compression;
- Air compressors (for air blown ISCG);
- Diluent nitrogen compressors (if required);
- Syngas compressor (for shallow seams <500 m), and Syngas expander (for deep seams >600 m); and
- Auxiliary power loads.

All other power loads at the power generation facility are expected to be essentially constant and do not impact this analysis.

#### 7.1.1 Power Requirements to Supply Oxidant

The normalized oxidant supply parasitic power load per tonne O\textsubscript{2} is shown in Figure 15.
Figure 15 - Normalized Auxiliary Power vs. Coal Seam Depth

Note from Figure 15:
- All the power loads that are impacted by coal seam depth were evaluated as described earlier in this Section;
- There is a significant reduction in the power requirements for an oxygen blown ISCG process as the coal seam depth increases. This is due to reduced number of ISCG modules, lower compression requirements for syngas to turbines and power generation by expanders at higher depths;
- At depths greater than 550 m, the lowest power requirement for the ISCG process is to use a 95 mol % purity oxygen stream; and
- Higher oxygen purity (99.5 mol %) is not justified for power generation – the parasitic power requirements for supplying the 95 mol % purity oxygen is lower for all seam depths; no operational impacts were identified by the ISCG technology vendors.

7.1.2 First year selling price for Syngas

Figure 16 illustrates the comparison of the required first year selling price (2016) of Syngas required to achieve an after-tax unlevered IRR of 9% for the comparative cases. The first
year cost of Syngas is derived by setting the price for Syngas sold to a third party in the first year, escalated by 2% in following years, such that the NPV of the ISCG Syngas project equals 0. This analysis was predicated on the assumption that the economic value of the following two plant ownership structures would be the same:

- An integrated ISCG Syngas power generation facility and Syngas processing facility (e.g. a power plant) under one owner; and
- The ISCG Syngas power generation facility is owned by one party and the Syngas processing facility (e.g. a power plant) owned by a separate third party.

Therefore the first year cost of power was used for all power sales and purchases. In reality the Syngas selling price would be negotiated by the seller and buyer.
Figure 16 - Comparison of the Required First Year Syngas Selling Price for Different ISCG Technology Cases

Note from Figure 16:

- Case 12* is a Hypothetical Parallel-CRIP Simulation.
- The greatest variability in the first year Syngas selling price is the cost of drilling. The drilling costs are found to be more sensitive to coal seam thickness, and horizontal reach, than coal seam depth. Thinner seams require an increased drilling, which leads to significantly higher drilling costs.
• Drilling costs appear less sensitive to seam thickness for the Parallel-CRIP technology than Linear-CRIP seams and may allow the recovery of thinner seams using the Parallel-CRIP technology.

• For all of the cases with coal seams thicker than 4 metres, capital recovery of the surface facilities is the largest component of the required selling price of Syngas.

• Since power is a major cost of Syngas production, it has been shown separately from other O&M costs. The variability in the power costs of the cases shown relates to the different oxygen requirements for each case.

• The cost of carbon capture and compression is similar for all cases.

The marginal cost of Syngas is approximately $1.50/GJ (for the incremental power required to generate Syngas); the facility would not switch back to natural gas unless prices dropped below $1.50/GJ. This is significantly lower than the current or projected price of natural gas; thus, ISCG Syngas plant once constructed could become a low, stable cost, supplier of energy for a fuel or Syngas processing application.

7.1.3 CAPEX Comparison - Overall Power Plant

An order-of-magnitude cost estimate for the overall power generation facility was developed based on the Syngas processing plant and power plant for the various cases excluding gasification well field development, surface facilities at the wells and the interconnecting piping to the ISCG wells. These results, shown in Figure 17 indicates that for a 95 mol% O$_2$ oxidant, the plant CAPEX drops significantly from 200 m to 550 m but then is relatively constant at the greater depths. For the air blown case, the cost is about 20% higher than the corresponding oxygen blown configuration at 200 m which is simply due to the significantly larger surface processing equipment requirements to process the larger volumetric gas flow.
7.2 CASES EVALUATED

In total, there are six potential cases that could be evaluated (see decision tree in Figure 18). Based on the findings on the comparison between oxygen blown and air blown ISCG operations, it was determined that using 95 mol% purity oxygen at a depth greater than or equal to 550 m optimized the cost and performance of the Syngas treatment and power plant flowsheet.
Figure 18 - Base Cases and Potential Study Cases - ISCG Syngas for Power Generation

Color Legend:  
- Base Cases  
- Scope of Work  
- Out of Scope

Abbreviations:  
- ASU: Air Separation Unit  
- IGCC: Integrated Gasification Combined Cycle
7.2.1 Base Cases

The two base cases for comparative purposes are:

- Base Case (Base-1): Current state of the art 500 MW Gasifier IGCC (Case 1) based on surface mined coal and surface gasification technologies.
- Base Case (Base-2): A base loaded natural gas combined cycle (NGCC) 2 X 1 F-Class power plant.

In consultation with the Study Group, the following unit operations were pre-selected for Base-1 to allow comparison to previous studies conducted: acid gas removal (AGR) (Selexol®), sulphur recovery unit (SRU) (Claus) and Gas Turbine (F-Class Syngas) technologies for Syngas processing.

7.2.2 Study Case

The target CO₂ emissions intensity for the partial capture cases is 0.420 tonne CO₂/MWh as stipulated by new Canadian Federal regulations for coal fired power generation facilities. Sufficient cost data for the partial capture Case P2 was provided to allow the cost estimate for the other complementary case (Case P1) to be approximated through elimination of major processing blocks. None of the air blown ISCG cases (Case P4, P5 and P6) were evaluated based on the initial assessment of air fired vs. oxygen fired ISCG plant.

7.3 KEY PERFORMANCE METRICS

The major operating metrics calculated in the Study are summarized in Table 10.
Table 10 - Summary of Major Performance Metrics

<table>
<thead>
<tr>
<th></th>
<th>ISCG (Case # P2)</th>
<th>Base-1 (IGCC)</th>
<th>Base-2 (NGCC)</th>
<th>Pulverized Coal Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>no CO₂ Capture</td>
</tr>
<tr>
<td>Net power generation (MW)</td>
<td>492</td>
<td>444</td>
<td>535</td>
<td>450</td>
</tr>
<tr>
<td>Design life (years)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Average capacity factor (%)</td>
<td>95</td>
<td>85</td>
<td>50</td>
<td>93</td>
</tr>
<tr>
<td>Relative capital intensities</td>
<td>2.3</td>
<td>5.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Available pre-combustion CO₂ Captured (%)</td>
<td>89</td>
<td>97</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Available pre-combustion carbon captured (%)</td>
<td>50.6</td>
<td>93.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GHG intensity (tonne/MWh)</td>
<td>0.42</td>
<td>0.08</td>
<td>0.35</td>
<td>0.90</td>
</tr>
<tr>
<td>Heat Rate (GJ/MWh)</td>
<td>7.1</td>
<td>12.8</td>
<td>7.1</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>with CO₂ Capture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>360</td>
</tr>
</tbody>
</table>

In all capture CO₂ capture cases, CO₂ is dried and compressed and sent to the battery limit. No transportation or sequestration costs are included in the analysis.

Capital intensities show that an ISCG plant could reduce the required capital expenditures by 60% from IGCC and almost 40% from a pulverized coal plant with CO₂ capture, but would still cost more than twice as much as NGCC.

7.4 GREENHOUSE GAS EMISSIONS

Table 11 shows CO₂ emissions for each case studied. The carbon content which exists within methane was not captured and hence ends up as CO₂ emissions from the power generation facility.
Table 11 - Comparison of CO₂ Emissions for Different Study Cases

<table>
<thead>
<tr>
<th></th>
<th>Base Case-1 IGCC (full capture)</th>
<th>Case P2 O₂ blown ISCG (partial capture)</th>
<th>Base Case-2 NGCC (no capture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% carbon capture</td>
<td>93.2</td>
<td>50.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Carbon intensity (Kg/MWh)</td>
<td>75</td>
<td>420</td>
<td>353</td>
</tr>
</tbody>
</table>

7.5 ECONOMIC EVALUATION

7.5.1 First Year Cost for Power

The first year cost of power is derived by setting the price for power in the first year escalated by 2% in following years such that the NPV of the project equals 0. This price forecast is sufficient to provide enough revenue to cover all costs. Figure 19 illustrates the comparison of the required first selling price (2016) of power required to achieve an after-tax un-levered IRR of 9% for the six comparative cases.
Note the following from Figure 19:

- An NGCC plant with a 95% capacity factor has a lower first year cost of power than the ISCG plant. This means that for the same all hour power price, the NGCC unit operating at 95% capacity factor would have a higher IRR than the ISCG plant.
- The required first year selling price for power for the ISCG case is comparable to that required for a traditional pulverized coal power plant, and significantly lower than for a pulverized coal power plant that deploys post-combustion carbon capture technology with a similar CO₂ emission intensity (0.42 tonne CO₂/MWh).
- The required first year selling price for power for ISCG is approximately 1/3 of the price required for a comparable IGCC facility ($82/MWh compared to $247/MWh).

### 7.5.2 Capacity Factor Sensitivity

Findings from the studies have indicated that the marginal costs of power production for ISCG, are relatively low as compared with the NGCC case:
• For the ISCG plant the marginal cost is related to the cost for the power required to run the plant when producing Syngas. The marginal cost is calculated to be about $10/MWh with a power price of $82.3/MWh.

• The marginal cost for the NGCC plant is essentially the cost of fuel which is about $4.85/GJ X 7.1 GJ/MWh = ~$35/MWh.

As a result it appears appropriate that the ISCG facility would be run as a base load facility. Because of the relatively high marginal cost of power production from an NGCC facility, and its flexibility in turning power production up and down, it appears likely that the NGCC facility would run on-peak.

Figure 20 shows a comparison between the first year cost of power for the ISCG and NGCC cases as the capacity factor of the plant changes. The NGCC case would have to operate with a capacity factor of just below 80% (blue line) to have a similar first year cost at the base loaded ISCG case operating at a 95% capacity factor. The capacity factor of the ISCG case would have to be reduced to just above 70% (green line) to match the first year cost of the NGCC case for operation at a peak loaded 50% capacity factor. However, given that the NGCC case is expected to run during higher priced periods it is not clear which of the two cases will be more profitable.

Figure 20 - Impact of Capacity Factor on Required First Year Cost of Power

7.5.3 Fuel Price Sensitivity

A main advantage of ISCG is that it has almost no commodity price fuel risk unlike natural gas fired power plants. While for the first few plants the finance community may seek higher returns to compensate for the higher technology risk associated with ISCG, this should be mitigated by the significant reduction in commodity price risk normally associated with
NGCC. New enhanced ISCG configurations based on less conservative operating conditions may yield improved economics compared to those shown here.

The first year price of power required for NGCC is highly sensitive to changes in the price of natural gas. Figure 21 illustrates the sensitivity of the first year cost of power to changes in the fuel price. The ISCG case is not sensitive to changes in natural gas prices. This graph also shows that the NGCC plant operating at a high capacity factor would have the same first year cost of power and the same 9% un-levered IRR as the ISCG plant at a natural gas price of about $5.80/GJ. Once the gas price exceeds this value an ISCG plant is expected to provide greater returns than an NGCC plant with a 95% capacity factor.

![Figure 21 - Fuel Price Sensitivity Between ISCG and NGCC](image)

The blue diamond shows the expected first year cost of power for the ISCG case at the expected transfer price for Syngas to a standalone combined cycle plant. It is not clear that the ISCG case has a competitive advantage. Even though the NGCC case may operate during higher power priced periods it appears that the ISCG case may have a higher IRR. The impact on the NGCC case is that a rising natural gas price will lead to required increases in the selling price of power in order to maintain the same IRR. Since Syngas is currently not subject to the supply and demand conditions of the natural gas market, ISCG fuel costs would remain constant and higher natural gas prices should benefit ISCG more than the NGCC case.
8.0 ISCG SYNGAS FOR STEAM ASSISTED GRAVITY DRAINAGE OPERATIONS

This section focuses on developing a quantitative understanding of the impact of using Syngas produced through in-situ coal gasification technology as boiler fuel to generate steam for Steam Assisted Gravity Drainage (SAGD) bitumen extraction operations. Natural gas is currently used as fuel in essentially all SAGD operations.

Steam assisted gravity drainage technology is growing rapidly as a means of bitumen production in Alberta (Section 5.1). A key energy consideration in SAGD is the quantity of steam that must be injected into the reservoir to produce a barrel of bitumen. The common energy metric used is the steam-to-oil ratio (SOR), measured as barrels of cold water equivalent (CWE) per barrel of bitumen produced. The current average SOR in Alberta is about 3. Use of this much steam makes SAGD operations relatively high in greenhouse gas emissions intensity (CO₂ emissions) compared to other forms of bitumen production. Although the SOR is dictated largely by reservoir conditions, the greenhouse gas emissions intensity of SAGD production will also depend on the carbon content of the fuel used to generate the steam. While natural gas is relatively lower in carbon content compared to fuels such as oil, ISCG Syngas potentially is even lower in carbon content than natural gas, due to the higher hydrogen content and the potential to capture and sequester CO₂ produced in the ISCG Syngas process prior to combustion of Syngas in the boiler.

8.1 CASES EVALUATED

8.1.1 Base Case

The base case was a SAGD facility producing approximately 35,000 bpd (barrels per stream day) bitumen based on natural gas-fired once through steam generators (OTSG) and imported electric power.

8.1.2 Study Case

The study case was a SAGD facility producing approximately 35,000 bpd (barrels per stream day) bitumen based on ISCG Syngas-fired OTSG and imported electric power.

8.2 KEY FINDINGS

Table 12 shows the performance comparison between the ISCG Syngas fired SAGD operation and the base case using natural gas. As can be seen there is no major difference in the performance of the two cases and both natural gas and Syngas can be used interchangeably for a SAGD operation.
Table 11 - Comparison of Natural Gas and ISCG Syngas Fuel Cases

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Natural Gas</th>
<th>ISCG Syngas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen Production</td>
<td>bpd</td>
<td>35 106</td>
<td>35 106</td>
</tr>
<tr>
<td>Steam Production</td>
<td>bpd CWE*</td>
<td>105 319</td>
<td>105 319</td>
</tr>
<tr>
<td>Steam to Oil Ratio (SOR)</td>
<td>bpd</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Import Gas Consumed (HHV)</td>
<td>TJ/day</td>
<td>36.3</td>
<td>36.5</td>
</tr>
<tr>
<td>Produced Gas Consumed (HHV)</td>
<td>TJ/day</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>CO₂ Emissions Intensity (relative)</td>
<td>%</td>
<td>100</td>
<td>89</td>
</tr>
</tbody>
</table>

Minimal operational impact can be expected if natural gas were substituted with ISCG Syngas on an existing SAGD facility based on the operational assessment undertaken in this Study, specifically:

- Once through steam generator designs typical of Alberta SAGD operations can be made to run on natural gas, ISCG Syngas or both. ISCG Syngas may be substituted for natural gas in existing boilers, with the primary effect being a slight loss of thermal efficiency and perhaps some increase in NOx emissions;
- Choice of fuel does not affect the vast majority of SAGD central processing facility (CPF) operations; use of ISCG Syngas instead of natural gas is analogous to use of high-hydrogen-concentration fuel gas in an oil refinery;
- Minimal cost impacts were estimated if ISCG Syngas was to be used as a fuel for SAGD operations:
  - reconfiguring the OTSG for ISCG Syngas increases the capital cost of the boiler and controls by a few percent (within the error of the level of cost estimate conducted);
  - a central processing facility with once through steam generators designed for ISCG Syngas may have a very slightly higher total installed cost, but well within the uncertainty of the accuracy of the current order-of-magnitude capital estimates;
  - while slightly more ISCG Syngas is consumed at constant steam production, the estimates of variable costs for either natural gas or ISCG Syngas are essentially the same; and
  - there was no difference in the fixed costs for the two fuel cases evaluated.
• There is a 10 - 15% decrease reduction in amount of direct CO₂ production when using ISCG Syngas compared to natural gas. The level of CO₂ reduction depends on the composition of Syngas, in particular the relative concentration of methane and hydrogen;
• The oil and water material balances and equipment design are not affected by the choice of fuel gas;
• Differences in the ISCG Syngas fuel heating value result in differences in fuel consumed to produce the same volume of high-pressure steam for the reservoir;
• Using state of the art low-NOx burners, NOx emissions can be controlled by appropriate adjustment of excess air and flue gas recycle for OTSG’s fired by natural gas or by ISCG Syngas; and
• Maintaining constant quality of ISCG Syngas, especially preventing inert gas upsets at the CO₂ removal plant, is critical in maintaining stable operation of the once through steam generators.
9.0 FISCHER-TROPSCH TRANSPORTATION FUELS FROM ISCG SYNGAS

This Section describes the key findings from a conceptual level engineering study on the design of a Fischer-Tropsch (FT) plant converting ISCG Syngas and/or natural gas to transportation fuel including diesel, naphtha, liquefied petroleum gas and butane.

A 14,000 bpd FT transportation fuel plant using ISCG Syngas was designed. This plant could operate on 100% natural gas or any combination of ISCG Syngas and natural gas with minimal incremental impact on capital intensity or production rates; it is found that a switch to natural gas may however not be justified given the low marginal Syngas production costs anticipated from ISCG. Using ISCG Syngas as a substitute feed could minimize (or eliminate) natural gas commodity price risk for a traditional natural gas based GTL plant, maximize capital utilization, and allow the plant to become the lowest cost producer of FT transportation fuels.

9.1 CASES EVALUATED

The following feedstock cases were evaluated for this Study:

- **GTL Case**: A FT plant using 100% natural gas feedstock;
- **50% ISCG Case**: An FT plant processing 50% natural gas and 50% ISCG Syngas on an energy basis; and
- **100% ISCG Case**: A FT plant using 100% ISCG Syngas as feedstock.

9.2 FEEDSTOCK FLEXIBILITY

Figure 22 shows the block flow diagram of the FT plant designed to process both ISCG Syngas and natural gas feed.

![Figure 22 - Block Flow Diagram for the Fischer-Tropsch Plant](image-url)
Note the following from Figure 20:

- The process blocks in the FT Conversion section (FT Reactors, FT Products) are identical for all three cases evaluated.
- The 100% ISCG Case consists of the ISCG Syngas Conditioning block and the FT Conversion block. The ISCG Syngas cases require the following additional processing blocks to provide oxygen and condition the raw Syngas from the wellhead to a clean Syngas suitable for the FT process:
  - an additional oxygen supply for the in-situ gasification process;
  - an acid gas removal (Rectisol) unit to remove the majority of the sulphur components and CO2 in the raw ISCG Syngas;
  - a sulphur recovery unit to process the hydrogen sulphide; and
  - a CO2 drying and compression unit to deliver pipeline ready, supercritical CO2 at the plant battery limits.
- There are significant opportunities for integrating the FT Conversion section and the ISCG Syngas production section which reduce the cost of syngas supply to the FT Conversion plant.
- For the ISCG syngas compositions evaluated, a 100% ISCG Syngas plant could utilize 100% natural gas with essentially no incremental capital cost.

### 9.3 ECONOMIC EVALUATION

An FT transportation fuels facility could:

- Become the lowest cost producer of FT transportation fuels, by using the lowest cost feedstock available at any point in time;
- Utilize ISCG Syngas as a low cost, price stable alternate feedstock to natural gas; and
- Mitigate technology risk associated with the production of ISCG Syngas by using natural gas.
- Capital recovery of drilling costs is relatively small as a component of required WTI for the deeper (> 1,000 m), thicker coal seams evaluated.

The greatest challenges to overcome in the development of ISCG to Fischer-Tropsch facilities appears to be the high up-front capital costs, and the technology risk in the as yet commercially unproven ISCG technology.
9.3.1 First Year WTI Selling Price for FT Liquids

The first year WTI selling price is derived by setting the price for transportation fuels produced, in relation to WTI, sold to a third party in the first year (2016), escalated by 2% in following years, such that the NPV of the project equals 0. Figure 23 illustrates the comparison of the required first year WTI price to achieve an unlevered after-tax IRR of 15% for the three comparative cases, over a range of natural gas prices from $1 to $7/GJ.

![Figure 23 - Required WTI Price to Achieve Unlevered after Tax 15% IRR](image)

Note the following from Figure 23:

- The 100% ISCG case requires a first year (2016) WTI price of approximately $108/bbl to achieve an unlevered, after-tax IRR of 15% independent of the price of natural gas. The United States Department of Energy (USDOE) Annual Energy Outlook 2012 predicts that WTI will rise to $117/bbl in 2015, $127/bbl in 2020 and to $145/bbl in 2035. Based on the USDOE prediction, the 100% ISCG case can return an unlevered after-tax IRR of greater than 15%.

- The flat line of the 100% ISCG case illustrates that ISCG can provide a tremendous opportunity to reduce, if not fully eliminate, the natural gas commodity price risk in the production of transportation fuels.
- The GTL case requires a higher first year WTI price than the 100% ISCG and 50% ISCG cases at a natural gas price in excess of approximately $2.30/GJ and $2.20 respectively, in order to meet the 15% hurdle rate. In other words both the 100% ISCG and 50% ISCG cases will provide a higher return than the GTL facility at any natural gas price in excess of $2.30/GJ. The marginal cost of producing syngas is much lower than the crossover point, and once an ISCG FT facility is built, it is unlikely that fuel switching to natural gas would occur.

- The 50% ISCG case requires a first year (2016) WTI price of approximately $102/bbl to achieve an unlevered, after-tax IRR of 15% when the natural gas price is $1/GJ, and about $128/bbl when the gas price is $7/GJ. At the predicted WTI of $117/bbl in 2015, the 50% ISCG case cannot return a 15% IRR unless the natural gas price is less than $4.50/GJ.

- The GTL case requires a first year (2016) WTI of $95/bbl at $1/GJ natural gas, $125/bbl at $4/GJ gas, and $154/bbl at $7/GJ gas respectively, to achieve an unlevered, after-tax IRR of 15%. Given the USDOE forecast of $117/bbl in 2015, the GTL case cannot return 15% IRR if natural gas is priced above $3.2/GJ. The April, 2013 Sproule & Associates AECO-C natural gas price forecast for 2016 is $4.85/GJ.

- The steep slope of the GTL curve in the graph illustrates that GTL is highly susceptible to natural gas commodity price risk.

Figure 24 illustrates the breakdown of the major cost components for the three cases and their relative contribution to the required first year WTI price to achieve a 15% unlevered, after-tax return.
Figure 24 - Required WTI Price to Achieve Unlevered after Tax 15% IRR

Note the following from Figure 24:

- The first year WTI price required is $119/bbl for the 50% ISCG case, $108/bbl for the 100% ISCG case, and $133 for the GTL case. This analysis was performed at a first year natural gas price of $4.85/GJ, the 2016 Sproule AECO C forecast for gas prices, and was escalated by 2% annually thereafter.

- The largest component in the selling price for all three cases to return a 15% un-levered after-tax return is the capital recovery of the surface facilities. Operations and maintenance are the next highest cost component for both of the ISCG cases. For the GTL case, the second largest cost component (approximately 34%) is the natural gas feedstock cost. Natural gas is a significant portion of the cost in the 50% ISCG case as well.

- Capital recovery of drilling costs is relatively small as a component of required WTI for the deeper (> 1,000 m), thicker (12 m) coal seams evaluated.

- The cost of power is not a significant component for the FT cases, unlike the stand alone Syngas analysis or the power generation case because the design of all three cases takes advantage of the large quantities of steam generated by the highly exothermic FT process. The air compressors in the ASU are condensing steam turbines, while all the remaining plant power requirements are generated using...
available steam. This eliminates the need for significant power generation, although the 100% ISCG case includes some power costs for CO₂ compression.

- Net CO₂ credits are $15 per tonne based on the total volume of CO₂ captured, less Alberta carbon tax levied on 12% of total CO₂ production. Total costs in both ISCG cases include the capture and compression of all CO₂ captured at the plant gate but do not include transportation and sequestration costs.

- The greatest challenges to overcome in the development of ISCG to Fischer-Tropsch facilities appears to be the high up-front capital costs, and the technology risk in the as yet commercially unproven ISCG technology. Capital intensities for the GTL, 50% ISCG, and 100% ISCG cases are $152,000/bpd, $164,000/bpd, and $180,000/bpd respectively to produce a final refined product. In comparison the recently completed Imperial Oil Kearl Lake project had a capital intensity of $120,000/bpd for an oilsands mine and upgrader producing a synthetic crude, which still requires refining to final product.

- Royalties & taxes is made up primarily of income taxes.
10.0 ENVIRONMENTAL AND REGULATORY CONSIDERATIONS

10.1 POTENTIAL ENVIRONMENTAL ADVANTAGES OF ISCG

Environmental benefits relative to conventional mining include:

- A substantially reduced surface land footprint
- Reduced greenhouse gas and other emissions;
- Carbon capture and sequestration opportunities; and
- Hydraulic control (establishing a positive hydraulic gradient towards the gasification chamber, therefore controlling the process and protecting groundwater – Brown, 2012).

10.2 THE ALBERTA REGULATORY REGIME

The Alberta regulatory regime with respect to ISCG is more highly advanced than most jurisdictions in the world due to the preponderance of conventional and unconventional oil and gas extraction in the province. Parallels can be drawn between ISCG, conventional oil and gas extraction, and in situ oil sands developments, as these activities use similar and complementary technologies for resource recovery (Section 5.0).

The Alberta Energy Resources Conservation Board (ERCB) has broad responsibility for regulating ISCG activities within the province and to ensure the orderly development of energy related resources in a fair, responsible manner. This role is set out under a number of pieces of provincial legislation including the Coal Conservation Act (“CCA”) and regulations (“CCR”), Oil and Gas Conservation Act (“OGCA”) and regulations (“OGCR”), the Pipelines Act, the amendments in Bill 16 and a number of Directives issued by the ERCB, which expand on and support the various acts.

The CCA regulates the development, operation and abandonment of in situ coal schemes approval. It is a requirement that all wells, namely evaluation, observation, production and injection wells, be licensed under the OGCA. Any person/s, who wants to undertake any operations, preparatory or incidental to the drilling, construction or operation of an in situ coal scheme, needs an approval (Section 29 of the CCA). The eligibility for a person to apply for an approval requires that this person be entitled not only to the rights to the coal but also to the petroleum and natural gas in the coal seam to be converted by the in situ coal scheme. According to CCA (pursuant to section 9), the ERCB is authorized to make regulations relating to specified aspects of in situ coal schemes approval. This allows regulatory requirements to be refined as the body of experience with ISCG expands.
10.2.1 Stakeholder Consultation

Most energy developments, including ISCG developments, require stakeholder consultation programs driven by Directive 056, which is a formalized process. The directive provides the energy industry with requirements and expectations to assist industry in its stakeholder consultation efforts. Stakeholder consultation is required by both the ERCB and Alberta Environment and Sustainable Resource Development (ESRD) and must be considered as a requirement and expectation both in advance of submitting an application for energy development and also throughout the life of that development. For ISCG the specific requirements for consultation would mainly depend on the project's impacts, and also on site selection (i.e. remote vs. urban). Directive 056 outlines the consultation requirements for different types of facilities, pipelines and wells based on type, size, number and potential for H₂S emissions. The requirements outline the radius of contact from the project, materials to be included in the consultation package and timing of consultation.

ESRD also requires that notice of the application, once it has been submitted, be published in local and provincial newspapers and that affected stakeholders be allowed to submit Statements of Concern for 30 days after publication.

10.2.2 Stakeholders to be Included

The applicant must develop and complete the stakeholder consultation/participation program prior to filing an energy development application and ensure that the participant involvement program includes those parties within the radius of 1.5 km identified in Directive 56. All Stakeholders with a direct interest in land, such as landowners, residents, occupants, other affected industry players, local authorities, municipalities, and other parties who have a right to conduct an activity on the land, such as Crown disposition holders must be notified. Also a minimum of 14 calendar days must be allowed to receive, consider, and respond to notification of the proposed development (Energy Development License Applications). General information about the applicant has to be provided to the ERCB as part of the licensing requirement. Various Government entities will have roles to play in an ISCG development including the following:

- Alberta Environment and Sustainable Resource Development (ESRD);
- Alberta Energy;
- Alberta Transportation;
- Alberta Utilities Commission;
- Municipalities; and
- Federal Regulation of ISCG Activities (if required).
10.3 POTENTIAL ENVIRONMENTAL EFFECTS TO BE ADDRESSED FOR ISCG

As described in Section 2.0, ISCG has several advantages and care must be taken to achieve these advantages in an environmentally responsible manner. The primary technology and environmental risk factors can be summarized as reaction zone collapse or roof subsidence, and groundwater contamination. The performance of the UCG operation depends on a number of factors and can be improved by more comprehensive combustion/gasification simulation models and monitoring/mitigation processes. Some of the potential environmental effects based on literature are:

- **Aquifer Contamination – Groundwater Contamination**

Potential contamination of groundwater could be from a number of compounds already present in the in the coal seam but would be generated at higher concentrations during the high temperature gasification process, including phenols, polycyclic aromatic hydrocarbons, benzene, carbon dioxide, ammonia and sulphide. There is a potential for these compounds to migrate from the gasification zone and contaminate surrounding groundwater. This is of particular concern if the UCG operations were to happen in or near a potable aquifer.

The mitigation of this risk begins with proper site selection and screening to ensure that geological and hydrogeological conditions are amenable to maximize containment within the gasification reaction zone, and to prevent migration from the gasification zone. The optimization of operating conditions, such that pressure within the gasification reaction zone is always maintained at a lower pressure than the surrounding strata results in the continuous flow of groundwater towards the chamber. Finally, a comprehensive monitoring plan must be maintained to demonstrate any impacts on the surrounding groundwater, and to take further preventative measures should that monitoring expose an issue.

- **Ground Subsidence**

Ground subsidence is the potential sinking or lowering of a surface region relative to the surrounding region. It may occur as a result of the removal of material from the underground coal formation. This process could impact land directly above the gasified coal seam. Ground subsidence should result in a relatively uniform lowering of the region as opposed to abrupt potholes. Primary concerns with subsidence is the effect it can have on re-routing surface waters and local impacts on shallow aquifers and infrastructure likes roads and pipelines.

The risk of subsidence lessens with the increased depth of the coal seam gasified. Locations of UCG operations should be monitored and the seismic events analyzed. Such analysis can discriminate between human-caused and natural seismic activity. At the same time hazard mapping in space and time is crucial to provide information to regulators and authorities.

- **Surface Water Contamination**
The gas solution produced by ISCG contains a component of liquid or vaporized water (produced water) which is removed from the gas before the gas is combusted in a power plant, or is otherwise utilized in the production of end-products. This water contains residual metals, sulphur compounds, hydrocarbons, benzenes and possibly phenols and polycyclic aromatic hydrocarbons. Water treatment processes to deal with these issues are well understood and currently in use in conventional and unconventional hydrocarbon refining.

- Air Emission - Contaminants in Released Residue (Fly Ash and Flue Gases)

Two categories of non-GHG air emissions are produced - criteria air contaminants (e.g., nitrogen oxides, sulphur dioxide, particulate matter) and volatile trace elements (e.g., mercury, arsenic, and selenium). Technologies are currently available to monitor and mitigate air emissions.

- Land Use

ISCG will use land - a series of wells drilled into a coal seam with connecting roads and pipelines on the surface as well as any surface facilities required to process the Syngas. The pilot ISCG project will have a minimal number of wells drilled during operation, but a commercial scale operation could occupy approximately two to three times the land area and could include a few hundred wells spaced 30 m to 100 m apart, and could potentially operate for 30 years (Moorhouse et al. 2010).

10.4 ENVIRONMENTAL MONITORING REQUIREMENTS

10.4.1 Specific Monitoring Requirements

ESRD would request from the proponent a detailed proposal for a Groundwater Monitoring Plan at the ISCG facility, for ESRD’s review and approval. In general, it might be expected that the monitoring program include:

- Definition of baseline conditions in the aquifers within the groundwater protection zone and, for deep ISCG operations, also below the groundwater protection zone;
- Testing of groundwater yield for wells completed within the groundwater protection zone;
- Monitoring for temperature, water levels, well yields, water quality; and dissolved/exsolved gas; and
- Definition of specific thresholds, triggers and actions should an effect be detected.

It would also be expected that the intensity of groundwater monitoring would be higher in areas with higher numbers of groundwater users and with closer proximity to the proposed facility.
Monitoring requirements for an ISCG project will be defined in the ERCB and ESRD approvals issued for the project. ERCB approvals will be required for all wells and pipelines associated with the project. Monitoring requirements will include, but not be limited to:

- Noise;
- Subsidence monitoring;
- Temperature, pressure, gas composition and inflow rate on the injection wells;
- Temperature, pressure, gas composition and outflow rate on the production wells;
- Microseismic activity;
- Hours on injection and production;
- Composition of injected fluid; and
- Annual tests of well casing conditions.

ESRD approvals will be required for air and water releases, access to public lands and any impacts to groundwater. Monitoring requirements will include, but not be limited to:

- Specifying permitted air emission sources with subsequent air emission limits;
- Surface water discharge sources;
- Surface water discharge limits;
- Groundwater monitoring for changes to water levels, quantity and quality;
- Waste management and reporting; and
- Soil management and reporting.

10.4.2 Swan Hills and Laurus Monitoring

For reference, a summary of the proposed monitoring that was provided in the Swan Hills and Laurus Energy applications is presented below.

- Erosion control monitoring;
- Groundwater monitoring in the shallow and deep formations above and below the coal seam;
- Monitoring of both injection and production wells;
- Produced Syngas composition analysis and monitoring;
- Air monitoring;
- Oxygen and water injection flow rates, pressures, and temperatures;
- Thermocouple temperature monitoring along the injection well liner;
- Thermocouple temperature monitoring in the production well;
- Syngas flow rate, pressure, temperature and online composition;
- Syngas continuous monitoring for oxygen content;
• Produced water recovery volume and makeup water volume measurement;
• Monitoring of trace injection elements;
• Injection water quality monitoring, including pH control for corrosion mitigation in the injection well; and
• Reclamation monitoring after decommissioning.
11.0 COMMERCIALIZATION OF ISCG TECHNOLOGY

A successful commercialization strategy for ISCG technology should address the following:

- A strategy to effectively demonstrate the most appropriate ISCG technology at a target site; capable of supporting a commercial scale operation;
- A strategy to effectively manage the captured CO₂; and
- A strategy for the use of the produced ISCG Syngas. Traditional approaches to commercialization have been centered on the stand-alone commercial scale production and use of ISCG Syngas. An alternative approach to be considered is the implementation of ISCG as a complementary feedstock for an existing (or new) commercial scale facility where the produced Syngas can be gradually integrated into a pre-existing process such as NGCC power, pulverized coal power plants, refineries, petrochemical complexes and natural gas to liquid conversion facilities.

Activities to be completed once a site is selected are discussed next.

11.1 COAL AND COAL SEAM QUALITY

11.1.1 Coal Thickness

Optimal thickness for ISCG is 5-15m. ISCG can be carried out on thinner coal, but heat loss becomes more of an issue as, reducing the quality of the Syngas that can be produced. Coal seam thickness is confirmed by core samplings, spaced at intervals that allow confidence in-seam identification and continuity of the coal seam.

11.1.2 Lateral Extent of Undisturbed Coal Seam

Fault free blocks of coal are required that are large enough for the layout of ISCG panels. Panels need to be close to horizontal and to achieve this may have to be aligned along the strike of the coal seam rather than in the direction of the seam dip. Panels need to be a safe distance from potentially permeable fault zones which vary with respect to the nature of the faults. The location of folding and faults is identified by one of:

- Closely spaced boreholes locating faults;
- Combination of boreholes with 2D seismic lines at a selected spacing;
- 3D seismic survey identifying fault locations, with depth to the coal seam using borehole control; and
- The coal seam should be relatively flat, preferably less than 25° dip.
11.1.3 Coal Quality

All types of coal can be suitable for underground gasification, but energy, water, volatiles and ash content affect Syngas quality. Representative core samples of the coal seam are required from the prospective ISCG site. Laboratory analysis of coal core with conventional proximate analysis (Ash, Moisture, Volatile and Fixed Carbon) and ultimate analysis (C, H, O, N and S) is adequate for preliminary modelling of anticipated Syngas quality, as was demonstrated in Section 6.0.

11.1.4 Suitable Cap Rock Conditions

A key selection criterion for an ISCG site is the presence of an appropriately sealing cap rock over the coal. Not all coal has suitable surrounding strata, as it varies with the depositional conditions that applied during growth of the peat that was converted into the coal deposit. It is typical that in any coal basin, a significant proportion of coal will have appropriate cover rock, but it must be verified during exploration. The extent of suitable cap rocks can be derived from facies maps of the overlying rock layers which reflect the distribution of different depositional environments during coal formation. If an overlying seal is not present, or there is permeable strata closely overlying the coal, ISCG cannot be carried out.

ISCG operates in a reaction zone created by the gasification and removal of coal. This reaction zone contains the injected oxidant gases, reaction products and the final product Syngas. The gas must be contained by overlying and underlying impervious strata or it will leak away, losing product gas and potentially carrying gasification by-products into nearby strata.

11.1.5 Groundwater Hydrology

There are two hydrological conditions which must be met by the groundwater surrounding an ISCG gasifier, as follows:

- There must be adequate groundwater pressure to contain produced Syngas within the reaction zone; and
- There must be sufficient distance (vertical and horizontal) from surrounding aquifers to prevent Syngas loss through the aquifer systems.

11.1.6 Groundwater Pressure

The ISCG gasifier is a reacting region of gas and reacting solids surrounded by rock and groundwater. As outlined above, impervious strata prevent the gas from escaping into the roof, but all coal seams are permeable and therefore offer potential routes for gas loss. In an ISCG reactor, gas loss is minimized by maintaining a water pressure in the coal around the reactor at a higher level than the gas pressure in the reactor. This results in water
continuously flowing into the reaction zone, preventing outflow of gas. The water is incorporated into the gasification reactions, providing significant amounts of hydrogen for the hydrogen and methane components of Syngas.

The groundwater pressure in a coal seam must be capable of being maintained at a high enough level to support efficient gasification in an ISCG reactor at a pressure which is 5-15% lower than the surrounding groundwater pressure. This is of particular significance with shallower coal seams and is the limiting factor with respect to a minimum depth for ISCG operations.

11.1.7 Preventing Gas Losses

Aquifers are by definition permeable and if they become connected with a reactor, they can transport gas away from an ISCG site. In addition, the by-products of gasification could potentially contaminate groundwater, which might have alternative uses. As a result, it is important that ISCG reactors are not located close to non-coal aquifers. Were this to happen, the aquifers could connect with the gasifier reaction zone or the fractures that form around the reaction zone which could lead to gas losses and groundwater contamination.

All aquifers near coal seams should be identified and tested for hydrological properties and water quality during the exploration program, and a groundwater hydrological model developed for the potential ISCG site. In creating the hydrological model the following tasks are required:

- Identify, sample and test aquifers encountered during exploration drilling; and
- Initiate a baseline study with water sampling and pressure monitoring.

11.2 SCALE-UP TO COMMERCIAL ISCG OPERATIONS

Scaling-up projects from the initial single module to full commercial operations involves increasing the number modules to match the total Syngas production required by the project. It is believed that the commercial scale-up should be done incrementally, as expanding from 2 (or 3) modules in parallel to, perhaps, 20 or more has not yet been attempted and consequently a number of factors need to be better understood before moving straight to full-scale commercial operations. These include:

- The response of the geology and hydrogeology to multiple modules running simultaneously;
- The optimum spacing between modules or panels to ensure minimum interaction between the active ISCG reactors, the exhausted reactors (outlet goaf area) and the decommissioned reactors;
- The optimum spacing to ensure maximum resource utilisation while ensuring the overburden remains supported by pillars between modules (room-pillar configuration);
• The design and operation of surface facilities able to process and utilise multiple Syngas streams that may differ in composition and heating value over time; and
• The finance strategy required to fund the expansion from early commercial to full commercial scale operations. The capital requirements of a fully commercial project will be significantly greater than the early commercial project. It may therefore not be feasible to scale-up from the early commercial project to full commercial output without a period of “commercial demonstration” e.g. operation of multiple modules and production of commercial end-products to demonstrate revenue and reduce perceived financial risks.

11.2.1 Economies of Scale

Capital expenditure for ISCG projects can benefit greatly from economies of scale. This is due to scaling factors generally applied to standard surface plant, such as Air Separation Units (ASU), Syngas processing plant, water treatment plant and Syngas end-use plants, during capital budgeting. Another important factor is the significant increase of the module output rate (or thermal power) with the depth, as this directly influences the scale of surface Syngas processing facilities and, consequently, their economies of scale. A large proportion of the operational expenditure (Opex) of an ISCG project is made up by:

• The ASU energy efficiency for oxygen production;
• Drilling costs particularly at shallow depths; and
• Module completion costs (wellheads, tubing, etc.).

11.2.2 Site Facilities & Infrastructure

The scale up from a single panel operation to a commercial operation would involve a detailed investigation of the site infrastructure required to accommodate a commercial scale operation. However, based on multiple pilot scale experiences, a single panel trial operation would require all of the facilities that a commercial operation would require, albeit on a significantly smaller scale. As a result, similar to the Process Utilities and ISCG aboveground facilities, it is believed that there would be significant economies of scale involved in scaling the site infrastructure from a single panel operation to a commercial operation.
12.0 CONCLUSIONS

In the in-situ coal gasification (ISCG) process, oxygen (or air) and steam are injected into a deep coal seam through an injection well. The oxidants react with the coal in-situ through a set of pyrolysis, gasification and oxidation reactions to produce synthesis gas (Syngas) comprising primarily of CH$_4$, CO, H$_2$, CO$_2$ and trace gases such as H$_2$S. Syngas, which is brought to the surface through a production well, can be used to produce a range of products including power, transportation fuels and petrochemicals.

The technical and economic value proposition of ISCG for deep Alberta coal seams is evaluated in this report. Key findings include:

- Alberta has vast quantities of geologically continuous, currently un-mineable deep coal resources that could potentially be recovered through in-situ coal gasification (1.5 trillion tonnes at depths of 250 – 3,600 m and with seam thicknesses of up to 12 m to support multiple commercial scale operations) within the Province;
- The well drilling and completions technologies required for in-situ coal gasification are essentially all well established and commercially proven for in-situ bitumen extraction, and could be readily adapted;
  - The marginal cost of Syngas production from a stand-alone ISCG facility is significantly lower than the current or projected price of natural gas. Once constructed, a facility using ISCG Syngas would switch back to natural gas only if prices dropped below this marginal cost. The marginal cost of Syngas production from an integrated ISCG/FT liquids facility can be significantly lower than ISCG for power due to the significant potential for integration between the ISCG Syngas production facility and the FT liquids facility.
  - An ISCG Syngas plant once constructed could become a predictable, stable, low-cost supplier of energy for a base load fuel or Syngas processing application for:
    - the production of Fischer-Tropsch (FT) transportation fuels and essentially eliminate the natural gas price volatility impact on the economics of a conventional gas to liquids plant – enabling such a plant to be the lowest cost producer of FT fuels;
    - power generation while meeting new Federal regulations on greenhouse gas emissions from coal based power plants and cost competitive with natural gas fired combined cycles operating as base load units (95% capacity utilization) at projected natural gas prices;
    - use as a boiler fuel for steam assisted gravity drainage operations with the added benefit of a 10 – 15% reduction in the greenhouse gas intensity for bitumen production. There would be essentially no change to the boiler performance due to the fuel switch to Syngas and minimal retrofit costs.
• Surface processing facilities to treat the Syngas are based on commercially proven processes; and
• Environmental and regulatory permits for an ISCG facility can be obtained; the Alberta regulatory regime is one of the most advanced jurisdictions in the world with respect to ISCG permitting.
13.0 RECOMMENDATIONS AND FUTURE WORK

The Study finds that the ISCG technology and economics look promising. However the analysis assumes a long term, consistent Syngas quality and quantity, which must be tested through site specific field demonstration. A key limitation of the study is the reliance on ISCG technology vendor computer simulation results for design conditions significantly outside their operating experience:

- Deeper coal seams (> 200 m depth); and
- Continuous operation at the claimed commercial scale Syngas production rates.

It is therefore recommended that commercialization of the technology follow from field demonstration of ISCG technology by a consortium of interested parties to generate the required performance and scale-up data to support commercialization, including:

- Investigating a strategy for commercialization of the ISCG technology as potentially a complementary, not primary feedstock source for an existing commercial scale facility where the Syngas can be gradually incorporated into the existing operations;
- Finalizing a strategy for field demonstration that stages promising ISCG Technologies, capital outlay, minimizes scale-up risk and maximizes scale-up data generation and results in an optimized ISCG Module configuration for a specific site;
- Conducting targeted screening level technical and regulatory work to define the requirements for a site-specific, scale-up and commercialization focused field demonstration of ISCG technology in Alberta;
- Evaluating additional options identified during the Study (but not evaluated) for even more economically attractive flowsheet options for power generation; and,
- Developing a better understanding of ISCG technology through controlled laboratory physical test work coupled with advanced computer modelling.
14.0 REFERENCES


23. Devon NEC Corporation, Pike 1 Project, Volume 1 – Project Description, June 2012

24. Statoil Canada Ltd. Leismer Demonstration Project (LDP) Approval No. 10935C


APPENDIX A

COAL QUALITY DATA
Selected coal properties and ranges for selected deep coal seams in Alberta, Canada is indicated below. The average values for each seam are to be used for any modelling and simulation work.

**Table A1 – Coal Quality Data**

<table>
<thead>
<tr>
<th>Ultimate Analysis (wt%, daf)</th>
<th>Horseshoe Canyon</th>
<th>Upper Mannville - Medicine River</th>
<th>Lower Ardley B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>Ref 1*</td>
<td>Ref 2</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>74.0</td>
<td>74.5</td>
<td>74.3</td>
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<tr>
<td>Hydrogen</td>
<td>4.7</td>
<td>5.0</td>
<td>4.9</td>
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<tr>
<td>Nitrogen</td>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
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<tr>
<td>Oxygen (by difference)</td>
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<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
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<table>
<thead>
<tr>
<th>Proximate Analysis (wt%, as received base)</th>
<th>Horseshoe Canyon</th>
<th>Upper Mannville - Medicine River</th>
<th>Lower Ardley B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>24.0</td>
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<td>22.0</td>
</tr>
<tr>
<td>Ash</td>
<td>9.9</td>
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<td>10.5</td>
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<tr>
<td>Fixed carbon</td>
<td>37.7</td>
<td>38.5</td>
<td>38.1</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>28.4</td>
<td>30.3</td>
<td>29.4</td>
</tr>
<tr>
<td>HHV (daf), K/g</td>
<td>28.4</td>
<td>29.3</td>
<td>28.9</td>
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<table>
<thead>
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<th>Reference Number</th>
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<tbody>
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<td>Ref 1*</td>
<td>International Journal of Coal Geology, 6 (1986) 55-70</td>
</tr>
<tr>
<td>Ref 2</td>
<td><a href="http://www.cspg.org/documents/Conventions/Archives/Annual/2008/081.pdf">http://www.cspg.org/documents/Conventions/Archives/Annual/2008/081.pdf</a></td>
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<tr>
<td>Ref 4</td>
<td>Swanhills Synfuels report, Page 48 36</td>
</tr>
<tr>
<td>Ref 5</td>
<td>Laurus report</td>
</tr>
</tbody>
</table>

Note the following from Table A1:

- **Upper Mannville – Medicine River Seam**, the composition of coal only (not including partings) is reported. The partings are reported to include mudstone, carbonaceous shale and stoney coal. The bulk density is reported to be 1.33 g/cc (coal only) and 1.42 g/cc for the coal zone including both the coal and partings. The partings are assumed to be 13.5% of the total seam thickness for each of the seams greater than 4m (total seam thickness). The weighted average properties of the two partings provided in Ref 4, Page 36 will be assumed for the parting composition.

- **Lower Ardley B coal seam** – the seam is reported to contain multiple thin bands of partings, including bentonitic clay, mudstone, carbonaceous shale and stoney coal. Thus, the average coal composition (including partings) is reported. The bulk density is reported to be 1.31 g/cc (coal only) and 1.37 g/cc for the coal zone including both the coal and partings.