Viability of Underground Coal Gasification in the "Deep Coals" of the Powder River Basin, Wyoming

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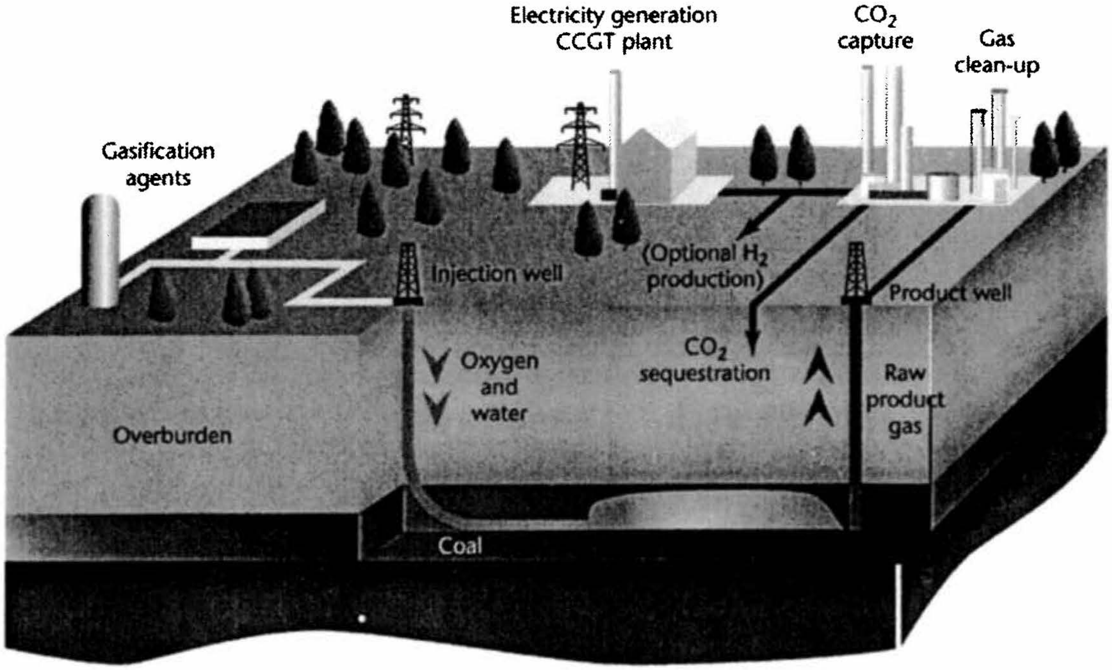

Prepared for the

Wyoming Business Council
Business and Industry Division
State Energy Office

GasTech, Inc.
Casper, Wyoming
June 2007

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Abbreviations

AFIT	After Federal Income Tax
BFIT	Before Federal Income Tax
BLM	Bureau of Land Management
CBM	Coal Bed Methane
CCP	Coal Combustion Processes
CCS	Carbon Capture and Sequestration
COE	Cost of Electricity
CRIP	Controlled Retracting Injection Point
DCF-ROR	Discounted Cash Flow Rate of Return
DME	Di-Methyl Ether
ECBMR	Enhanced Coal Bed Methane Recovery
EIS	Environmental Impact Statement
ELW	Extended Linked Well
EOR	Enhanced Oil Recovery
FT	Fischer-Tropsch Process
GIS	Geographic Information System
HHV	Higher Heating Value
HPA	High-Pressure Air
IGCC	Integrated Gasification Combined Cycle
LLL	Lawrence Livermore Laboratories
LPG	Liquefied Petroleum Gas
LVW	Linked Vertical Well
NPDES	National Pollutant Discharge Elimination System
NPV	Net Present Value
NRHP	National Register of Historic Places
PRB	Powder River Basin
QA/QC	Quality Assurance/ Quality Control
R&DTL	Research and Development Testing License
RM1	Rocky Mountain 1 UCG Trial
RZCS	Reactor Zone Carbon Storage
scf	standard cubic feet
scfd	standard cubic feet per day
SCG	Surface Coal Gasification
SDB	Steeply Dipping Bed
SNG	Synthetic Natural Gas
TDS	Total Dissolved Solids
UCG	Underground Coal Gasification
UIC	Underground Injection Control
USFS	United States Forest Service
USGS	United States Geological Survey
WDEQ-AQD	Wyoming Department of Environmental Quality – Air Quality Division
WDEQ -LQD	Wyoming Department of Environmental Quality – Land Quality Division
WDEQ-WQD	Wyoming Department of Environmental Quality – Water Quality Division
WGS	Wyoming Geological Survey
WOGCC	Wyoming Oil and Gas Conservation Commission

Acknowledgements

This study was prepared under a grant from the Wyoming Business Council. GasTech would like to thank the Business Council and Mr. Thomas Fuller, Business and Industry Division, Manager, State Energy Program, for supporting this analysis of a potentially very significant new business development for Wyoming. This work has supported the concept that Underground Coal Gasification in deep Wyoming coals is viable. This opens up tremendous coal resources, which are otherwise not available to the economy of the State.

In the preparation of this report, GasTech has relied on a skilled pool of technical consultants. Major contributions, especially in UCG project definition and cost estimates, were made by B.C. Technologies, Laramie, Wyoming. Their key personnel were John Boysen, Deidre Boysen, Erin Bohnet, and Tarn Bohnet. Equally important was the contributions of Jim Covell, EG&G. Both Covell and Boysen have been involved in UCG pilots for over 25 years. Hence, they contributed a very real insight into the potential complexity and details of UCG, as well as the environmental impacts and mitigation schemes.

This report has built extensively on UCG research and trials conducted by the US Bureau of Mines, the Department of Energy and the Laramie Energy Research Center, and Lawrence Livermore National Lab. Current contact with LLNL has been with Dr. Julio Friedmann and Dr. Elizabeth Burton. Their recent work at LLNL has been focused on UCG and Carbon Capture and Sequestration. Access to numerous DOE publications on UCG through the extensive UCG library at B.C. Technologies has also been very helpful.

The Wyoming Geological Survey provided several special coal investigations. Thanks to Dr. Ron Surdam, Director, Mr. Nick Jones, coal geologist, and Dr. Yuri Ganshin, geophysicist.

Coal bed methane and oil and gas well data were provided by the Wyoming Oil and Gas Commission through their website and by special data extractions performed by Mr. Rick Marvel, engineering manager.

As this work was progressing, GasTech has maintained contact with the University of Wyoming, who has expressed ongoing interest in UCG. Thanks to Dr. William Gern, VP Research, Dr. Myron Allen, VP Academic Affairs, Dr. Gus Plumb, Dean of the College of Engineering, and Dr. Carol Frost, Interim Director School of Energy Resources. We hope that as UCG progresses in Wyoming, this clean coal research technology can become a "cornerstone" of the School of Energy Resource's coal program.

Viability of Underground Coal Gasification in the "Deep Coals" of the Powder River Basin, Wyoming

1.0 EXECUTIVE SUMMARY

Coal is our most abundant fossil fuel. While oil and natural gas account for 64 percent of the world's energy consumption, they total only 31 percent of the world's known fossil fuel reserves. When known reserves and estimated future resources are considered, coal overshadows oil and gas, accounting for 95 percent of the known fossil fuel reserves plus resources. Additionally, one third of the world's coal is in the United States. We must develop new clean coal technologies to utilize our vast coal resources.

Background- Wyoming's energy resources most notably lie in the huge coal resources of the Powder River Basin (PRB). The US Geological Survey estimates that the Basin contains 510 billion tons of coal in place, but that 95%+ of that coal is not economically extractable by current mining technologies. These resources, at depths of 500 to 2,000 feet below the surface, are the "deep coals" of the Powder River Basin. Each square mile of the Powder River Basin Project area contains an average of 100 million tons of deep coal. Each ton of coal has 300 times the energy content of the coal bed methane (CBM) in that same ton of coal, thus making the coal a much higher value energy resource than the CBM.

These deep coals can be tapped by Underground Coal Gasification, or UCG. UCG involves drilling wells into the coal seam and injecting air or oxygen and steam into the deep coal seam. The coal is ignited in situ, and the hot product gases are captured in recovery wells. These hot, combustible gases recovered by UCG are called "synthetic gas" or "syngas". Syngas can be used for producing Fischer-Tropsch (FT) fuels, such as clean diesel, and can also be used to generate electric power in Integrated Gasification Combined-Cycle (IGCC) gas turbines. UCG trials indicate that UCG will have the lowest cost of liquid hydrocarbons and power generation of any clean coal technology. An average square mile of the Powder River Basin, containing 100 million tons of coal, can support a UCG IGCC power plant of 200 MW for about 100 years.

UCG development may occur in areas that geographically overlap coal bed methane and other oil and gas operations. The UCG development can either follow CBM extraction, or it can co-produce the methane with the UCG syngas. In any event, much installed oil and gas infrastructure may be useable for UCG products.

The benefits to Wyoming for developing commercial UCG in the Powder River Basin include:

- Access to most of the 510 billion tons of Powder River Basin deep coal which is otherwise "locked up", too deep for conventional mining
- Severance taxes, ad valorem taxes, and royalties on the coal extracted by UCG
- Ability to produce low cost F-T diesel, ammonium nitrate, and electricity for consumption in the PRB by existing coal operations
- Reduced environmental impact relative to open pit coal mining
- Low cost power generation for sale into an expanded grid serving out-of-state markets

- Use of extensive pipeline infrastructure, especially as Coal Bed Methane production is depleted, for the gathering and distribution of UCG gas products
- Low cost production of liquid hydrocarbons, as FT diesel, for export from Wyoming to the Colorado, Nevada, and California markets, and possibly DoD
- Potentially, the storage of sequestered CO_2 in cavities left after UCG coal harvesting.

The objective of this work is to evaluate the PRB coal geology, hydrology, infrastructure, environmental and permitting requirements and to analyze the possible UCG projects which could be developed in the PRB. Project economics on the possible UCG configurations are presented to evaluate the viability of UCG.

The PRB Resource- There are an estimated 510 billion tons of sub-bituminous coal in the PRB of Wyoming. These coals are found in extremely thick seams that are up to 200 feet thick. The total deep coal resource in the PRB has a contained energy content in excess of twenty times the total world energy consumption in 2002. However, only approximately five percent of the coal resource is at depths less than 500 feet and of adequate thickness to be extracted by open pit mining. The balance is at depths between 500 and 2,000 feet below the surface. These are the PRB "deep coals" evaluated for UCG in this report.

What is UCG- UCG is a mining method that utilizes injection and production wells drilled from the surface and linked together in the coal seam. Once linked, air and/or oxygen is injected. The coal is then ignited in a controlled manner to produce hot, combustible gases which are captured by the production wells. This process is conducted below the water table as water flows into the gasification zone and is utilized in the formation of the gas, known as syngas. The syngas is brought to the surface and cleaned for power generation and liquid hydrocarbon formulation.

History of UCG- The concept of UCG is thought to have been first conceived by Sir William Siemens in 1868, however, the first experimental work was led by William Ramsey in County Durham, United Kingdom in 1912. Ramsey was unable to complete this work before the beginning of World War I and all efforts to continue UCG development in Western Europe were discontinued until the end of World War II. Efforts to gasify coal have been conducted since that time in the U.S., Russia, England, Australia, France, Spain, Yugoslavia, Belgium, New Zealand, and China (Burton et al. 2005). The USSR's intensive research and development program during the 1930s, costing approximately $75 billion (US dollars in 2005), led to the operation of industrial scale UCG in the 1950s at several coal sites.

During the 1960s, all European work was stopped due to an abundance of energy and low oil and gas prices. In the U.S., several UCG programs were initiated in 1972, which built upon Russian experience and included the implementation of extensive field testing programs, the latter being supported by a number of research institutes and universities. These trials established the basic technology of UCG.

UCG vs. Surface Coal Gasification - UCG and surface coal gasification (SCG) can each be used to produce similar syngas that have identical downstream uses. Gasifying the coal in situ allows the energy extraction from large coal resources that are not economically or technically recoverable by conventional mining techniques. The hazards related to conventional mining are also reduced. Surface disruption is minimized as less surface space is required for a UCG facility, and surface handling of solid materials are eliminated i.e. coal and ash handling at the surface is not required. UCG consumes less surface water and generates less atmospheric pollution compared to SCG. Good thermal efficiencies can be expected as a result of the well insulated gasification cavity. Capital investment costs and syngas production costs are reduced by at least 25 percent compared to SCG (Draffin 1979).

Ground subsidence and leakage of gas from the cavity into adjacent strata such as nearby aquifers or groundwater are environmental concerns associated with UCG. Subsidence must be controlled by leaving adequate pillars in the coal seam to support the overburden stresses. This is accomplished by distributing the multiple geo-reactors properly. Groundwater must be protected by operating the geo-reactor at pressures below hydrostatic pressure. This ensures an in-flow of groundwater into the geo-reactor and prevents the forcing of gases out of the geo-reactor into the coal overburden. The process control variables, which include injection pressure, injection flow rate, oxygen and steam concentration, and well configuration, must be adjusted according to real-time surface measurements.

UCG and Coal Geology- The PRB in Wyoming is a structural and sedimentary basin located in the northeastern part of the state. It contains more than 8,000 feet of Upper Cretaceous and Tertiary rocks along the axis in the western part of the basin. The basin is asymmetrical with rocks dipping an average of 20-25 degrees along the western part of the Basin and 2 to 3 degrees in the eastern part of the Basin.

In the PRB, coals at depths less than 500 feet are available to strip mining and are not considered targets beds for UCG. For UCG consideration in this study, coals deeper than 500 feet and thicker than 30 feet have been included. This represents 307 billion tons of coal, or 74% of the coals deeper than 500 feet. For perspective, the current strip mines in the Basin produced about 440 million (0.44 billion) tons of coal collectively in 2006. The 307 billion tons of coal is a tremendous UCG resource.

UCG Suitability Selection- Based on geologic data from various sources, the coal zones in the PRB were evaluated for suitability for UCG development. The criteria applied are listed in Tables 5-1, 5-2, and 5-3. Based on these selection criteria, specific Townships have been selected as being highest priority for UCG development; they are listed in Table 5-5.

Hydrology and Subsidence- In the UCG operations, overburden material participates in the gasification process. The overburden participation increases as the UCG cavity matures and more overburden is exposed to the process. The major concerns with the UCG process and overburden are excessive subsidence, groundwater influx, mixing of aquifers (or water bearing strata), and groundwater contamination.

Subsidence is very site and design specific. Subsidence can be controlled by design. However full extraction of thick seams can result in high surface impact which would be incompatible with high surface use. In the PRB, the extraction plan and percentage resource recovery must be planned according to the site specific coal seam thickness, depth, and existing surface uses.

In UCG, groundwater influx into the geo-reactor is required for the gasification reactions to occur (Section 2.2.2). However, excess water influx consumes energy, cools the geo-reactor, and lowers the heating content of the syngas. Site selection is important to verify that groundwater influx will be within acceptable ranges. Therefore, lower permeability mudstones overlying the geo-reactor are favorable rather than higher permeability sandstone units.

Permitting UCG - UCG activities in Wyoming are regulated primarily by the Department of Environmental Quality. Section 7 details the permitting process and estimated time for acquiring requisite permits. Key environmental performance standards relate to impacts to groundwater, surface water, air quality, and surface uses of the affected permit area.

PRB Infrastructure – The PRB has a long history of agricultural and energy development. This has resulted in a network of roads, power lines, pipelines, and railroads which will support future UCG development. In selecting areas considered most prospective for UCG, the infrastructure was considered.

However, the existing surface and subsurface uses in the PRB also represent potential conflicts for UCG development. One potential conflict is between CBM operator and existing deeper oil and gas producers and the UCG developer. The most likely resolution of these conflicts is by having sequential development, especially of CBM. As CBM is depleted from the east side of the Basin to the west, the CBM infrastructure of wells, gathering systems, and pipelines all will have value to the UCG operator. UCG developments, which may reach commercial scale in the PRB over the next 5 to 10 years, will find many CBM areas depleted by that time. Deeper oil and gas well bores will need to be avoided by a safe distance. Where deeper the oil and gas operation is significantly depleted, these reservoirs may benefit from carbon dioxide injection and enhanced oil recovery, or these reservoirs may simply serve as a sequestration site for carbon dioxide. Therefore, a potential conflict may have synergistic benefits for both the oil and gas lessee and the UCG developer.

UCG Configurations- All UCG configurations require at least two wells completed in the coal seam, one for injection of oxidant and one for syngas product recovery. Oxidant can be air or oxygen enriched. In so-called air-blown systems, the resulting syngas has a low BTU value, about 150 BTU/scf. The oxygen-blown systems produce medium BTU syngas, about 300 BTU/scf, as there is less dilution by nitrogen.

Once the wells are completed, they must be linked together prior to gasification initiation. Several methods of linking are discussed and the preferred method selected. The linking conduit between wells must be the highest permeability path for the produced syngas to follow such that the syngas is captured at the production well and does not escape into the coal seam.

The syngas can be used for manufacture of synthetic natural gas (SNG), for power generation, Gas to Liquids, as formulation of clean diesel fuel, or other chemical synthesis, including hydrogen, methanol, ammonia, and di-methyl ether (DME) production. The various processes are described.

UCG can also be used in combinations of these processes, known as poly-generation. For example, a UCG facility many have an air blown process using the product gas to fire a combined cycle power plant which could generate the power necessary for the UCG process as well as an oxygen separation plant. This would allow for the production of electrical power and medium-BTU syngas to be used as feedstock for heating or other technologies previously described.

Carbon Capture, Storage, and Sequestration - Carbon capture and sequestration (CCS) is the process to remove and store "greenhouse gases" from process streams to reduce buildup of these gases in the atmosphere. CO_2 is a major greenhouse gas of concern in fossil fuel processes. CCS usually involves extraction, separation, collection, compression, transporting, and geologic storage. UCG processes have the same CCS options as surface gasification processes except for the potential to store the captured CO_2 in spent UCG cavities. This has been referred to as Reactor Zone Carbon Storage, or RZCS (Burton et al. 2005). This unique feature of UCG CCS, although requiring further testing, may make UCG the lowest cost clean coal technology for CCS.

Economics Conclusions of UCG in the PRB- The capital and operating costs for surface gasification facilities are somewhat available in the literature and from engineering firms and vendors that supply surface gasification process facilities. However, the capital and operating costs for UCG are literally absent from the literature, at least in any level of detail that would be useful for planning and economic scoping purposes. Therefore, in this report, we have concentrated the most effort in describing the UCG configuration, operating methods and preferred methods, and the capital and operating costs of UCG, especially in the PRB. This has required extensive modification and updating to UCG cost models developed by the primary contributors to this report. This should provide the most useful information for planners interested in evaluating UCG in the PRB and elsewhere.

Markets for electricity, SNG, clean liquid hydrocarbon fuels, and ammonia products exist with in the PRB. Existing pipelines provide take-away capacity. For electricity, at least three new transmission projects are being analyzed which would require an additional 1,400 MW of new power generating capacity in this part of Wyoming.

The air-fired UCG raw syngas production costs were evaluated for a base case typical of much of the deep coal in the PRB. The base case considered a 112 foot thick coal seam in the PRB with a depth to the top of the coal of 1,054 feet. The UCG facility utilized a 200 foot process well spacing. The base case air-fired UCG facility produces low-BTU syngas with a HHV of 150 BTU/scf. This compares conservatively with the ARCO Rocky Hill air-fired UCG test in the PRB, where syngas with an average HHV in excess of 200 BTU/scf was produced. The base case conservatively estimated a 65 percent coal resource recovery leaving pillars in the coal seam to control subsidence.

The base case air-fired UCG facility will produce adequate syngas to fuel a 200 MW power generation plant for twenty years and only consume 0.27 square miles of the coal seam. The base case facility would require $58.3 MM total investment and $13.5 MM annual operating expenses, resulting in a raw low-BTU UCG syngas cost of $1.62/MM BTU, including all state taxes, royalty, and a 15% return on investment. Sensitivities on coal seam depth, thickness, heating value, recovery, and well spacing are also presented and discussed. These result in a range of raw syngas costs of $1.40 to $2.35 per MMBTU.

These raw syngas costs have been tied to the economics of a 200 MW air-fired UCG-IGCC power plant in the PRB. Total capital cost of $263 million for the combined UCG-IGCC plant, with annual operating costs of $19.9 million, yields an After Federal Income Tax (AFIT) return of 18.3% DCF-ROR, and an NPV@15% discount of $44.3 million, using an average electricity sales price of $62 per MW-hr. Such a plant would return a 15% DCF-ROR at an electricity sales price of $51.68. Sensitivities on +/- 25% on capital costs, operating costs, and electricity sales price are given, resulting in a range of DCF-ROR's from 13% to 23%.

The UCG-IGCC configuration has been further compared to a "mined-coal" surface gasifier IGCC power plant. The results are summarized as:

	Surface Gasifier IGCC	UCG IGCC	% UCG Advantage
Capital/kW Installed	$1,544	$1,180	24%
Op Cost, $/MW-hr sold	$21.99	$11.96	46%
Breakeven Sales Price for 15% ROI	$80.60	$51.68	36%
DCFROR (as described here)	10.39%	18.28%	75%
Payback, years	10.77	7.64	29%

The UCG IGCC has clear cost advantages across the board.

Oxygen-blown UCG has also been evaluated for producing medium BTU syngas suitable for feedstock for FT or other chemical synthesis. The resulting medium BTU syngas has an estimated HHV of 306 MM BTU/scf and a cost of $2.55 per MMBTU, with the same assumptions as the air-fired UCG, including a 15% return on investment.

Because most oxygen-blown UCG systems have included steam injection, we have further investigated the cost impact of adding steam injection to the oxygen stream. This results in a high cost penalty, raising the overall cost of the medium BTU syngas to $3.49 per MMBTU. Because previous analysis of the Rocky Mountain 1 test concluded that the steam injection was actually water at the injection well head temperature and pressure (Boysen et al 1998), we believe that oxygen fired UCG is functional without steam injection. Therefore, medium BTU syngas can be produced for closer to the $2.55 per MMBTU than the steam injection at $3.49 per MMBTU.

These oxygen-fired UCG economics have also been evaluated for an FT plant utilizing the medium BTU UCG syngas. A modest size UCG FT project, producing 10,000 barrels per day of naptha and diesel combined, has a total capital cost of $622 million and annual operating costs of $53.2 million. This yields an NPV @ 15% discount of $103.5 million, and a DCF-ROR of 18.0%. The payback is a moderate 7.7 years. After reaching steady state production, it produces about $142 million in cash flow from gross revenues of $257.7 million. Sensitivities on capital costs, operating costs, and revenues being varied from 75% to 125% of the base case produce DCF-ROR's ranging from 11% to 23%.

In summary, UCG in most of the deep coal seams in the PRB is economically feasible and economically favorable compared to surface coal gasification. These advantages hold for air-fired UCG used in an IGCC power plant as well as for oxygen-fired UCG used in an FT plant.

Resource Conclusions on UCG in the PRB – The coal deposits in the Powder River Basin of Wyoming are thick, laterally continuous, and nearly flat lying. These deposits are ideal for development by Underground Coal Gasification because:

- Thick, deep coal beds, from 30 to over 200 feet thick and below 500 feet deep, provide a 307 billion ton UCG resource
- This resource is in a small area and has good thermal characteristics for the UCG process
- Commonly overlain by thick siltstone strata, the coals have a favorable structural and hydrologic setting
- The coals are sub-bituminous in rank, having adequate heat value (8,200 BTU/lb) and good reactivity to the UCG process
- The coals are low ash, averaging 6%, which is waste left in the UCG cavity
- There is no significant faulting (possible conduits for gas loss) in most of the Basin
- Coals depths of 500 ft + are below most aquifers and the deeper horizons, over 1,000 feet deep, will minimize surface effects of subsidence
- There are no intrusive rocks in the coal seams
- There is adequate hydraulic head, often several hundred feet, above the coal seams
- The coal is non-swelling upon heating, very favorable for UCG, and
- Coal permeability is high, helping to establish well linking before UCG ignition.

Environmental Conclusions of UCG in the PRB- The thick deep coal seams of the PRB can be harvested using UCG and be protective of groundwater, air resources, and with minimum subsidence. Protection of these environmental values requires correct site selection, site characterization, impact definition, and impact mitigation. The operating "lessons learned" of previous UCG operations, especially the "Clean Cavity" concepts developed at Rocky Mountain 1, should be incorporated into the future UCG operations. UCG can be conducted in the PRB with acceptable environmental consequences.

Recommended UCG Development Program - The commercial development of UCG technology has the potential to open up vast coal resources of the Powder River Basin of Wyoming for energy production and fuel generation far into the future. The recommended development components for UCG commercialization consist of the following:

- Selection of the UCG technology and end use with the greatest potential for commercial development.
- Select a suitable site to demonstrate UCG feasibility and commercial potential.

- Demonstrate UCG technology in the thick coals of the PRB on a pre-commercial scale.
- From the experience gained in the demonstration, expand the UCG demonstration to commercial operation.
- With the initial commercial operation underway, evaluate and develop other end use potential.

A pre-commercial demonstration project, using several commercial sized UCG modules, should be installed and operated for approximately one year. All commercial cost , operating, and environmental data should be collected to allow scale up to a small commercial operation. The demonstration project should be air-blown and generate electricity. The first commercial project should scale up UCG operations, generate electricity, and introduce and test value-products. Expansion to full commercial will include oxygen-blown UCG to provide feed stocks for value-product plants.

UCG, both air- and oxygen-blown, should have diverse applications for power generation, transportation fuel formulation, and other value-products. This industry, because of the immense UCG resources in the Powder River Basin, should operate for many decades with tremendous economic benefits for Wyoming.

2.0 INTRODUCTION

Coal is our most abundant fossil fuel. While oil and natural gas account for 64 percent of the world's energy consumption, they total only 31 percent of the world's known fossil fuel reserves. When known reserves and estimated future resources are considered, coal overshadows oil and gas, accounting for 95 percent of the known fossil fuel reserves plus resources. Therefore, a shift in our energy consumption away from oil and gas, and to coal, is inevitably in the world's energy future.

There are an estimated 510 billion tons of sub-bituminous coal the PRB in Wyoming. These coals are found in extremely thick seams that are up to 200 feet thick. The total deep coal resource in the PRB has a contained energy content in excess of twenty times the total world energy consumption in 2002. However, only five percent of the coal resource is accessible to open pit mining. The balance is at depths between 500 and 2,000 feet below the surface. These are the PRB "deep coals" (GasTech Evaluation 2005).

"The PRB is the single most important coal basin in the U.S. in terms of production, supplying over 37 percent of the total coal produced in the U.S. in 2003" (USGS 2007). PRB coals are known worldwide for their low sulfur content and their moderately high heating value. These coals are recovered extensively with conventional surface mining on the east side of the basin. In 2006, Wyoming mines produced 440 million tons of sub-bituminous coal. In addition, coal bed methane (CBM) recovery is occurring on a large scale throughout the basin. In 2006, 368 BCF of methane was recovered from 16,550 producing CBM wells in the PRB (WOGCC 2007). Many of the coal seams in the PRB have been penetrated by oil and gas and CBM wells and determined to be too deep for economic recovery by current mining technologies. Of the 500+ billion tons of coal in the PRB, 95 percent is too deep for economic extraction by surface mining (USGS 1999). However, it is that same depth that makes these coals an appropriate target for development using UCG.

Test trials for UCG began in Wyoming around 1975 and ended in 1995. The trials proved that UCG was possible, however not economical at the time. The trials also verified the possibility of the commercialization of UCG in the Powder River Basin. The Rocky Hill trial was conducted by ARCO Coal in Campbell County, WY in 1978 and gasified Wyodak coal. The test was successful because of the high heating value of the product gases produced and the limited groundwater contamination that resulted. Three UCG trials (Hoe Creek I – III) were also conducted in the 1970s by Lawrence Livermore National Laboratory in Campbell County, WY, that tested the feasibility of gasifying coal in the much shallower Felix seam. These tests were not considered successful for reasons that included improper site selection and over-pressurization of the UCG reactor that led to contamination of fresh water aquifers. The purpose of this study is to expand on the findings of previous tests by confirming the suitability of PRB deep coals for recovery using UCG, and evaluating locations across the basin, with knowledge gained regarding UCG strategies in the past twenty years, for their suitability as sites for a UCG trial.

2.1 WHAT IS UCG?

UCG is a mining method that utilizes injection and production wells drilled from the surface and linked together in the coal seam. Once linked, air and/or oxygen is injected. The coal is then ignited in a controlled manner to produce hot, combustible gases that are captured by the production wells, brought to the surface, and cleaned for power generation and liquid hydrocarbon formulation.

The UCG process produces commercial quantities of gas for power generation and for chemical processes such as clean diesel fuel formulation. UCG enjoys the advantages of surface gasification of coal with lower capital and operating costs to produce the same end products.

UCG gas, also known as syngas, is suitable for combustion in a gas turbine to produce electricity. Relative to all other coal-based generating technologies, UCG has the lowest Cost-of-Electricity (COE), which has been estimated to be as low as $34/MW-hr for Integrated Gasification Combined Cycle (IGCC) generation. UCG also has the same opportunity for carbon capture as surface gasification, with much lower costs than carbon capture in conventional coal-fired generating plants. Moreover, the deep cavities left by UCG may be suitable for carbon sequestration of dense-phase carbon dioxide, an attribute that no other clean coal technology can provide. Syngas can also be used to formulate synthetic natural gas, hydrogen, clean fuels, ammonia, and other chemical products. UCG syngas is the lowest-cost feedstock for these formulation processes.

UCG is a proven technology for converting unmineable coal seams into recoverable energy. In its most basic configuration, UCG involves the drilling of two wells from the surface to the coal seam. Various methods are used to connect or link the wells within the coal seam. UCG relies on the natural permeability of the coal seam to transmit gases to and from the combustion zone, or on an enhanced permeability created through reversed combustion, a drilled inseam channel, or hydro-fracturing. Linkage of the two wells is crucial to UCG success, as the highest permeability (lowest resistance) path for the produced gases must be to the production well. After linking, full production begins by igniting the coal seam and injecting air, oxygen, and/or steam into one well, the injection well, and producing hot combustible gas, called syngas. The zone of gasification is sometimes referred to as a "geo-reactor" as it is a gasification reactor in situ in the coal seam. The syngas recovered at the second well, the production well, is taken to the surface for processing. The UCG process is conducted below the water table. Ground water flows into the gasification zone and is utilized in the formation of the syngas. The syngas is cleaned and processed on the surface for use in power generation and/or liquid hydrocarbon formulation. There are many variations to this process and they are discussed in later sections of this report.

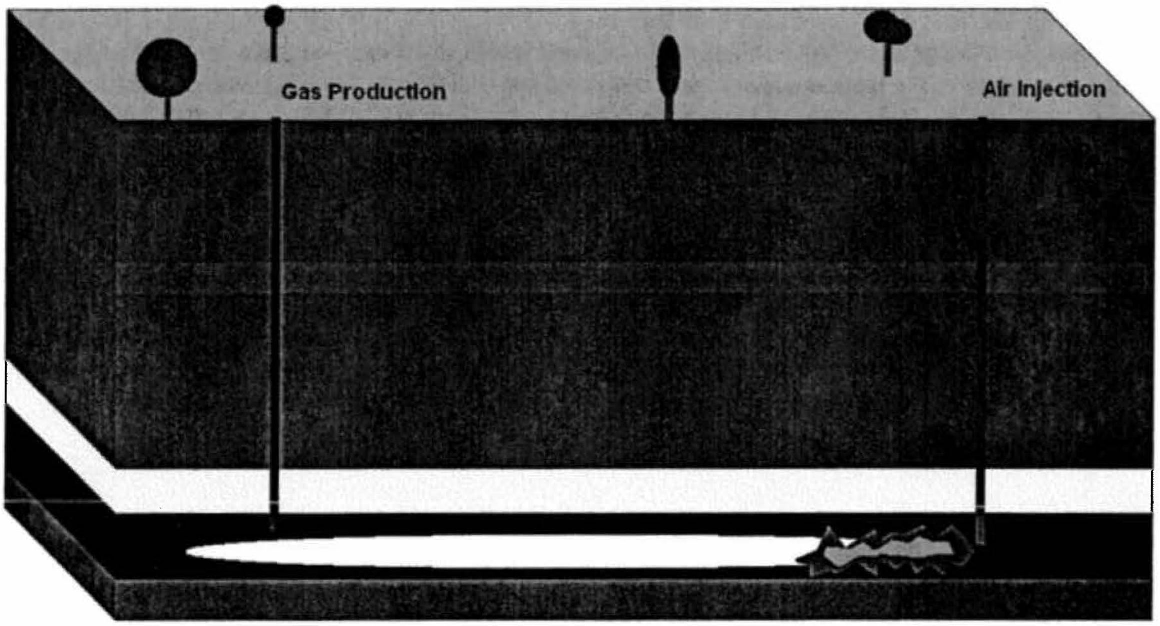

FIGURE 2-1 BASIC UNDERGROUND GASIFICATION PROCESS

Figure 2-1 is a schematic that shows the basic UCG process configuration (Diversified Energy 2007).

Figure 2-2 is a schematic that shows the main components of a commercial UCG site for power generation.

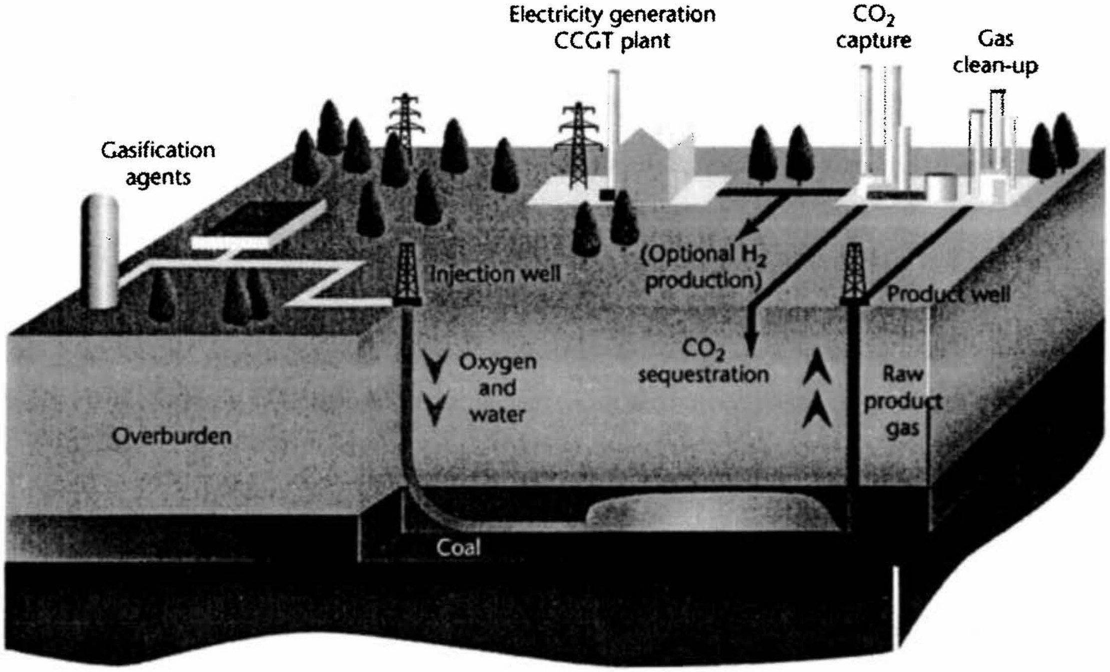

FIGURE 2-2. COMPONENTS OF A COMMERCIAL UCG SITE FOR POWER GENERATION

2.2 UCG CHEMISTRY

The chemical structure of coal is very complicated, and contains a myriad of structural forms that include a variety of organic and inorganic constituents. The chemical constituents of coal are generally very reactive, particularly for the lower ranked coals such as the PRB sub-bituminous coals. When coals are heated to temperatures greater than 500^0F, coal begins to thermally degrade (pyrolysis or carbonization). The chemical structure of the coal begins to change. Gases and liquids begin to evolve. The gases are mostly carbon-based but also include some inorganic constituents such as hydrogen sulfide and ammonia. Coal pyrolysis continues to approximately 1800^0F; however, most pyrolysis products evolve at temperatures below 1200^0F. The solid material (char) resulting from the pyrolysis process contains mostly elemental carbon (char) and inorganic residue (ash). The char provides the energy source to propagate the UCG process. The liquid products of coal pyrolysis include water, light oils, and tars. The tars are viscous with relatively high pour points. The relative yields of the pyrolysis products (percent moisture-ash-free, at 1470^0F) for a subbituminous coal are shown below (Cameron Engineers 1975):

Char	60.3
Water (formed)	10.5
Tar	9.2
Light Oil	1.3
Gas	18.3
Hydrogen Sulfide	0.4

The pyrolysis gas constituents and percent concentrations for the gas at 1400^{0}F are:

Carbon Dioxide	12.0
Carbon Monoxide	17.3
Hydrogen	43.6
Methane	26.5

Small concentrations of higher hydrocarbon gases are also generated.

2.2.1 UCG Process

Figure 2-3 shows the conceptual design of the UCG process. There are three concurrent parts or phases of the UCG process. The first part is oxidation where air or oxygen is injected into the coal to burn the char and coal near the coal injection point. The basic reactions of the oxidation process are shown in equations 1 through 3.

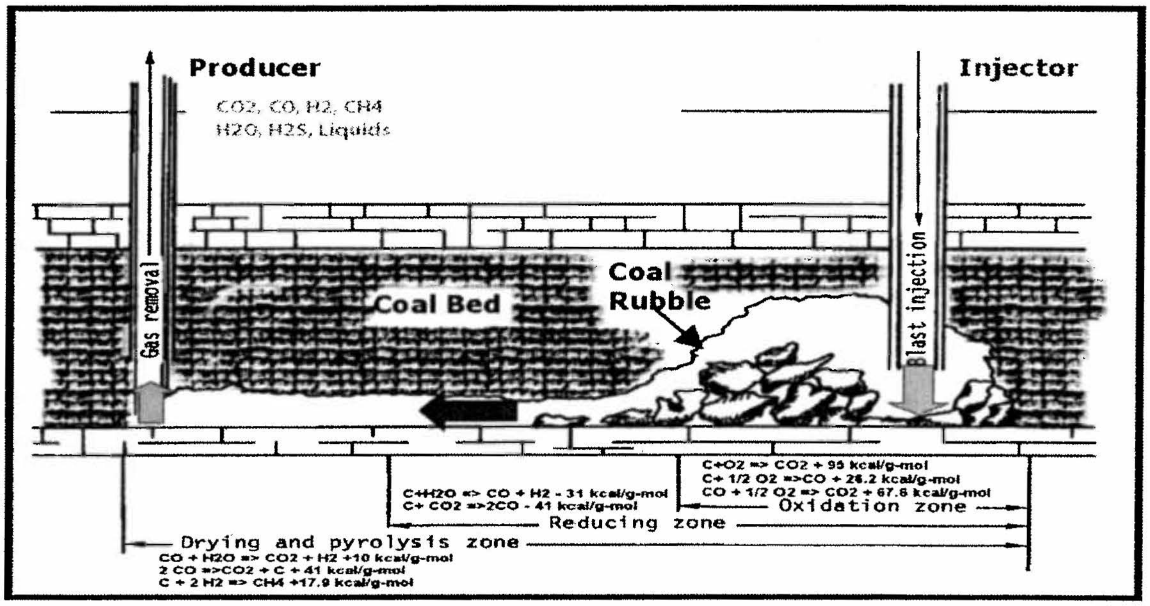

FIGURE 2-3. THE UCG PROCESS

$$C + O_2 => CO_2 + 95 \text{ Kcal/g-mole} \quad (1)$$

$$C + O_2/2 => CO + 26 \text{ Kcal/g-mole} \quad (2)$$

$$CO + O_2/2 => CO_2 + 67.6 \text{ Kcal/g-mole} \quad (3)$$

The heat generated during oxidation, fuels the other two parts of the UCG process, reduction and the drying and pyrolysis. The temperature in the UCG reactor generated from the oxidation phase can exceed 2800^{0}F.

The second phase of the process is reduction. Reduction occurs after oxygen is consumed in the oxidation phase. Because of the high temperatures in the UCG reactor, the products of the oxidation and pyrolysis reactions, CH_4, CO_2, CO, and H_2O, thermally decompose and react with each other and the char. Reactions 4 and 5 are the most important reactions of the gasification process.

$$C + H_2O \Rightarrow CO + H_2 - 31 \text{ Kcal/g-mole} \qquad (4)$$

$$C + CO_2 \Rightarrow 2\ CO - 41 \text{ Kcal/g-mole} \qquad (5)$$

Methane also degrades at the high temperatures of the UCG reactor according to Reaction 6 and 7.

$$CH_4 + 2\ H_2O \Rightarrow CO_2 + 4\ H_2 - 46 \text{ Kcal/g-mole} \qquad (6)$$

$$CH_4 + H_2O \Rightarrow CO_2 + 3\ H_2 - 54 \text{ Kcal/g-mole} \qquad (7)$$

As the gases pass through the subsurface channel in the coal into the production well, some gas cooling occurs. This reverses the direction of equations 4-7 with a reduction of H_2 and CO concentrations and increased concentrations of CO_2 and CH_4.

Another important reaction that occurs in the UCG process is the gas-shift reaction that affects the relative concentrations of H_2, CO, and CO_2. Equation 8 shows this reaction.

$$CO + H_2O \Rightarrow CO_2 + H_2 + 7 \text{ Kcal/g-mole} \qquad (8)$$

As the gas composition changes with the reduction in gas temperatures in the subsurface, the heating value of the gas changes very little. This results from the almost equal trade-off between the H_2 and CO concentrations with the CH_4 concentration.

The final phase of the UCG process is pyrolysis and drying. The hot gases within the UCG reactor vaporize the water in the coal and pyrolyze the coal. Reaction 9 shows the products of the drying and pyrolysis products.

$$\text{Coal} + H_2O_{\text{liq}} + \text{Heat} \Rightarrow \text{Char} + H_2O_{\text{Gas}} + \text{Gases} \qquad (9)$$

Some of the gaseous products condense to tar and oil liquids as described previously. Constituents of the non-condensable gases were described previously.

2.2.2 Site Selection Impacts on the UCG Process Chemistry

Site specific characteristics are important in determining the potential for efficient UCG operations. The most efficient use of the energy generated in the oxidation phase of the UCG process is the pyrolysis of the coal and the reduction reactions. Energy used to vaporize excessive water and overburden material detract from the beneficial use of the oxidation energy. For these reasons, high water content and influx, coal seam thickness, and overburden interaction are important considerations for selecting a UCG site.

As shown in Equations 4, 5, 6, 7, 8, and 9, water participates in UCG reactions and is a reactant in the important steam-char reaction (Equation 4). However, excessive water participation causes reduced process efficiency. Excessive water vaporization can result from high water content in the coal, excessive water influx caused by high permeability in the coal or overburden or collapse of overburden with high water content. Excessive groundwater volatilization reduces the UCG reactor temperature and that reduces the resultant gas heating value. At temperatures greater than approximately 1300^0F, the disassociation of CO_2 to CO will increase CO to concentrations greater than CO_2. As temperatures decrease below this temperature, CO concentration decrease and CO_2 concentrations increase. Soviet experience has shown that increased water inflow rate decreased product gas heating value (Gregg and Olness 1976).

Coal seam thickness is also important in gasification efficiency and the resultant heating value of the UCG product gas. For thin coal seams, thermal conduction to exposed overburden or water influx from the overburden will reduce the temperature of the gasification reactor and will result in reduced product gas quality (heating value). The time to expose the overburden to the UCG process is directly related to the coal seam thickness and the vertical location of the UCG channel. The thick coal seams of the PRB will provide for low overburden interaction.

2.3 UCG IN THE PRB

The U. S. is striving to reduce its reliance on foreign energy supplies and is actively seeking technologies that can recover unconventional domestic resources such as the deep coal found in the PRB. Historically, tests completed on PRB coal seams indicate that UCG can be successfully conducted, and results from the economic analysis provided in Section 10.0 show that it can be done at costs that compare favorably with other gasification strategies. However, because of the variability of coals and the geologic conditions in which the coals reside, results are highly dependent on site selection. This study examines coal seams in locations throughout the PRB and considers variables that are critical to successful site selection. Technical, regulatory and economic issues are elements that were used in the determination of PRB coal suitability for UCG development.

The PRB coal is attractive for UCG development due to coal type and abundance. The Wyodak, which is the target coal seam in the PRB, averages approximately 100 feet in thickness. When a coal seam is this thick, fewer wells need to be drilled to achieve the same production as from thinner seams. The UCG production in the PRB would continue almost indefinitely due to the estimated 510 billion tons of coal, which has the energy equivalent of about 1.4 trillion barrels of oil. Also, the PRB coal has low sulfur and ash content and is especially favorable for meeting strict emissions requirements.

Table 2-1, which was developed using data from research described in Section 5.0, summarizes selected UCG attributes and compares it to those attributes in the PRB. The coals of the PRB, in virtually every attribute, are suitable or superior for UCG.

TABLE 2-1. COMPARISON OF OPTIMAL COAL ATTRIBUTES WITH PRB COAL ATTRIBUTES.

Coal Attribute	Optimal	Powder River Basin
Seam Thickness	30+ Feet	30 – 250 Feet
Rank	Sub-bituminous to High Volatile Bituminous	Sub-bituminous "B"
Ash	<40%	6.4%
Faulting	Rare	Rare
Depth	>1,000 Feet	500 – 2,500 feet
Dip	0 – 20 Degrees	1 – 3 Degrees
Intrusions	Minimal	None
Immediate Roof	Strong, Stable	Low Permeability Siltstone
Hydraulic Head	>600 Feet	500 – 2,500 Feet
Swelling Character	Non-swelling	Non-swelling
Coal Permeability	High	High
Water Quality	Poor	Stock Quality
Natural Gas Availability	Available, Low Cost	Very Low Cost

While the PRB area is sparsely populated, there are still many avenues available to market the products from UCG. The PRB has a well-developed energy infrastructure of roads, power- and pipe-lines, and support service industry. Electrical transmission infrastructure is currently being considered to Utah, Nevada, California, and to the Denver, CO and Phoenix, AZ areas. The high demand for and ease of transportation of liquid hydrocarbon products makes them attractive. Several major natural gas pipelines in the PRB could be utilized if synthetic natural gas production was chosen. A market for the manufacture of clean synthetic diesel could be found in the existing coal mines and through railroad industry demand. Ammonia and fertilizer production could be considered as well as manufacture of ammonium nitrate for blasting agents.

3.0 UNDERGROUND COAL GASIFICATION

3.1 HISTORICAL OVERVIEW OF UCG

The concept of UCG is thought to have been first conceived by Sir William Siemens in 1868, however, the first experimental work was led by William Ramsey in County Durham, United Kingdom in 1912. Ramsey was unable to complete this work before the beginning of World War I and all efforts to continue UCG development in Western Europe were discontinued until the end of World War II. Efforts to gasify coal have been conducted since that time in the U.S., Russia, England, Australia, France, Spain, Yugoslavia, Belgium, New Zealand, and China (Burton et al. 2005).

Russia was the first country to heavily research and test the feasibility of gasifying coal seams in situ. The Soviet decision to pursue UCG was made in 1928, and the first field experiments were conducted during the 1930s (Gunn 1976). The USSR's intensive research and development program during the 1930s, costing approximately $75 billion (US dollars in 2005), led to the operation of industrial scale UCG in the 1950s at several coal sites. Activity subsequently declined due to the discovery of extensive natural gas resources in the USSR. The only site in operation today is located in Angren, Uzbekistan.

Between the years 1944 and 1959, the shortage in energy and the diffusion of the results of the UCG experiments in the USSR (1934-1940) created new interest for UCG in Western European coal mining countries. The first research work was directed to the development of UCG in thin seams at shallow depths. The stream method was tested in Belgium on the site of Bois-la Dame (1948) and in Morocco, on the site of Djerada (1949). The borehole method was tested on shallow coal seams in Great Britain at the sites of Newman Spinney and Bayton (1949-1950). A few years later, a first attempt was made to develop a commercial pilot plant: the P5 Trial in Newman Spinney, Derbyshire (1958-1959). Although gasification was successful, the National Coal Board later abandoned the project for economic reasons (The Coal Authority 2006). During the 1960s, all European work was stopped due to an abundance of energy and low oil prices. In the U.S., a UCG program was initiated in 1972, which built upon Russian experience and included the implementation of an extensive field testing program, the latter being supported by a number of research institutes and universities. These trials established the basic technology of UCG.

3.1.1 Former Soviet Commercial Experience

As stated earlier, the former Soviet Union was the first country to heavily research and test the feasibility of UCG. This research peaked in the mid-to-late 1960s, then had a dramatic decline in the early 1970s. Commercial-scale production of gas was achieved at numerous locations and for long periods of time, most notably at Angren, Shatskaya, Kamen, Yuzhno-Abinsk, and Podmoskovia. Uzbekistan is still operating its UCG facility at Angren, a facility they initiated operations in 1959. Table 3-1 (Burton et al. 2005) summarizes the former Soviet Union's UCG trials.

TABLE 3-1. SUMMARY OF SOVIET UNION UCG TRIALS

Basin	Site	Development Date	Coal Type	Depth (ft)	Seam Thickness (ft)	Energy Content (BTU/lb)	Gasification Characteristics
Donets	Shakhta	1933	Anthracite	Depth unknown, dipping 19-22^0	1.3	--	67.2 – 140.0 BTU/scf
	Lisichansk	1933	Bituminous	79-453 ft, steeply dipping 20-60^0	1.3 – 8.9	8100 - 9000	33.6 – 246.4 BTU/scf Alt. air and steam3.5 x 10^9 ft^3/yr (1959)
	Gorlovka	1935	Bituminous	131-361ft, Steeply dipping 70^0	6.2	--	100 – 112 BTU/yr (steam and O$_2$)
	Kamensk	1960					
Kuznets	Leninskt	1933	Bituminous	92-98ft Dipping 20^0	15.9	--	100 – 269 BTU/scf
	Yuzhno-Abinsk	Podzemgaz Station 1955	Bituminous	Steeply dipping 55-70^0	6.6 – 29.5	9000 – 10,800	112 BTU/scf 13.7 x 10^9 ft^3/yr (1965)
	Stalinsk	1960	--	--	--	--	--
Moscow	Krutova Mine	1932	Lignite	53-66ft, Horizontal	6.6	--	110 BTU/scf
	Podmoskovia Station (Tula)	1940	Lignite	131-197ft, Horizontal	6.6 – 13.1	3600 - 9000	78.4 – 100 BTU/scf 16.2 x 10^9 ft^3/yr
Near Tashkent	Shatskaya Angren	1960 1962	Lignite	361-820ft, Horizontal 5-15^0	13.1 – 78.7	6570	89.6 – 95.3 BTU/scf 49.4 x 109 ft^3/yr (1965)

3.1.2 U.S. Trials

UCG trials in the United States started in the 1940s and advanced the technology of control through the use of the controlled retracting injection point (CRIP) technique and oxygen injection. By the end of the 1980s, UCG was considered in the U.S. to be a technology ready for commercialization. Although commercial projects were evaluated, most notably the synthetic natural gas (SNG) plant at Rawlins, WY, the low cost of natural gas in the early 1990s prevented these projects from being realized. During the period between 1960 and 1990, 33 UCG tests were conducted. Several of those tests were completed in the State of Wyoming. A selection of these tests and their results are summarized in the following sections.

3.1.2.1 Gorgas Underground Gasification Project (1946-1947 and 1950)

The Synthetic Fuels Act of 1944 authorized UCG research. The first U.S. UCG experiment was conducted in Gorgas, Alabama in 1946-1947 by the Bureau of Mines and the Alabama Power Company.

In 1950, they conducted a second UCG test at the same location. The process they utilized in the second test involved connecting mine entries (tunnels) that were over 150 feet deep containing 42 inch thick coal seams, to the surface by boreholes drilled at 300 foot intervals. The coal was then fired and the energy was obtained in the form of hot products of combustion. The test was considered unsuccessful due to leakages. Additional experiments were conducted in the 1950s using grouted boreholes and other gasification methods. Those tests showed that it was possible to produce gas and adjust the quality of the products; however, the processes were not economically viable (Bureau of Mines 2001).

3.1.2.2 The Hanna Trials (1972-1979)

Hanna I (1972-1973). Hanna I was the first of four underground coal gasification trails initiated by the Bureau of Mines in 1972. The Hanna site contained a 30 ft thick sub-bituminous coal seam ranging in depth from 350 ft to 400 ft. Preparation of the trial began in 1972 with first attempt at ignition beginning in March of 1973. Permeability was established and ignition of the coal seam began. After 18 hours of operation low permeability conditions began to affect injection rates, low permeability was presumed to be caused by formation of coal tars in the combustion zone. The well was then shut down and vented, after re-igniting injection rates were at acceptable levels. However, the gas recovery factor had fallen to 16 percent indicating that during venting the well casing had been damaged and injection air was being lost to the overburden. Heating values achieved during the forward combustion phase ranged between 29 BTU/scf to 263 BTU/scf, this wide range of heating values is due to the losses of injection air to the combustion zone.

Reverse combustion was attempted next in May of 1973. Injection rates and pressures were similar to those seen during the forward combustion phase, however after several weeks large volumes of gases began flowing from the production well indicating that excellent communication between wells had been established. The heating values of this test were below 100 BTU/scf. The second reverse combustion test followed the construction of a large flare. This test exhibited similar characteristics to the first reverse combustion test, however heating values ranged from 109 to 166 BTU/scf.. This was due to the increased air injection rates. Initial problems with the second phase began when a bypassing condition started. This bypass allowed injection air to bypass the combustion zone and react with the product gases creating a high temperature condition that was resolved by making changes in the air injection system.

The duration of Hanna I was approximately 180 days. Gasification of 4,000 tons of coal occurred during this time. The average heating value was 126 BTU/scf and 1.6×10^6 scf/day of dry gas was produced. This test proved feasibility of UCG and gave rise to issues associated with forward and reverse combustion such as plugging of fractures, bypass conditions, system pressure maintenance and control of gas loses and heating values.

Hanna II (1975-1976). Hanna II was a three-phase trial starting in April of 1975. Phase I was initiated to further investigate the reverse combustion technique. This phase proved the feasibility of seam preparation using reverse combustion. Completion of the wells near the bottom of the coal seam allowed for linking to occur in the bottom half of the seam, preventing any gas overriding. Phase I lasted for 38 days of gasification between two wells consuming approximately 48 tons of coal per day. The gases were produced at a rate of 2.7 MM scfd with a heating value of 152 BTU/scf.

Phase II consisted of linking two sets of wells by reverse combustion while utilizing extensive instrumentation to indicate the linkage path. This instrumentation showed the placement of a narrow linkage path at the bottom of the coal seam and also showed the combustion front was utilizing the entire 30 ft thick seam. Phase II consisted of 27 days of gasification producing 8.6 MM scfd with a heating value of 175 BTU/scf. This phase consumed more than 100 tons of coal per day.

Phase III began immediately after Phase II. This phase planned to simultaneously inject into two wells and produce a broad reverse combustion link utilizing one of the links created in Phase II as a line source for air injection. This operation did not succeed and the test was continued using one well pair. Approximately 4,200 tons of coal was used during this 38 day burn which produced gases of 138 BTU/scf. (Brandenburg et al. 1976).

Hanna III (1977). The Hanna III experiment was designed to investigate the effects of UCG on ground water quality. This test utilized the reverse combustion technique in June of 1977. Communication between wells was determined to be successful when injection rates increased dramatically and injection pressure dropped. Gasification was then started and continued normally until production well temperatures increased which indicated lack of groundwater. Gasification was suspended until a water injection system was installed. Gasification was started again and continued until temperatures increased once more, at which time the gasification was terminated. This trial lasted 38 days and produced an average heating values of 130 BTU/scf and consumed approximately 2,850 tons of coal.

Hanna IV (1977-1979). Hanna IV started in late 1977 and continued into1979. It was the largest in scope of the Hanna experiments and was conducted to determine the commercialization scale of UCG. The first phase of Hanna IV was unsuccessful due to the drop of the gas heating value of the product gas. After the addition of two injection wells, the product gas never exceeded 90 BTU/scf, which was also considered unsuccessful. The second phase of Hanna IV was also considered unsuccessful. Researchers determined that geologic faults within the test area, not recognized prior to the test, caused the failed UCG attempts. The duration of Hanna IV was 24 days and 1500 tons of coal were consumed producing an average heating value of 133 BTU/scf (Covell et al. 1980).

3.1.2.3 Hoe Creek (1975-1979)

In the early 1970s Lawrence Livermore Laboratories (LLL) became interested in developing a commercial process for gasifying western coals to produce pipeline quality gas. In 1972, they developed a unique approach to in situ coal gasification. The LLL approach utilized an array of chemical explosives that were detonated to enhance the permeability of a reaction zone within a thick bed of coal. They believed that a permeable, fractured coal bed within a relatively impermeable medium should permit intimate mixing of the coal and the reactants (oxygen and steam) and allow heat transfer and reactant access to the coal. They hypothesized that the low permeability of the surroundings should minimize leakage of reactants and products from the fractured zone. In essence, the LLL concept is much like an underground packed bed reactor, which is described in Section 9.

Hoe Creek I (1975). Hoe Creek I was carried out by LLL on November 5, 1975 in the PRB in Campbell County, Wyoming, and was a "simple 2-spot fracturing experiment." It tested the concept they had developed in 1972 and consisted of two – 750 lb. explosive charges fired simultaneously at the bottom of the Felix 2 coal seam. This seam is approximately 20 feet thick and 160 feet deep. Results from this test showed that communication between the wells was insufficient for gasification. During the 11 days of gasification, 129 tons of coal was gasified producing product gas with an average heating value of 102 BTU/scf. The experiment was deemed unsuccessful (Stephens et al. 1976).

Hoe Creek II (1977). In September 1977, LLL started Hoe Creek II 58 day gasification process to test reverse combustion linking. Good quality gas with an average heating value, 108 BTU/scf, was produced during the first part of the test. However, an override situation developed which caused combustion to occur across the top of the coal seam. The gasification zone of the test moved rapidly from the Felix 2 coal seam into the overlying Felix 1 coal seam. Groundwater contamination resulted from the test because of sustained gas lost during gasification. This led to a sharp decline in the quality of gas.

INDEPENDENT SCIENTIFIC PANEL REPORT ON UNDERGROUND COAL GASIFICATION PILOT TRIALS

June 2013

Queensland Independent Scientific Panel for Underground Coal Gasification (ISP)

Professor Chris Moran, Director, Sustainable Minerals Institute, The University of Queensland.

Professor Joe da Costa, School of Chemical Engineering, The University of Queensland.

Em. Professor Chris Cuff, C&R Consulting, Townsville Queensland.

Acknowledgements

The Independent Scientific Panel (ISP) has worked on a part-time basis to provide advice to government on the underground coal gasification (UCG) trials currently underway in Queensland. The ISP has worked with a number of government departments and the two companies, Linc Energy and Carbon Energy, to assess company data and reports and to design a process for reporting the essential outcomes of the investigations of the companies without breaching their confidentiality.

The members of the ISP would like to express their gratitude to the government officers who assisted at various stages throughout the process. They would also like to thank staff of Carbon Energy and Linc Energy who approached the reporting process with a positive attitude. At various times, the ISP, government officials and company members have been challenged with changing external context, e.g., environmental evaluation, changing staffing in government and companies and a state election.

The reports produced by Linc Energy and Carbon Energy are amongst the most thorough compilations of information on any UCG pilot trials to date. A great deal of useful information and lessons are incorporated into the reports. It is not possible to do justice to the quantity of technical information provided by each of the companies in a summary set of recommendations. No doubt, over time, the companies will see fit to release at least some of this technical information into the public domain so that others are able to make their own assessments of the merits and risks associated with UCG.

The ISP initially reported to government in confidence in November 2012. Government considered that report, consulted the two companies concerned and concluded that a review process should be undertaken. Terms of reference for the review are appended. The Queensland Chief Scientist convened a review panel consisting of Dr Steve Ward (Department of Natural Resources and Mines), Professor Paul Greenfield AO and Dr Geoff Garrett AO (as chair). Under the terms of reference the Chief Scientist also considered expert advice and input from Professor Robin Batterham AO, who had also previously provided independent scientific advice to both Carbon Energy and Linc Energy. The group was convened in June 2013 with the chair of the ISP, Professor Chris Moran and a technical representative of each of the two companies, to work towards referenced term 7. Following subsequent consultation with the ISP, this document is the result of the review process.

Executive Summary

Underground coal gasification (UCG) is a technology that has been in use in various forms for many decades. Queensland is possibly currently leading the world in UCG technology development and testing. The Queensland government needs to come to a conclusion regarding UCG in the context of its broader energy policy in the medium and longer terms. A great deal of coal that is economically inaccessible to mining (too deep or poor quality) and from which coal seam gas will have been extracted could potentially be a source of syngas in the future.

The Queensland government approved three UCG trial sites over a period of years with a view to making their own assessment. The Independent Scientific Panel (ISP) was established to assist government with these assessments. The main roles of the panel were to apply individual and collective expertise to analyse, assess and evaluate various technical and environmental factors and to report the outcomes of the trial activities including recommendations on the prospects and future management of UCG in Queensland.

The two companies that have provided pilot trial reports that are the subject of this assessment are Linc Energy and Carbon Energy. Both companies have developed versions of the controlled retracting injection point (CRIP) technology. The reporting process was designed around the combination of the operational life cycle (site selection -> commissioning -> operation -> decommissioning -> rehabilitation) and a conventional process industry risk assessment. Both companies have used their extensive technical databases, which have been gathered from experience of a number of gasifiers with evolving technologies. The integration of technical data into the necessary risk assessment is an important challenge in the process.

Both companies have demonstrated capability to commission and operate a gasifier. Neither company has yet demonstrated their proposed approach to decommissioning, i.e., the self-cleaning cavity, is effective. The ISP remains open to the possibility that the concept is feasible. However sufficient scientific/technical information, particularly relating to decommissioning, is not yet available to reach a final conclusion. Important work has been undertaken but more is yet to be done. For example, neither company has gained access to a gasified cavity, sampled it and provided information on the current contents and condition of surrounding materials.

At mid-2012, neither company had completed a burn of sufficient duration to create a final cavity of the dimensions that are expected under a commercial process. Until this is done it is difficult to come to a final conclusion regarding the technology. Given this situation, the ISP believes it would be pre-emptive to consider commercial scale. However, given the considerable investment by the companies and Queensland government to date, and the undoubted future importance of UCG as a viable energy source of global significance, the ISP is of the view that the gasifiers currently operating should be permitted to continue until a cavity of significant dimensions is available for full and comprehensive demonstration. At that time, commercial scale UCG facilities could be considered. There is more work to be done on the design and environmental and operational safety for multi-panel operations.

Given the pilot project reports presented, the ISP has come to three overarching recommendations and eight (8) specific recommendations. The latter cover each of the life cycle stages (5), the interaction between CSG and UCG (1) governance (1) and the question of commercial multi-panel operations (1).

Following consideration of the materials made available to the ISP from companies and in the public domain, the ISP has come to the following overall conclusions.

- Underground coal gasification could, *in principle*, be conducted in a manner that is acceptable socially and environmentally safe when compared to a wide range of other existing resource-using activities.
- The ISP is of the opinion that for commercial UCG operations in Queensland *in practice* first decommissioning must be demonstrated and then acceptable design for commercial operations must be achieved within an integrated risk-based framework.

Consequently, the ISP makes the following three (3) overarching recommendations.

Overarching recommendation 1.

The ISP recommends that the Queensland government permit Carbon Energy and Linc Energy to continue the current pilot trials with the sole, focused aim of examining in a comprehensive manner the assertion that the self-cleaning cavity approach advocated for decommissioning is environmentally safe.

Overarching recommendation 2.

The ISP recommends that a planning and action process be established to demonstrate decommissioning. Successful decommissioning needs to demonstrate the self-cleaning process and/or any necessary active treatment. To achieve this:

1. *A comprehensive risk-based plan for decommissioning must be produced;*
2. *The Plan must take account of the fact that both companies now have connected cavities suitable for demonstration [Linc Energy is still gasifying];*
3. *The Plan must include at a minimum a conceptual model and relevant numerical models, a sampling and verification/validation strategy, and event-based milestones that, where possible, are time bound.*
   Two significant phases are recognised:
   - *a. Sampling of the zone surrounding the cavity; and*
   - *b. Direct cavity access.*
4. *The government must establish a process by which the plans and their implementation are assessed for adequacy.*

Overarching recommendation 3.

The ISP recommends that until decommissioning is demonstrated, as per Overarching Recommendation #2 no commercial facility should be commenced.

Specific Recommendations

Specific recommendation #1

The government together with the UCG industry and an independent advisory body, should develop guidelines and standards for site selection. The ISP recommends that site selection is a process that should be preceded and informed by appropriate geological surveys, hydrogeological modelling and an assessment of the community and environmental context. Such assessments must serve as Go / No Go gates for decision to develop or not any site for UCG operation, i.e., any limiting factor should signal No Go for the site.

Specific Recommendation #2

The ISP recommends that for each new panel, the UCG industry adopts a 'commissioning' approach rather than 'start-up' or 'ignition' regardless of size or multiplicity, to reduce the risks associated with this phase. Commissioning should involve world's best practice for risk management in process industries including HAZOP, fault tree analysis, event tree analysis, LOPA including all the controls to ensure that the inherent risks of UCG activities are minimised from the outset.

Specific Recommendation #3

If the UCG reaction has been extinguished, then restarting the panel should follow the pre-defined risk protocols. If restart is deemed unacceptable the process should proceed directly to decommissioning and rehabilitation.

Specific Recommendation #4

No further panels should be ignited until the long term environmental safety provided by effective decommissioning is unambiguously demonstrated. Evidence of the effectiveness of decommissioning must be comprehensive.

Specific Recommendation #5

The companies should immediately propose, test and establish acceptable and agreed processes and outcomes for rehabilitation.

Specific Recommendation #6

The ISP recommends that any UCG operation should be licensed on the basis that it is responsible for maintaining and controlling all its operating conditions, taking into account the conditions of the site at the time of approval, including maintenance of groundwater pressure.

Specific Recommendation #7

The government should consider establishing two new entities to support a UCG industry at the level necessary to ensure its best chance to be environmentally, socially and economically viable.

1. Queensland UCG Independent Assessment, Evaluation and Advisory Group.
2. The Queensland UCG R&D Network.

Specific Recommendation #8

A commercial operation should be designed from the outset on a foundation of well-established principles i.e. a risk-based approach from the outset in all phases of the life-cycle of multi-panel operation.

The Carbon Energy and Linc Energy sites have been operated as pilot sites. Any consideration of commercial activity should be preceded by a comprehensive, multi-panel, risk-based plan.

Table of Contents

1 Preamble

The Terms of Reference for the Scientific Expert Panel, Underground Coal Gasification Policy Implementation were defined in Version 1.4 of September 2010. This document stated (*inter alia*) that "While the Report will consider the benefits and costs of a potential UCG industry in relation to its environmental, social and commercial impacts, the panel will focus on the technical and environmental aspects of the UCG technology."

The Independent Scientific Panel (ISP) has examined the materials from the two pilot projects in the light of background information from international experiences. The information used on the two pilot projects included:

- Final summary reports and associated appendices;
- Company performance during the environmental evaluation process; and
- Company interactions during the ISP process development and carriage.

In this report the ISP takes the view that the UCG trials on which it has received information are *pilot trials*. This is distinguished from the term *demonstration trials* in that the latter would imply that the technology for all phases of the life cycle is well understood and that the single cavity/panel[1] trials are to demonstrate the scale-up for commercial UCG facilities. The ISP does not accept that the information supplied, the manner in which it has been supplied and the overall design of the pilot underground facilities warrants assessment as demonstration trials. As such, it is important that as many lessons as possible are drawn from the pilot trials to allow the companies the opportunity for future demonstrations to provide confidence, that an environmentally safe and socially acceptable process can be established that is economically viable.

In keeping with the individual confidentially agreements signed by each member of the ISP with the companies, this report does not necessarily include technical information and data. The technical supporting evidence for the recommendations made has been obtained from detailed consideration of the technical material provided.

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[1] Throughout this report the terms "panel" and "cavity" are used to refer to the underground void created by UCG. It is recognized that a panel refers to a specific design and a cavity is a more general term. Attempts have been made to use the term panel when reference requires implied information about the design and therefore some likely features of the cavity. Otherwise the term cavity has been used. The ISP recognizes that this may be an imperfect separation of the terms and their use.

The ISP has taken a life cycle approach to its considerations. The life cycle for UCG that has been adopted is shown in **Figure 1**. The major phases of the life cycle are:

- Rehabilitation
- Decommissioning
- Production
- Commissioning
- Site Selection

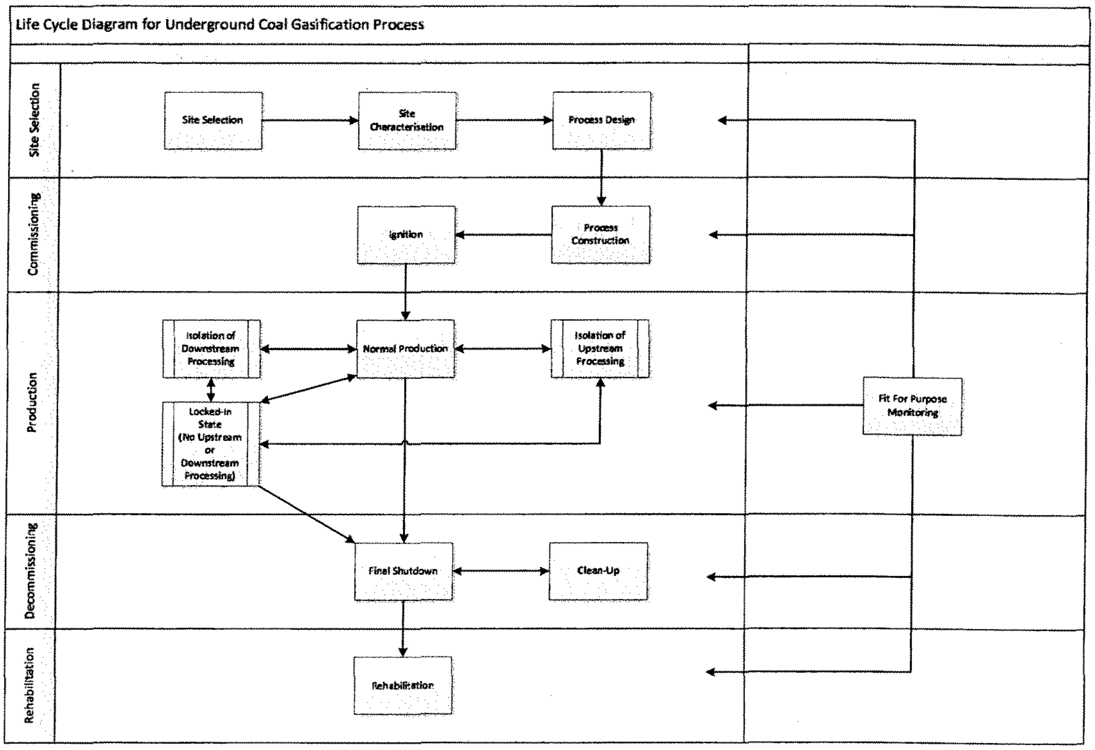

Figure 1 - Schematic of Life Cycle Stages for a UCG Plant

In assessing the pilot trials of Carbon Energy and Linc Energy it was apparent that the site selection is now historical and therefore this report deals with the critical characteristics of a site suitable for UCG and makes observations on the extent to which the Carbon Energy and Linc Energy sites meet those characteristics, i.e., a formal risk assessment approach was not considered appropriate.

For commissioning and operation, the ISP has structured its assessment around a risk assessment. The report sets out what the ISP considers to be the significant critical risks associated with these phases of the life cycle. The Carbon Energy and Linc Energy reports were assessed with regard to how well they represented and dealt with these risks and what lessons could be drawn from the experience gained to date. In general the ISP found that the company reports contained sufficient information to undertake the analyses although accessing the information was made far more difficult than it need have been because of the poor integration of data and risk assessment (see Section 4).

In contrast, for the decommissioning phase, the ISP determined that the company reports did not include sufficient information to undertake an analysis of the extent to which the proposed technologies meet the necessary risk management standards. The ISP has raised what are believed to be the major risks and outlined what would be required from the companies to demonstrate that these risks can be effectively mitigated.

No significant information has been received regarding site rehabilitation beyond general statements of similarity to other rehabilitation challenges elsewhere. Therefore, the ISP is unable to make any assessment on this life cycle stage.

Recommendations are made throughout the report and these are consolidated into a single section for ease of access. However, the ISP does not advise reading or quoting of individual recommendations out of context.

The ISP has determined that an overarching recommendation can be made regarding UCG in Queensland at this point in time and in regard to the two pilot trial sites examined herein.

The approach of using an Independent Scientific Panel to comment on the viability of pre-established and pre-approved pilot trials has been challenging for all involved. The ISP would like to acknowledge that the companies engaged in this unusual process in good faith and with cooperation at all stages. Below (Section 3) the ISP presents a critical appraisal of the reporting by the companies. It must be noted that this critique is written with respect to an ideal process. The real world is not an ideal place and the time pressures and challenges of day-to-day demands on company staff are understood by the ISP. We therefore express our gratitude for the way in which company staff worked with the ISP throughout this process.

Finally, at various times throughout the ISP process, the ISP has been challenged to understand government processes. Better integration of information flow and alignment of goals between departments would have greatly facilitated various aspects of the ISP deliberations and timeliness of reporting. The ISP understands that individuals must be given opportunities for career development as and when they arise. However, the frequent changes to the officers and secretariat supporting the ISP constrained the process from being as effective as it might otherwise have been.

The ISP is a part time role for each of the participants. We acknowledge that our inability to devote large amounts of time to the activities of the ISP has been a contributing factor in the time taken to finalise reporting. Nevertheless we accept responsibility for the shortcomings that are inevitably embedded in this report.

2 Overarching recommendations

Following consideration of the materials made available to the ISP from companies and in the public domain, the ISP has come to the following overall conclusions.

- Underground coal gasification could, *in principle*, be conducted in a manner that is acceptable socially and environmentally safe when compared to a wide range of other existing resource-using activities.
- The ISP is of the opinion that for commercial UCG operations in Queensland *in practice* first decommissioning must be demonstrated and then acceptable design for commercial operations must be achieved within an integrated risk-based framework.

Consequently, the ISP makes the following three (3) overarching recommendations.

Overarching recommendation 1.

The ISP recommends that the Queensland government permit Carbon Energy and Linc Energy to continue the current pilot trials with the sole, focused aim of examining in a comprehensive manner the assertion that the self-cleaning cavity approach advocated for decommissioning is environmentally safe.

Overarching recommendation 2.

The ISP recommends that a planning and action process be established to demonstrate decommissioning. Successful decommissioning needs to demonstrate the self-cleaning process and/or any necessary active treatment. To achieve this:

1. *A comprehensive risk-based plan for decommissioning must be produced;*
2. *The Plan must take account of the fact that both companies now have connected cavities suitable for demonstration [Linc Energy is still gasifying];*
3. *The Plan must include at a minimum a conceptual model and relevant numerical models, a sampling and verification/validation strategy, and event-based milestones that, where possible, are time bound.*
   Two significant phases are recognised:
   a. *Sampling of the zone surrounding the cavity; and*
   b. *Direct cavity access.*
4. *The government must establish a process by which the plans and their implementation are assessed for adequacy.*

Overarching recommendation 3.

The ISP recommends that until decommissioning is demonstrated, as per Overarching Recommendation #2 no commercial facility should be commenced.

3 Underground Coal Gasification (UCG) - some context

UCG can be used to extract energy from coal seams that are otherwise low grade and/or too deep to economically exploit by more traditional open cut or underground coal mining methods. Injection wells from the surface supply oxidants and steam to ignite and fuel the underground gasification process. The product gas is brought to the surface via separate production wells (although one well has been used for both functions in a small number of cases). Gasification is typically conducted at a temperature between 900°C and 1200°C but may reach up to 1500°C. The process gasifies the coal and generates what is referred to as Syngas which is principally composed of carbon dioxide, hydrogen, carbon monoxide, methane, nitrogen, steam and gaseous hydrocarbons. The proportion of these gases varies with the type of coal, the efficiency and control parameters of the gasification process. The product gas can be used for fuel for power generation, chemical feedstock, gas to liquids fuel conversion or fertiliser.

Approximately 90% of the available energy of the part of the coal seam that is incorporated by the cavity is released by the UCG process (compared to conventional open-pit technology which is ~60%).

It is important to manage oxygen flow to the coal to ensure appropriate Syngas production for the designed purpose and to avoid underground uncontrolled burning, which otherwise cannot occur because of lack of oxygen. The gasification process involves pyrolysis in various aspects of operation. Inevitably this produces chemicals that become serious contaminants if they escape the gasification cavity into the surrounding environment. The key aspect to ensuring an environmentally safe and socially acceptable UCG operation is to provide certainty of containment and/or removal of these chemicals. Therefore, an important focus of the ISP is on the decommissioning phase of the pilot UCG trials that are the subject of assessment of this report. Unambiguous evidence of clean cavities as a result of decommissioning is essential.

The ISP has not focussed on potential subsidence as this is considered to be well understood and regulated from the experiences of underground long wall coal mining.

The pilot trials in Queensland have become well known globally in the UCG community because of the longevity and quality of the work to date. The ISP has come to the view that Queensland's investment in commercial research via the pilot trials is potentially valuable to the State in the medium term.

4 Company reporting

Over the period of time the ISP has been overseeing the pilot trials and development of the pilot trial reports a great deal of change has occurred. It is clear that the companies have learned a great deal from the trials. The technical lessons are highlighted throughout this report. There has also been considerable advance in the structure and reporting of information.

However, there is more to be learned in both the technical and information areas. The ISP is firmly of the view that UCG should be treated as an industrial process and therefore operations should employ standard approaches (appropriately adapted to their particular circumstances).

Over time, each of the companies has produced information that accords with a risk-based approach. The ISP requested that pilot project reports follow the basic structure below.

1. A detailed background description of the technology (and/or technologies) being employed/tested in each trial;
2. A description of the life cycle stages of the technology;
3. An assessment of the risks associated with each stage of the lifecycle including description of hazards, pathways and receptors and proposed mitigation/control measures including levels of protection analysis. The companies were asked to supply supporting technical information to the level of detail necessary to allow the ISP to assess whether or not we were in agreement with the companies over the level of risk assigned and whether the mitigation measures were likely to be sufficient.

The ISP provided guidance to the companies in the form of a document outline and held a significant number of face-to-face meetings to assist with clarification.

The ISP was of the view that risk assessment should be used as a core integrating framework to assess the success or otherwise of the pilot trials to demonstrate the environmental and social acceptability of UCG. This is not the same as ensuring industrial quality risk assessment to operate the pilot facility. Each company took a different approach to the overall pilot risk assessment. In producing the risk assessments it is critical that headline significant risks are supported by only the information and monitoring data required to provide confidence in the mitigation and control measures proposed. The ISP found that the companies produced significant quantities of relevant information but they could have been more efficient in targeting the data provided to the threats identified. It will be important that the plans that will be delivered for decommissioning demonstrate that the integrating value of such a risk assessment has become embedded into company processes.

5 Assessment of Underground Coal Gasification Industry and Queensland Pilot Trials

5.1 Lifecycle of an Underground Coal Gasification Plant

This report is structured around the life cycle of a UCG operation. The essential stages are: site selection, commissioning, production (including temporary shutdowns for maintenance and subsequent re-starts), decommissioning and eventual site rehabilitation. Each of these stages consists of several smaller phases or operating modes, with multiple interconnections and relations as shown schematically in **Figure 1.**

5.2 Site Selection

Selection of an appropriate site for Underground Coal Gasification (UCG) operation is the single most important risk mitigation strategy and is therefore crucial to the economic and environmental viability of any UCG proponent. The site selection process should follow a structured approach that progressively analyses the characteristics of the site with the effort and expense escalating with each subsequent phase. Therefore, effort and development cost scale appropriately to reflect a site's potential. Selection of a suitable site for the operation of a UCG facility involves the investigation and consideration of the factors below:

- Target resource
- Regulatory Environment
- Social and community context
- Local land use context
- Receiving Environment
- Geological, geomorphological and hydrological parameters
- Risk

The particulars of the target resource that must be accurately assessed as part of the site selection procedure should include quality, size, geological and hydrological setting, and commercial viability of the resource. The efficiency of the combustion process and the quality of the product is partly governed by the saturation level and hydrostatic pressure within the coal seam. The *deeper the seam* the less probability there will be for operational problems e.g. uncontrolled ingress of air to the combustion chamber.

As a general guide a UCG site should operate under a rigorous risk-based approach and include, at least, the following attributes:

- Coal seam at sufficient depth to ensure that any potential environmental contamination can be demonstrated to have minimal environmental consequences. With deeper coal, there are fewer useable aquifers and, if appropriate sealing horizons are present above the gasification depth, there is a much lower probability of materials (gas or liquid) moving to the surface.
- Coal seam sufficiently thick to sustain gasification with reasonable likelihood of economic viability
- Rank of coal should be lignite to non-swelling bituminous coal.
- Hydraulic head sufficient to contain efficient gasification
- Coal seam capped by impermeable rock.
- Target coal located so that there is sufficient thickness between the target coal seam/measure and any valuable aquifer higher up the geological succession
- Sufficiently distant from rivers, lakes, springs and seeps to avoid contamination should chemical escape the cavity
- Absence of faulting or intrusions in the vicinity of the site. This is dependent on the size of the cavity
- Sufficient distance from the nearest town and/or intensive surface infrastructure, e.g., irrigation or feedlots, and areas of significant environmental value, e.g., world heritage forests or wetlands, to avoid contamination should chemicals escape the cavity and to minimise impacts of odours.

Pilot Trial Issues and Lessons Learned

The ISP recognises that much has been learned about site selection since the pilot trials were established. However, given the international experience at the time of the decision to approve the trials, the ISP was uncertain why deeper coal seams were not targeted from the outset.

Figure 1 shows that process design is considered part of site selection. This is important because it indicates that site characterisation is *not* independent of the technology to be employed (including the surface downstream processing of the Syngas). The Linc Energy site (and report) contains a number of different pilot trials each with different designs. Consequently, it is certain that site characterisation was not optimised for the process design *a priori*. This is one reason why the trials must be considered pilot trials as opposed to demonstration trials (see Section Overarching recommendation 1).

An important link between site characterisation and process design is fit-for-purpose monitoring. It is necessary to know in advance the details of technology design to ensure that monitoring is sufficient, appropriately located and robust for the process envisaged. In Section 5.4.1.2 reference is made to the failure of infrastructure and the failure of monitoring systems to adequately inform the operators of the problems. An important aspect of process design as part of site characterisation is the scale up to multiple CRIP panels for a commercial operation. Site characterisation for a single panel is not the same as for multiple panels (particularly if they are to be testing different technologies). Site-wide monitoring design must be in place at the outset to ensure sufficient baseline and site behaviour information is available as panels are gasified, is essential. Such site characterisation is yet to be tested by Linc Energy because each pilot trial has been different and no site-wide technology-specific monitoring design has been implemented. Carbon energy has a site design that envisages multiple panels. However, no full site monitoring plan has been presented. Further, the technology attempted in their first panel required design alteration to increase the probability of success in the second panel trial. On both sites, the monitoring schemes have evolved dramatically from the original designs and continue to do so over time. Overall, therefore, the pilot trials have not demonstrated successful site selection for a commercial scale operation.

The ISP does not accept the retrospective assessment by Linc Energy indicating that their site meets the requirements of a good site for UCG. The ISP remains to be fully convinced that the Linc Energy and Carbon Energy sites are sufficiently deep. Recognising that shallower sites have higher risks, demonstration of a single clean cavity at these sites is not enough to suggest *automatic* acceptability of commercial operations.

Specific recommendation #1

The government together with the UCG industry and an independent advisory body, should develop guidelines and standards for site selection. The ISP recommends that site selection is a process that should be preceded and informed by appropriate geological surveys, hydrogeological modelling and an assessment of the community and environmental context. Such assessments must serve as Go / No Go gates for decision to develop or not any site for UCG operation, i.e., any limiting factor should signal No Go for the site.

5.3 Commissioning

The initial start-up operation for a UCG panel is a complex process that incorporates elements from site selection to ignition. During the start-up sequence for a panel, there are a number of process deviations which may occur resulting in risk scenarios. These are listed below:

- Deviation of geology / hydrogeology of site from that predicted in the site characterisation and design phases
- Improper well design for a selected site
- Deviation of well construction from design
- Failure of mechanical or electrical equipment aboveground
- Blockage of the injection, ignition or production wells or the panel itself
- Failure of the control systems
- Underground explosion
- Over-pressurisation of coal seam
- Ignition failure

As with any chemical process the likelihood of a deviation occurring is greater during the start-up phase than during normal operation. This is a well-accepted fact in the process engineering industry because any operation that has not reached 'steady-state' is inherently more difficult to predict and control. To combat this increased risk, process engineering guidelines and standards dictate that a risk management based 'commissioning' approach be undertaken. Commissioning should involve world's best practice for risk management in process industries including HAZOP, fault tree analysis, event tree analysis, levels of protection analysis (LOPA) including all the controls to ensure that the inherent risks of UCG activities are minimised from the outset. It is important that this process be implemented from the beginning, across the entire operation and not applied on an *ad hoc* basis or only to specific process equipment.

It is the strong opinion of the ISP that the ignition sequence of a panel is analogous to the initiation of a new process plant. Therefore it is recommended that a commissioning approach based on risk management be utilised by all UCG proponents every time a new panel is to be commenced. The fact that the consequences of a hazard event during commissioning are predominately economic rather than environmental is not material to this recommendation. This style of risk management, from the process industry, should pervade every aspect of a UCG operation, beginning with site selection, design and commissioning. Therefore, "commissioning" is the appropriate standard term and concept from the processing industry. The ISP is of the view that this term be adopted and consistently applied in the UCG industry.

Pilot Trial Issues and Lessons Learned

The risks associated with commissioning can be minimised by proper site selection, adherence to world's best practice for UCG technology and cavity design as well as appropriate commissioning procedures. However, it is clear from the documentation provided by both proponents that the risk management approach advocated by the ISP was *not* followed from the outset. This should change in any future activities.

The ISP has formed the view that the major commissioning risk is explosion in the initiating cavity. This may adversely damage or weaken the mechanical performance of the well heads, well casings, well liners, control valves and above ground systems. Safe operating procedures (SOPs) for the ignition sequence are a critical component of risk management and part of best practice. SOP's have not been provided so it is not possible for the ISP to assess their adequacy.

Linc Energy, in their Risk Assessment Section discussed risk from high oxygen as a percursor of explosive environments. Significant work on Gasifer 5 was specifically discussed with respect to this risk and additional measures were employed to monitor this risk. The procedures during monitoring should be addressed in an SOP. It is the opinion of the ISP that it is the responsibility of Government to ensure compliance with the SOP and monitoring procedures in order to minimise risk.

Conclusions

The ISP concludes that, based on the Linc Energy and Carbon Energy pilot trials and the experience gained, that the two companies have the knowledge to establish world's best operating procedures for mitigating the significant risks during commissioning including the highest risk, i.e., underground explosion.

Specific Recommendation #2

The ISP recommends that for each new panel, the UCG industry adopts a 'commissioning' approach rather than 'start-up' or 'ignition' regardless of size or multiplicity, to reduce the risks associated with this phase. Commissioning should involve world's best practice for risk management in process industries including HAZOP, fault tree analysis, event tree analysis, LOPA including all the controls to ensure that the inherent risks of UCG activities are minimised from the outset.

5.4 Production

The production phase (see Figure 1) of a UCG plant is in principle a normal process involving non-ambient temperatures, pressures and the production of chemicals such as syngas and heavier hydrocarbons. The operation of a UCG plant should therefore be considered within the risk management ethos of any chemical or processing industry. This should include contingencies for scheduled and unscheduled maintenance on all unit operations of the UCG process and measures for emergency shut-down procedures. The major difference between UCG and other process industries is that the reactor for the UCG process is underground and it is exposed to some unknowable and uncontrollable conditions, which are not found in above ground operations. This is also the primary source of increased risk for the UCG process in comparison to other gasification processes. These uncertainties include aspects of the coal geology, hydrogeology, strata morphology and overall cavity growth.

As with its above ground analogue, coal gasification, the UCG process involves pyrolysis, combustion and gasification that will inherently produce contaminants such as benzene, toluene, ethylbenzene, xylenes (commonly referred to together as BTEX), various phenols, polycyclic aromatic hydrocarbons (PAHs) and other toxic compounds. Some of these compounds may be naturally present in coal seam aquifers. Therefore an appropriate baseline study is necessary to differentiate natural from contaminant products.

If contaminant chemical species are present then these have the potential to become environmental contaminants if they escape the controlled UCG process. In an ideal UCG process situation, everything that is produced in the underground reactor should either be extracted or remain within the cavity. Any contaminants brought to the surface should then be treated in appropriate waste facilities to reduce their inherent risks. However, as the UCG process continues, the uncertainties in the site geology ensures that there will be variations and deviations in temperature, pressure, groundwater flow and gas and vapour movement into and out of the UCG cavity. As a result there is a risk of contaminants leaving the cavity and entering the surrounding strata and aquifers. This has the potential to lead to underground water contamination or syngas egress towards the surface through the overburden via faults / fissures or high permeability regions. Detection of potential contaminants reaching the surface is a matter of compliance with an adequate monitoring programme using a spatially valid array of suitably constructed monitoring wells. All these matters fall within the jurisdiction of the Government.

UCG drilling technologies and cavity designs have evolved significantly in the last 30 years. However, the UCG process itself remains complex and the scope, scale and severity of the emissions will depend on the risk mitigation strategies adopted by the UCG proponents the aim of which is to deliver results that are environmentally, socially and economically acceptable for all stakeholders. In view of these issues, the ISP has taken that approach of Layers of Protection Analysis (LOPA) to examining the normal Production Mode. After reviewing the final summary reports and associated appendices from Carbon Energy and Linc Energy the ISP proposes a suitable LOPA (Table 1).

Table 1. Layers of protection proposed by the ISP for UCG risk management in the operation phase of the life cycle.

Layer	Description
1	Site Selection
2	Process Design
3	Process Control
4	Critical Alarms
5	Safety Instrumented Systems
6	Pressure Relief Systems
7	Physical Protection
8	Plant Emergency Response
9	Community Emergency Response

The interpretation of Table 1 is that the preference is that mitigation of any potential risk should be effective at the lowest (smallest numbered) layer possible. Risks are inherently associated with any industrial activity, and only after mitigation from a lower level is insufficient (or fails) should the rest be relied upon (needed). Nine layers of protection are considered appropriate to ensure an environmentally safe and community-acceptable UCG production mode. If the cost of implementing the layers renders the operation uneconomic, it should not proceed, i.e., compromise on layers of protection for economic viability is not acceptable.

Issue and Lesson Learned

Given retrospective knowledge of incidents that occurred during the pilot trials it is apparent that the conventional process engineering risk management based approach (LOPA - Layers of Protection Analysis) was not part of the original operating ethos of the pilot trials.

To their credit, both Carbon Energy and Linc Energy have rectified inadequate operations and improved their UCG operational management and knowhow over the course of the pilot trials. It is expected that the experience of having put in place LOPA for the pilot reporting that the companies are in a strong position with respect to operating a single cavity operation.

5.4.1 Assessment of levels of protection

5.4.1.1 Site Characterisation

Observations and a recommendation regarding site selection are provided above (Section 5.2). Sufficient site characterisation and process design is the most critical factor in identifying and controlling risks with the operational phase. A sound understanding of the variability of the various strata and their interrelationships provides significant risk mitigation. Sufficient distance from environmental and community assets of concern is key in ensuring safe operating conditions can be maintained.

Pilot Trial Issues and Lessons Learned

Linc Energy manages a site that is clearly an experimental facility (of world leading standard). Linc Energy makes no pretence that the site was selected and characterised with the risks associated with a particular commercial-ready design in mind. Therefore, it is not reasonable to expect that the site characterisation necessarily meets the optimal requirements of first layer of protection for all the designs tested to date. In this regard it is important to observe that the most recent pilot (gasifier 5) is substantially different to gasifier 4 in a number of non-trivial design respects.

Carbon Energy has managed their site with a view to scale up of their operation to multiple panels. The failure of the first panel to progress beyond a short distance before collapse of a critical underground pathway required design change for the second gasifier (which appears to be functioning more effectively). Clearly, Carbon Energy is still evolving towards a final design. Once this is achieved it will be possible to assess the site selection in terms of a multiple panel design. It is clear that both companies have learned a lot about gasifier design as would be hoped from well run pilot programmes. Optimal site characterisation (careful and comprehensive matching of site characterisation and process design) is yet to be convincingly demonstrated. The ISP is of the opinion that both companies have gained sufficient knowledge to be able to demonstrate this in selecting a new site.

5.4.1.2 Process Design

Both Carbon Energy and Linc Energy have developed their UCG technology designs to a variation of the current state-of-the-art parallel controlled retracting injection point (CRIP) design with directional drilling. This is a significant advancement from older designs utilised in international UCG experiences where vertical wells with reverse combustion linking or hydraulic fracturing were used. Parallel CRIP designs are less prone to the generation of fractures or fissures in the coal seam or surrounding strata, and are therefore useful in mitigating risks associated with syngas egress and underground water contamination.

The process and geotechnical modelling of cavity growth and UCG reaction conditions presented in the final reports of both proponents is limited. Carbon Energy do not provide any modelling on cavity growth, which should be backed by general mass and energy balances and specific data from the pilot trial for validation. A simplified example of a multi-panel site design based on long-wall coal mining software (COSFLOW) with no evidence of calibration or validation was provided. Some information is provided on cavity location and morphology for panel 1, but this is more relevant to the decommissioning phase and as such is discussed in Section 5.5.

Linc Energy presented a model of cavity growth based on computational fluid dynamics and coal reaction, consumption and gas generation. Linc Energy has therefore developed in-house expertise in modelling cavity growth. However, the model deals with ideal conditions and is not validated. It is unclear how well it would perform at forecasting variations that cannot be controlled from the surface, which may result in preferential reaction pathways occurring which in turn, will influence the cavity growth and morphology. No attempt has been made to compare modelling with actual cavity data (see Section 5.5)

There are considerable differences in the amounts of information available between the Linc and Carbon models. The most important missing information is related to the validation of the Linc model. Detailed confidential information related to cavity modelling was presented by Linc to the ISP for evaluation. This may be available to Government if formal requests are made.

Information about cavity growth and the performance of the underground reaction chamber is crucial to the process design, especially for commercial operations. The level of uncertainly in the behaviour of the cavity during operation limits the effectiveness of the process design and therefore compromises the process engineering risk management approach advocated by the ISP. This reinforces the view of the ISP that the pilot trials still remain as formal development and learning experiments and as such they do not meet the information requirements of a scaled up process.

Conclusion

Cavity growth models must be developed and suitably validated for single panel UCG operations before UCG could progress to a multi-panel design.

In this LOPA, process design also incorporates all aspects of mechanical integrity. Of particular importance are materials selection, corrosion allowances and the mechanical ability of the design to cope with high pressures, temperatures and flow rates.

Pilot Trial Issue and Lesson Learned

The pilot trials have been subject to mechanical design problems relating to the ignition, injection and production wells. Mechanical failures of the well casings and / or well heads resulting from inadequate design, selection of materials and construction have been experienced. Deviations caused by temperature and pressure resulted in weakening of the liners or lifting of the wells that subsequently failed. Whilst petroleum engineering designs were adopted, these did not account sufficiently for the higher temperatures associated with UCG operation and there is a clear need for a shift to design standards that do, such as for those associated with geothermal wells.

Carbon Energy and Linc Energy have evolved their well designs to account for UCG operations to enable operation and acceptable deviation within appropriate temperature regimes and *in situ* removal of well blockages. This greatly reduces the risk of well head failure.

Downstream processing of the syngas and associated condensates including surface water treatment is an integral part of the entire UCG operation and as such should be designed accordingly to deal with the significant variability and process deviations associated with normal production. It is observed that several issues relating the treatment of process water in the pilot trials could have been avoided if this principle was followed. For example UCG process water has exceeded piping and knock-out pot capacities resulting in minor spills directly onto soil or into local watercourses. Whilst these incidents have been thoroughly investigated by EHP (formerly DERM) and appropriate remedies taken, that they were allowed to occur in the first place leads the ISP to conclude that the original process design was not carried out using an appropriate risk management approach and/or that the necessary controls were *not* in place.

Conclusion

All downstream processing for the syngas and process water should cater for process deviations (including inherent safety factors) and unit operations should be designed and sized accordingly. Equipment should be designed to account for any corrosion that may result from the presence of syngas and water.

The flare is an integral part of the process design and is necessary for safe operation of both upstream and downstream processing facilities.[2]

The ISP recognises that should the downstream processing fail, it may not be wise to shut-down the operation of the cavity and as such systems, such as the flare, should be in place in order to safely combust the excess syngas.

Conclusion

A flare is a crucial part of the UCG operation and should be incorporated into the process design and be able to cope with process variation and deviations.

In view of the complexities associated with UCG operation, the LOPA design process requires inclusion of monitoring as an integral aspect of protection. In fact, the design of monitoring systems should be considered at the inception of the design process and must be appropriate for the site conditions and knowledge of possible deviations and indications that deviations may be occurring.

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[2] Current monitoring processes are specific to each pilot and are considered, generally adequate, by the ISP. Prior to any commercialisation, detailed specific monitoring strategies should be developed for each UCG operation. Compliance with the monitoring requirements should be a Government responsibility. In principle, flares will decompose or combust hydrocarbons and condensates. Without specific strategies for removal, remaining issues would relate to H_2S, Hg, Ar, Cd, Ni and possibly silica at ppm or ppb concentrations. Industrial processes are available to assist in removal of these components.

Pilot Trial Issue and Lesson Learned

Pilot trials have corroborated conventional understanding that monitoring systems are an integral component of the UCG process design. For example, the operating pressure of the cavity should not exceed the hydrostatic pressure of the surrounding groundwater. When the hydrostatic pressure is exceeded for a sustained period an increased presence of contaminants in the monitoring wells has been observed and reported. Carbon Energy and Linc Energy acknowledge that operating pressures greater than the hydrostatic pressure lead to gas and vapour diffusion into the surrounding strata resulting in detection of products of pyrolysis in groundwater. Therefore groundwater monitoring wells should be setup prior to the construction or drilling of any panel. The pilot trials have included monitoring wells which have been setup as regulatory and reporting requirements from the various regulatory bodies, or as deemed appropriate by the individual UCG proponents.

Carbon Energy has provided data indicating that when operating pressure dropped below hydrostatic groundwater pressure, contaminants migrated and that these could be redirected to the cavity by control of the rate of air injection and thereby internal cavity pressure. This is an important lesson of successful monitoring, deviation detection and corrective action.

Given that the pilot trials have demonstrated that flow reversal to the cavity occurs and that it can be effectively monitored, then the ISP concludes that it can be effectively monitored in practice. Monitoring the performance of the pilots on an ongoing basis as they proceed is a Government responsibility not that of the ISP. The experience of the panel indicates that this is feasible.

The evolving design of the monitoring wells has been subject to regulatory pressures, albeit to varying degrees across the UCG proponents, with several pilot trials required to install additional wells to better monitor the UCG process. To their credit all the UCG pilot trials have installed monitoring wells additional to the initial environmental licences for their own understanding and monitoring of the process.

Companies have yet to fully demonstrate the capability to design and install a monitoring network suitable for multi panel operations and that some of the groundwater data may not be representative. For example, the Linc groundwater monitoring bores are self-purging (gas lifted groundwater). This may result in the loss of volatile organic carbon contaminants during sample collection. In addition some doubts exist as to the construction of the Carbon groundwater monitoring bores which may inhibit the collection of representative groundwater samples.

It is possible that these aspects may prevent an accurate assessment of underground impacts related to chemical species transported via groundwater and/or gas. The ISP acknowledges these difficulties as do the pilot reports, particularly the Carbon Energy report. Suggestions are made for the use of improved systems. The ISP also notes that Government Departments have instigated an environmental evaluation on the basis of such monitoring.

Conclusion

The layout of groundwater monitoring wells should be integrated into process design. It is recognised that some wells are necessarily to be sacrificed as the gasifier grows. Sacrificial wells may be used to access the UCG cavity during commissioning and rehabilitation. Monitoring wells should be setup prior to commencement of any operations. The capability to design and install monitoring suitable for multi-panel operations has not been demonstrated.

5.4.1.3 Process Control, Critical Alarms, Safety Systems and Pressure Relief Systems

LOPA layers 3 through 6 cover various aspects of basic and advanced process control and automated safety systems for the UCG process and as such have been combined for the purposes of this summary. These layers of protection are commonly associated with the oil and gas processing industry. The UCG process produces syngas at moderate temperatures and pressures and therefore operates within the parameters of this industrial sector.

Pilot Trial Issue and Lesson Learned

The pilot trials suggest that many of the risk management systems adopted by the process industry for LOPA 3-6 have not been adequately implemented by any of the UCG proponents. However, the risk assessment reports provided by both Carbon Energy and Linc Energy have shown the incorporation of some of these layers of protection and discuss others that are under current consideration.

Carbon Energy has provided Piping and Instrument diagrams (P&IDs) containing pressure, temperature indicators, process control valves, pressure relief valves, flare systems among other basic and advanced control systems. The risk assessment report from Carbon Energy and R4Risk (attached as Appendix K) contains a detailed analysis of the hazard events, and specifics of the control systems with links back to equipment tags allowing full analysis of their systems. The ISP commends the content of this report, but its full value is not properly integrated into the main document (see Section 4). The R4Risk report is significantly more comprehensive than that provided by Linc Energy who provided more qualitative information regarding their control systems. Linc Energy did not provide P&IDs nor did they give expected details of specific references to the layers of protection, basic controls or advanced controls in place or under consideration.

Basic process controls form the first line of monitoring to measure deviations associated with pressure, temperature, flow rates and gas quality. These parameters can and should be monitored and controlled online in real time. However, any process deviation that causes significant environmental impacts (such as groundwater contamination) may only be detected by monitoring wells several weeks or months after the event. It is therefore imperative that operational procedures allow continuous or near continuous monitoring of these parameters. For the scope of the pilot trials this approach allows the operators and engineers the greatest opportunity to analyse the cause of a particular environmental trigger and investigate the appropriate course of remedial action.

The ISP observes that several of the incidents reported during the pilot trials came about through a lack of sufficient automatic monitoring of pressure, temperature, flow rates and gas quality. For example there is evidence in various submissions relating to the Carbon Energy pilot trial, that cavity pressures have in several instances increased beyond that of the hydrostatic groundwater pressure. This resulted in contamination plumes of greater or lesser extent in April 2010 and March 2011. In the opinion of the ISP, had appropriate control systems been in place, the risks posed as a result of the initiation of the events would have been significantly decreased. However, the monitoring records did allow Carbon Energy to identify the cause of the contamination plume and take appropriate remedial action to reduce the consequences.

For larger, commercial operations where sufficient process and groundwater modelling has been undertaken, this level of monitoring would allow operators to take immediate corrective action and thus reduce the severity or timeframe of the event and thus reduce its consequences. Basic process controls will incorporate low and high set points to address the UCG process variability. Examples include:

- The pressure difference between the cavity and the hydrostatic pressure of the groundwater to avoid gas egress and underground water contamination.
- The cavity and well temperatures that may cause well head or liner damage or increase the production of pyrolysis components.

- Injection and production well flow rates that directly relate to blockages of water and ash.
- Mass balances to check for gas losses.
- Gas quality to ensure that the UCG design is meeting syngas specifications.

Critical alarms are those devices related to independent sensors for process parameters, interlocks, isolation valves and redundancy where appropriate. Critical alarms require a quick diagnosis from the operator or engineer and a quick decision regarding the need for intervention to correct a process deviation. The documentation surrounding the pilot trials suggests a lack of critical alarms and appropriate decision-making procedures from the outset. For example on one occasion during the Carbon Energy pilot trial, backpressures on an injection well spiked to 37 bar resulting in emission of process water through the flare. This represents an injection pressure 270% in excess of the expected hydrostatic pressure. In this instance the high pressure was caused by a blockage in the well. This appears to have been noted by Carbon Energy, yet they made the decision to keep injecting under the premise that the blockage would clear itself. It is the opinion of the ISP that had this scenario been examined in an appropriate risk management culture, prior to or as part of the commissioning process, then a different decision (for example to cease injection, isolate the injection or provide pressure relief) would have been taken. More importantly, the decision taken would have followed a specific procedure designed to mitigate the risk scenario, rather than the apparent *ad hoc* decision process that took place. However, the ISP does observe that the post-deviation analysis undertaken by Carbon Energy resulted in new operating procedures being developed to avoid similar risk scenarios in the future.

Safety instrument systems (SIS) are required as part of the LOPA philosophy. SIS are advanced control systems that automatically instigate emergency shut-down procedures to safely isolate parts or the entirety of the plant.

Pilot Trial Issue and Lesson Learned

Incidents occurred during the pilot trials that indicate that sufficient safety instrument systems were not in place. One example of this may be emergency shutdown buttons for the injection compressors following over-pressurisation of the cavity and failure of pressure control systems. This may include provisions for emergency depressurisation of the cavity, sending the syngas to the flare.

The pilot trial reports do not indicate such a sophisticated level of process control. However, the risk assessment reports for both Carbon Energy and Linc Energy have indicated that the UCG proponents have learned the necessary awareness of these issues and plan to have provisions in place in the future.

Pressure relief systems are required to protect equipment which operates under pressure and which can cause environmental consequences through uncontrolled atmospheric discharge. Although the pressure of the cavity is not excessive, it is important that any depressurisation is carried out in such a way as to not instigate reaction extinction, cavity collapse or flooding. As such the pressure relief system must be designed and operated independent to other controls within the UCG process.

Conclusions

The ISP concludes that the UCG industry should adopt world's best practice for basic and advanced control systems (LOP 3 through 6) from the oil / gas and petrochemical industries.

The ISP further concludes that the basic process controls be adopted as the first line of monitoring.

5.4.1.4 Physical Protection Systems

Physical protection systems are used to mitigate the severity and prevent escalation of a risk scenario. They include systems such as physical bunds on tanks and fire curtains. There were several instances during the pilot trials for all UCG proponents when it appears that inadequate provisions were made for bunds on knock-out pots, process water/odour containment and process liquid containment. In one example, when knock-out pots overflowed or piping ruptures occurred, the spills proceeded directly onto soils or into local waterways. In another example, Linc Energy and Carbon Energy have been subject to odour complaints from local landowners.

These problems were appropriately addressed following the incident investigations, but it does once again highlight that the majority of the UCG risks have been managed on a post-incident basis.

The ISP is aware that the transport of odourous gases may occur and the degree of transport will depend upon site specific management and local weather conditions. Thus a zone beyond which no site derived odourous gases are detectable is needed. Government should develop evidenced-based guidelines as soon as possible and that the distance specified should be either appropriate to the meteorological conditions on site as ascertained by modelling or as regulated by the environmental licence of the site.

Conclusion

The ISP concludes that physical protection systems are required and should include gas detection for flammable and toxic gases, bund areas for excess process water or process liquids and fire protection systems.

5.4.1.5 Plant and community emergency response

Each site is unique in terms of geographical features, boundaries and access points. Therefore these plans should be developed in consultation with appropriate regulatory and community bodies, according to world's best practice and appropriate industry standards.

Conclusion

Plant and community emergency response plans should be developed in consultation with appropriate regulatory and community bodies, according to world's best practice and appropriate industry standards.

5.4.2 Other operating modes – Temporary Shutdown and Re-Start

Temporary shutdown and re-start are important phases of any process industry and may be associated with scheduled or unscheduled maintenance of equipment directly related to the UCG operation. The timeframe associated with temporary shutdown may be short (1-3 days) or medium term (for several weeks) depending on the scope of work. Issues relating to temporary shutdown and restarting an on-going UCG panel are very similar to those for the initial commissioning or final decommissioning phases. Long periods of temporary shut-down may lead to reduction in the cavity temperature to such a point where coal pyrolysis becomes prevalent. In these conditions the production of undesirable contaminants increases.

Pilot Trial Issue and Lesson Learned

A point of concern is if temporary shutdown leads to the extinguishment of the UCG reaction. This is the worst-case scenario, possibly leading to an inability to restart the operation, and/or associated unacceptable risks (repeated failures to reignite and possibility of explosion).

Difficulties are associated with the size of the cavity and lack of design features for such an occurrence.

The ISP observes from the pilot trial reports that the companies have learned how to successfully deal with temporary shutdowns lasting from several days to several weeks over which time the reaction was maintained as viable. Subsequently the panels were successful restarted without incident.

Specific Recommendation #3

If the UCG reaction has been extinguished, then restarting the panel should follow the pre-defined risk protocols. If restart is deemed unacceptable the process should proceed directly to decommissioning and rehabilitation.

5.5 Decommissioning

The decommissioning sequence is an important process that transitions between full production and site rehabilitation. The final shutdown sequence for a UCG panel is complex with a medium to long-term timeframe. The shutdown sequence is different to the temporary shutdowns discussed in Section 5.4.2 because the aim is to extinguish the reaction and bring the materials surrounding the final cavity into thermal equilibrium with the surrounding coal seam and over- and under-lying strata. The ISP is advocating a decommissioning approach rather than 'shut-down'. This is analogous to the risk-based 'commissioning' approach advocated during start-up and ignition.

Necessarily, the cavity must transition from gasification temperatures eventually to that of surrounding conditions. A second important change of state relates to pressure. As the cavity is cooled and the gasification is suppressed (most notably by reduction in supply of oxygen) the internal pressure decreases, which is a clear deviation from normal operating conditions. The rate of pressure decrease is important, somewhat variable and dependent on the conditions within the cavity.

During cooling there is an inherently high probability of formation of potentially contaminating chemicals (e.g., benzene, toluene, xylene (BTEX), phenols, various polycyclic aromatic hydrocrabons (PAHs) and other hydrocarbons). This is a result of the ongoing coal pyrolysis at temperatures between 250°C and 700°C, which favour their formation and so cooling of the reactor cavity will inevitably produce these unwanted chemicals. Carbon Energy and Linc Energy have appropriately highlighted these chemicals and their properties. They have also demonstrated capability in their detection and measurement.

Literature from overseas trials was reviewed by the members of the ISP and a literature review was provided by one of the proponents. There is reasonable evidence from the USA that a clean cavity may have been achieved. For information relating to the "clean cavity" concept reference should be made to the available literature. Government should seek to obtain the bibliography relating to the literature review from the company concerned.

The ISP has viewed a small core taken from one of the USA trials. Examination of the mineralogy of this core suggested a cooling pathway. It is up to the companies to design and undertake comparable sampling from the two pilots. If this is not possible, then the technology has a significantly greater degree of uncertainty than would be the case if direct mineralogical and chemical analysis of the remnant material were undertaken. Identification of the solids and liquids remaining in the cavity would reveal a greater degree of certainty for any contaminant phase transport modelling undertaken.

It is the responsibility of the companies to design appropriate sampling or measurement regimes to monitor the cleanliness of the cavity. Thus, the ISP believes, it is the responsibility of the companies to solve with the Government concerns relating to compliance with these regimes. If a "clean cavity" is not able to be demonstrated then the technology is not sufficiently well designed to be considered safe.

Carbon Energy and Linc Energy propose a "self-cleaning" approach to decommissioning (although both also note the possibility of having to actively clean the cavity if necessary). Under such a scenario the reduced pressure in the cavity is advantageous in that a local zone of low pressure draws groundwater from all directions towards the cavity. This is important because any residual chemicals from the active zone (or beyond), that are not adsorbed to the coal, are, in principle, flushed into the cavity. The residual heat in the cavity vaporises the water and contaminants which are then brought to the surface for appropriate handling and treatment. In principle, this is an attractive process if it can be demonstrated in practice in large cavities partially filled with rubble and with significant temperature gradients due to the size of the cavity and longevity of the panel gasification duration.

Pilot Trial Issue and Lesson Learned

Carbon Energy and Linc Energy both propose design panel systems of several hundred metres of length and tens of metres of width and significant height (depending on the coal seam but of order 10m). To date, there is no evidence of the capability to control the temperature and pressure changes in such large cavities because no such cavity has yet been completed. The panels currently under gasification by Linc Energy and Carbon Energy are the best opportunity to date to investigate these important issues. Extrapolation from other small cavities is inadequate as is taking analogies from overseas experiences with different designs (and also small cavities). It is simply not possible to demonstrate that self-cleaning is effective in a large cavity until a large cavity is available on which to conduct the necessary monitoring.

Linc Energy and Carbon Energy have learned the necessary monitoring and measurement capabilities to be able to demonstrate self-cleaning but to date no cavity exists upon which a convincing demonstration can be undertaken. Demonstrations on current small cavities have been unconvincing (access to cavities appears to be a very challenging design issue).

Conclusion

Several cavities (some panels) have been shut down during the pilot trials and are undergoing various stages of decommissioning and, presumably, rehabilitation. However, insufficient information has been gathered or provided regarding decommissioning during the pilot trials. A formal process model, mass and energy balances and appropriate data support were all lacking. The reliance on analogues from overseas experiences is insufficient. Therefore, the ISP is of the opinion that the best strategies have not been fully developed at this time.

5.5.1 Panel/Cavity Information and Unidentified Risks

Neither Carbon Energy nor Linc Energy provided sufficient information on the operational modelling (including morphology and growth) and decommissioning of their previous cavities or currently operating panels for the ISP to reach a recommendation of safety in practice.

The ISP decided not to review operational processes, but rather focus on the risk assessment and supporting background data.

The information provided by Carbon Energy on panel morphology and size was inconclusive. An attached consultant report (Appendix J) concluded that a new technique trialled for the purpose of mapping the decommissioned panel 1 was successful. However, the figures lacked scales and colour coding of the spatial information was not described, making independent analysis and verification by the ISP all but impossible. Indeed, one possible interpretation of the information is that the morphology of the cavity did *not* match expectations. That is, the cavity appeared as toroidal, possibly due to rubble collapsed in the centre of a more spherical cavity. Further, there appeared to be void space behind the ignition point, which would not be expected. The ISP concluded that Carbon Energy would not have presented such information if this interpretation were correct and not remark upon it themselves. Consequently, the ISP does not concur with the consultant that the technique was successfully applied to UCG. Further the ISP suggests Carbon Energy reassess the data or apply another technique to this important aspect of UCG.

The composition of the cavity following operation is important for decommissioning and rehabilitation strategies.

The plausible options for contents of a final cavity include that it is filled with:

a. rubble from gasified coal (ash and tar), collapsed overburden, interburden and disturbed underburden; or
b. underground water containing a range of constituents native to the groundwater, e.g., salts, and products of gasification and pyrolysis; or
c. syngas mixed with air and coal seam gas (methane and carbon dioxide); or
d. a mixture of all of the above.

The ISP is of the view that (d) a mixture of all of the above contents, is the most plausible and that the gas mix and water constituents are likely to vary over time.

Linc Energy provided a (partial) framework (see figures L4 and L6) in their decommissioning report. This model acknowledges that the overburden and underburden are compromised by the gasification process and that the final cavity includes "rubble-altered overburden". The ISP suggests that the critical variables of the framework be more fully elucidated and formalised into a formal engineering conceptual model. This must include a set of reference equations that can be used as a basis for statements as to the likely content of the cavity and include an appropriate conversion from 2D (as in the figures) into 3D (as exists in the real cavities). Such a model will be critical in gaining confidence that the company knows what it is dealing with. Without this, the relative quantities of water, ash, tar, rubble and gas are speculative and no mass balance or dynamic prediction models of sorption or water movement can be made with confidence. Such a model will also provide a basis to complete the picture of the cavity because measurements will always only be a partial information source for delivering the certainty required to deliver confidence that a clean cavity has been achieved.

Appendix J of the Carbon Energy report concludes that rubble-filled is the best model fit for the contents of the cavity. This conclusion means that the cavity is likely dominantly filled with material collapsed from the overburden. By comparison, Linc Energy provided a visualisation of the "material affected zone – MAZ" of gasifer 3. In that visualisation it was clear that both overburden and underburden were part of the zone, although what was intact and what was merely altered was not able to be discerned. That is, the MAZ extended above and below the coal measures and therefore the integrity of the overburden and underburden were affected by the UCG process consistent with the Linc Energy conceptual framework as presented. Surprisingly the Linc Energy decommissioning report did not make reference to this issue. Given the conclusion by the Carbon Energy consultants that their cavity is likely rubble-filled it is difficult to see how the Linc cavity would not also contain material that collapsed from the overburden (again as it was indicated in their conceptual model).

With respect to the earlier gasifers the process used to confirm that the coal has ceased to burn after decommissioning was monitoring the composition of the gas produced. There are very clear trends which indicate the shutting down of the gasification process. These include decreasing concentrations of CO, CO_2 and N_2 (which are monitored on-site) and the decline of CH_4 back to baseline. All pyrolysis will ultimately cease when the air/O_2 supply is turned off.

Once the source of oxygen is removed and at geologically suitable sites, all burning will ultimately cease and the fire will be extinguished. This is unlike underground coal fires. For example, Jharia in India has experienced a coal fire that has burned underground for approximately 100 years in spite of attempts to extinguish the fire by using nitrogen. The failure to extinguish the burn relates to failure to cut off all supply of oxygen via ventilation shafts, the numerous open pits and old mineshafts in the area. Comparably, spontaneous combustion cannot occur in UCG operations once any oxygen supply is removed.

With current Carbon and Linc gasifiers, the decommissioning is not yet complete, hence the recommendation that decommissioning trials continue (Overarching Recommendation 2). At the end of this period, a definitive statement relating to the cessation of burning should be possible. All the indirect evidence currently available indicates that burning of coal (pyrolysis and gasification) ceased soon after the injection of air or oxygen stopped.

Background information from both Carbon Energy and Linc Energy indicated that the Springbok Sandstone overlying the coal measures contains small discontinuous aquifers interspersed by dry aquicludes (lenses through which water cannot move or through which water moves so slowly as to be negligible). Carbon Energy and Linc Energy indicated that no aquifer directly overlies their reactor panels and that the tight Springbok Sandstone forms an effective seal against gas egress from the cavity. However, if the post-gasification cavity is at least partially rubble-filled, as proposed by Carbon Energy, implied by Linc Energy conceptual model and possibly MAZ visual rendering data and accepted by the ISP; then it stands to reason that the rubble is from the overburden. This implies that the integrity of the seal is potentially compromised. It is important that this risk is identified and controls articulated. It is expected that a move to commercial operation and larger cavities would increase this risk. That is, it is increasingly likely that over a length of several hundred metres gas migration pathways are formed by the collapse of the cavity roof.

A second risk is also created with respect to the final hydrological integrity of the cavity. Both Carbon Energy and Linc Energy have highlighted that the dry material overlying the cavity is an advantage because water ingress to the cavity is not important either in terms of the oxygen/water mix or the potential to drain overlying aquifers in commercial operations. However, neither Carbon Energy nor Linc Energy deal with the risk that a lack of integrity in the cavity roof may provide an escape pathway for contaminated water as the original groundwater pressure in the coal measures re-establishes following decommissioning (the local hydraulic head is above the level of the top of the cavity). Given that the overburden does not have the activated carbon or background coal capacity to adsorb pollutants (discussed further in Section 3.5.3) this is a potential pathway for their transport into the surrounding environment.

Neither of the company reports provided data to indicate that gases have been detected at the surface. All possible pathways should be examined including well and surface infrastructures to determine possible sources of any gases.

Therefore, the ISP concludes that for UCG to be safe in practice, the compromise of integrity of the overburden must pose no environmental threat. Undertaking UCG at significant depth (as per the recommendations in Section 5.2) would appear the easiest way to ensure this. An alternative would be to demonstrate that the stratum above the direct overburden is tight, not an aquifer and remains intact after gasification. There is no substitute for direct measurement coupled to a sound numerical model of the system, to demonstrate this.

5.5.2 Coal activation and pollutant adsorption

Carbon Energy and Linc Energy present information on the importance of coal as an adsorptive medium for gasification products that may assist with risk limitation during decommissioning. Linc Energy provides adsorption isotherms for coal that has been thermally altered under laboratory testing conditions. The ISP notes that the university report presented on this carried a strong disclaimer regarding the inappropriateness of the use of the experimental results for interpreting behaviour of coal in a real gasifier (although within the report there appeared to be a counter statement). Nevertheless, the ISP is of the view that laboratory heating of Macalister is not a substitute for coal sampled from the wall of an actual cavity because the complexity of alteration conditions is greater than only thermal effects.

No significant attempt was made by either Carbon Energy or Linc Energy to compare the likely available adsorptive capacity of the decommissioned cavity wall with the likely production of pollutants. This information is significant and would have demonstrated to the ISP whether contaminant load and capacity may be expected to balance. Both Carbon Energy and Linc Energy did provide either simplistic models or initial results which suggested that the contaminant plume would be restricted to within a few hundred metres of the cavity, even under worse case scenarios. However, given the lack of knowledge surrounding the final contaminant profile, cavity volume, morphology, composition, amount of water to be removed for treatment and altered ground water flows; the ISP cannot accept these conclusions without more rigorous assessment (under multiple cavity conditions) by the UCG proponents.

Evidence of the effectiveness of decommissioning must be comprehensive and include:

1. A comprehensive detailed step-wise process flow for decommissioning that can convincingly demonstrate a completed panel (as envisaged in the proposed technology for both companies) is clean and environmentally safe in the long term.
2. A conceptual model/framework for decommissioning including all material and energy flows.
3. Validated numerical models and accompanying data for the decommissioning process. This must include as a minimum:
    a. Convincing 3D estimates of the morphology and size of existing cavities;
    b. Data from the existing cavities on the material properties of the cavity walls (coal seam, overburden and underburden);
    c. Mass balance estimates of pollutant loads based on measurements;
    d. Mass loading estimates of adsorption capacity of "activated" and nearby coal, i.e., coupling of measured isotherms with adsorptive capacity and loading of a water-filled cavity;
    e. Measurements of critical pollutants and mass balances for the water and tar pollutants exiting the cavity via the production well.
    f. Measurements of critical pollutants and mass balances for the water its constituents and tar pollutants exiting the cavity via the production well.

Conclusion

For the currently operating panels, Carbon Energy and Linc Energy should establish integrated shut down and clean-up procedures to establish world's best practices for decommissioning a UCG cavity.

Specific Recommendation #4

No further panels should be ignited until the long term environmental safety provided by effective decommissioning is unambiguously demonstrated. Evidence of the effectiveness of decommissioning must be comprehensive.

5.6 Rehabilitation

Other than general definitions borrowed from the mining industry the pilot reports provided little information on rehabilitation. Therefore, this phase of the life cycle is yet to be assessed and no conclusions regarding adequacy of processes can be made.

Specific Recommendation #5

The companies should immediately propose, test and establish acceptable and agreed processes and outcomes for rehabilitation.

6 Coal Seam Gas and Underground Coal Gasification

The issue of overlapping tenure between CSG extraction and UCG was raised with the ISP. The essential issue is that CSG requires that groundwater pressure be reduced so that methane can desorb from the coal and make its way to extraction points. However, UCG requires that hydrostatic pressures be maintained at a minimum value to ensure the cavity growth is controllable and that contaminants cannot escape into the surrounding environment. Unfortunately, the minimum pressure of methane desorption is below that required to maintain a UCG gasifier.

The interaction between CSG and UCG has policy and legal issues. The ISP considers that it should *not* have the role of making a determination as to the legal situation regarding liabilities for water pressure under current legislation. Nevertheless the following observations are made.

The ISP recognises three cases for consideration of the interactions between CSG and UCG.

1. Current approved UCG trials and approved CSG overlap. The government needs to determine whether approved CSG activities will jeopardise the ability of the UCG pilots to demonstrate effective decommissioning. If so, resolution is required with respect to groundwater pressure and any potential contaminant transport from UCG cavities.
2. Potential UCG and approved CSG. The ISP is of the opinion that where it is known in advance that CSG will reduce groundwater pressure, any proposed UCG must include a risk strategy to control the groundwater pressure necessary for safe operation.
3. Greenfields. Policies to deal with such future situations are needed.

In the longer-term it should be recognised that UCG resources can be sterilised by groundwater depressurisation until recharge, which can take many decades.

Pilot Trial Issue and Lesson Learned

The ISP is of the view that no generalised buffer distance recommendation is technically sound. The distance between any active UCG gasifier and the nearest CSG well will be controlled by the details of the gasifier depth and pressure conditions and the rate of water injection required to meet the minimum pressure operating requirements.

A key issue is whether a UCG operation can be made responsible for the critical operating condition of hydrostatic pressure. Linc Fnergy provided information on the trialling of control of local water pressure via injection wells. Carbon Energy did not provide any information regarding design or trialling of a suitable ground water control technology. However the risk assessment conducted by Carbon Energy and R4Risk indicated that the use of injection wells to control the local groundwater pressure was a principle risk mitigation measure for multi-panel operation.

It is clear that both companies have learned the potential advantages for being responsible for hydrostatic pressure control. Control by creating a local a curtain via a series of injection wells is yet to be demonstrated. The ISP notes that the CSG industry has a large amount of coal seam co-produced water to dispose of and UCG could be one use for this water.

Specific Recommendation #6

The ISP recommends that any UCG operation should be licensed on the basis that it is responsible for maintaining and controlling all its operating conditions, taking into account the conditions of the site at the time of approval, including maintenance of groundwater pressure.

7 Regulatory Environment

The regulatory environment establishes the criteria for the approval of a proposed UCG facility, stipulates monitoring requirements and guides operational priorities. The regulatory environment also drives the site investigation. To satisfy the intent of existing legislation and the aims of the agencies that administer the legislation, consideration should be given to the identification and understanding of the Acts and other instruments of governance under which authority to explore and mine the coal, and to operate the UCG facility, is granted.

In Queensland, an application for a UCG facility is made under the *Mineral Resources Act 1989 (MRA)* and the *Environmental Protection Act 1994 (EPA)*. Although the *MRA* and the *EPA* most directly apply to the authorisation and regulation of a UCG facility, a number of other legislative instruments (such as cultural heritage and native title legislation) apply to the approval and operation of a UCG facility.

The majority of the relevant Acts are applicable to all aspects of mine related activities. These are listed below and must be understood and followed by the UCG proponent. However, a number of Acts may be confusing, misunderstood, or are considered of particular relevance to the UCG activity. These Acts will be detailed within this Guideline.

It should be noted that understanding the intent of the Legislation, and seeking clarification as necessary, will facilitate better performance, creative problem solving, success in satisfying Regulatory Authorities, and produce a proactive, rather than a reactive, approach to the problem solving situation.

7.1 Observations on policy and governance

Different parts of legislation contain sometimes conflicting or confusing definitions. An important example is *syngas*, which is petroleum under the meaning of the Petroleum Legislation and is a mineral under the meaning of the Mineral Resources Act 1989

Overlapping tenures can exist under Petroleum and Gas (Production and Safety) Act 2004 (P&G Act) and the Mineral Resources Act 1989. Existing legislative arrangements concerning rights to groundwater (e.g. dewatering) should be reviewed. An important example is that the operational parameters within the coal seam for CSG are incompatible with those for UCG. Where two different tenure applications for petroleum and mining do overlap, legislative arrangements are complex and decision-making is complicated and necessarily on a case-by-case basis. Equally, legislation can hold certain operators responsible for groundwater changes that are ultimately controlled by a separate decision regarding a different development. For example, dewatering for an approved coal mine could result in groundwater pressure changes that a CSG company had been made responsible for that a UCG company then is impacted by.

UCG is a relatively new technology to Australia and is not widely practiced globally. Professional expertise and experience is not readily available. If the UCG industry can demonstrate environmental safety and community acceptance with economic viability, the eventual establishment of a UCG industry will require significant government and technical support. Currently, it is challenging for government to develop policy and for regulators to be as effective as they might because of a limited skills base. Further, there is little non-company research being undertaken. Independent research is required to ensure broad confidence in the significant questions that remain to be answered about UCG, particularly as a commercial activity. Research is also the foundation of a tertiary education institution's ability to effectively educate the necessary workforce for a new industry. The government should establish two new entities to ensure that if it is deemed acceptable to establish a UCG industry that it can be supported at the level necessary to ensure its best chance to be environmentally, socially and economically viable.

The Government needs capability and capacity to effectively deal with the issues surrounding a potential UCG industry. Given the challenges of building internal capacity in a short time the government could consider appointing Queensland UCG Independent Assessment, Evaluation and Advisory Group[3] of persons with understanding of (a) the science behind the UCG process, (b) sufficient knowledge to predict problems that may occur, and (c) sufficient knowledge to discern solutions to unforeseen problems. Suggested components of terms of reference for the group are below.

- Reviews and monitors risk related issues (environment; safety etc) for UCG operations.
- Provides policy, legislative and regulatory information support for government.
- Neutral broker between industry and government.

  Identifies research problems/targets from risk perspective and asks R&D network (see below) to develop responses.

Important initial tasks with which the group could assist government and industry are:

- A UCG Policy should be constructed that adequately reflects the tenets of the Government's concerns and requirements.
- A set of clearly defined Guidelines should be constructed that are unambiguous and allow for variations in regional and local conditions.

A research and development programme, The Queensland UCG R&D Network[4], should be initiated immediately and tied into international expertise. It is not envisaged that a large fund should be

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[3] To avoid any perceptions of conflict of interest, members of the ISP propose that they would be excluded from participating in the Advisory Group for a period of two years lest it be suggested this recommendation is an attempt by ISP to position for a future advisory role.

[4] To avoid any perceptions of conflict of interest, members of the ISP propose that they would be excluded from participating in the R&D network for a period of two years lest it be suggested this recommendation is an attempt by the ISP to position for future research.

made available. The main aim initially is to bring together research capability so that government and industry can draw upon a network of expertise. Such a network would form an excellent base upon which industry and government could draw, in due course, for educators as well as researchers. Projects would then be funded on a case-by-case basis with contributions as the parties see fit. It is suggested that government mandate that the UCG companies, as part of their license to operate, contribute to establishment of the group to meet the administrative and networking costs, which should be ~$1m p.a. Companies would also be required to participate in priority setting and communication of outcomes of activities of the network. State government would be encouraged to contribute in-kind and eventually financially to projects as the State budgetary situation improves over time. A number of alternative resourcing models for the network could also be explored, for example, the federal schemes for rural research, e.g., grains research and development corporation, or the Australian Coal Association research Program (ACARP), which is fully industry driven and funded.

Specific Recommendation #7

The government should consider establishing two new entities to support a UCG industry at the level necessary to ensure its best chance to be environmentally, socially and economically viable.

1. Queensland UCG Independent Assessment, Evaluation and Advisory Group.
2. The Queensland UCG R&D Network.

8 Industry scale-up (multi-panel operations)

The ISP would like to highlight the lack of detailed data presented regarding the plans for multi-panel operation and commercial scale-up. The reports on the pilot trials show that no multi-panel operation has been carried out thus far. The panels that have been gasified, to a greater lesser extent, have been for the purpose of data gathering and experimentation. Whilst this is a suitable approach for a pilot trial, it appears to have followed an *ad hoc* design evolution rather than a systematic design evolution. It is therefore not possible for the ISP to assess the design for scale-up.

Significant issues remain to be dealt with including:

- the altered hydrogeology across a multi-panel site;
- the relationship between completed panels (cavities) and active gasifier(s);
- the potential for unacceptable odour production from multiple simultaneous gasifiers and the consequent need for a substantial distance buffer to potentially exposed neighbours;
- multi-panel design that avoids connectivity between final cavities and active, potentially contemporaneous, panels resulting in:
    - unacceptable surface subsidence;
    - groundwater transport of contaminant and wild fire because of loss of control of oxygen conditions; and
- the need for external injection of water to maintain the hydrostatic pressure across the site. It is clear that the observations made above on challenges associated with water injection to maintain hydrostatic pressure (see Section 5.5) are amplified considerably for multi-panel operations. Depending on the final design chosen it may indeed be necessary (and possible) to establish a minimum distance from a UCG *facility boundary* and other activities, e.g., CSG that require different hydrostatic operating conditions.

All of these design considerations will have significant implications towards multi-panel operation and commercial scale-up, site decommissioning and rehabilitation.

For commercial scale multi-panel operation, it is the opinion of the ISP that full consideration should also be given to critical systems (see Section 5.4.1.3) during the design phase. These systems should include temperature relief systems for the well head (i.e., water quenching / steam injection), gas detection for flammable and toxic gases, bund areas for excess process water or process liquids and fire protection systems. The ISP recognises that a further system of physical protection is the establishment of an active zone around the cavity which may contain similar or lower levels of contamination in the ground water as is found inside the cavity due its intimate proximity.

Conclusions

Physical protection systems for a full scale multi-panel operation should include temperature relief systems for the well head, gas detection for flammable and toxic gases, bund areas for excess process water or process liquids and fire protection systems.

Above ground and underground buffer or active zones be established as the final layer of physical protection once the final design for a multi-panel system is known.

The UCG proponents must establish acceptable and agreed decommissioning procedures before proceeding to the commercial phase of operation.

Multi-panel operation requires a full understanding of the site geology and hydrogeology. A systematic design of the multi-panel operation should be undertaken prior to the commencement of any commercial activities.

Specific Recommendation #8

A commercial operation should be designed from the outset on a foundation of well-established principles i.e. a risk-based approach from the outset in all phases of the life-cycle of multi-panel operation.

The Carbon Energy and Linc Energy sites have been operated as pilot sites. Any consideration of commercial activity should be preceded by a comprehensive, multi-panel, risk-based plan.

9 List of Recommendations

9.1 Overarching recommendations

Overarching recommendation 1.

The ISP recommends that the Queensland government permit Carbon Energy and Linc Energy to continue the current pilot trials with the sole, focused aim of examining in a comprehensive manner the assertion that the self-cleaning cavity approach advocated for decommissioning is environmentally safe.

Overarching recommendation 2.

The ISP recommends that a planning and action process be established to demonstrate decommissioning. Successful decommissioning needs to demonstrate the self-cleaning process and/or any necessary active treatment. To achieve this:

1. *A comprehensive risk-based plan for decommissioning must be produced;*
2. *The Plan must take account of the fact that both companies now have connected cavities suitable for demonstration [Linc Energy is still gasifying];*
3. *The Plan must include at a minimum a conceptual model and relevant numerical models, a sampling and verification/validation strategy, and event-based milestones that, where possible, are time bound.*
   Two significant phases are recognised:
   a. *Sampling of the zone surrounding the cavity; and*
   b. *Direct cavity access.*
4. *The government must establish a process by which the plans and their implementation are assessed for adequacy.*

Overarching recommendation 3.

The ISP recommends that until decommissioning is demonstrated, as per Overarching Recommendation #2 no commercial facility should be commenced.

9.2 Specific recommendations

Specific recommendation #1

The government together with the UCG industry and an independent advisory body, should develop guidelines and standards for site selection. The ISP recommends that site selection is a process that should be preceded and informed by appropriate geological surveys, hydrogeological modelling and an assessment of the community and environmental context. Such assessments must serve as Go / No Go gates for decision to develop or not any site for UCG operation, i.e., any limiting factor should signal No Go for the site.

Specific Recommendation #2

The ISP recommends that for each new panel, the UCG industry adopts a 'commissioning' approach rather than 'start-up' or 'ignition' regardless of size or multiplicity, to reduce the risks associated with this phase. Commissioning should involve world's best practice for risk management in process industries including HAZOP, fault tree analysis, event tree analysis, LOPA including all the controls to ensure that the inherent risks of UCG activities are minimised from the outset.

Specific Recommendation #3

If the UCG reaction has been extinguished, then restarting the panel should follow the pre-defined risk protocols. If restart is deemed unacceptable the process should proceed directly to decommissioning and rehabilitation.

Specific Recommendation #4

No further panels should be ignited until the long term environmental safety provided by effective decommissioning is unambiguously demonstrated. Evidence of the effectiveness of decommissioning must be comprehensive.

Specific Recommendation #5

The companies should immediately propose, test and establish acceptable and agreed processes and outcomes for rehabilitation.

Specific Recommendation #6

The ISP recommends that any UCG operation should be licensed on the basis that it is responsible for maintaining and controlling all its operating conditions, taking into account the conditions of the site at the time of approval, including maintenance of groundwater pressure.

Specific Recommendation #7

The government should consider establishing two new entities to support a UCG industry at the level necessary to ensure its best chance to be environmentally, socially and economically viable.

1. Queensland UCG Independent Assessment, Evaluation and Advisory Group.
2. The Queensland UCG R&D Network.

Specific Recommendation #8

A commercial operation should be designed from the outset on a foundation of well-established principles i.e. a risk-based approach from the outset in all phases of the life-cycle of multi-panel operation.

The Carbon Energy and Linc Energy sites have been operated as pilot sites. Any consideration of commercial activity should be preceded by a comprehensive, multi-panel, risk-based plan.

Terms of Reference
Peer Review of Independent Scientific Panel Report into Underground Coal Gasification

Background

1. The Queensland Government appointed an Independent Scientific Panel (ISP) to assist the Queensland Government in the assessment of the technical viability and environmental sustainability of underground coal gasification (UCG).
2. On 30 November 2012, the ISP delivered its final report (the ISP Report) to the Queensland Government.
3. The ISP's three overarching recommendations suggest that the trials should continue for six months, albeit under strict conditions, to effectively demonstrate decommissioning is environmentally safe and sustainable and until decommissioning is successfully demonstrated, no commercial facility should commence.
4. The ISP also provided eight additional specific recommendations, largely relating to the operation of a UCG industry in Queensland.

Peer Review

5. A Peer Review process will be led by Dr Geoff Garrett AO, Queensland Chief Scientist.

Scope

6. The Peer Review will focus on reviewing the ISP Report on UCG to assess the reasonableness of the three overarching recommendations, the eight specific recommendations and the conclusions (including any interim recommendations).
7. This review may result in a consensus perspective which may lead to modifications or additions to the ISP Report.
8. In undertaking these activities, submissions from the trial proponents and the ISP will be considered where relevant to any assessment of the ISP Report.
9. In undertaking the Review the Chief Scientist will engage other experts if and as he deems necessary. He will also be supported by an officer of the Department. The Peer Review process will also involve, as appropriate, technical experts from the UCG trial companies, and member(s) of the ISP, as required.

Key Deliverable

10. A report responding to the matters outlined in section 6 of these Terms of Reference.

Timeframe

11. The key deliverable target is 1 July 2013.

Shannon Anderson

From:	Don Fischer <don.fischer@wyo.gov>
Sent:	Friday, October 11, 2013 11:58 AM
To:	Kevin Frederick
Cc:	Shannon Anderson
Subject:	Re: question
Follow Up Flag:	Follow up
Flag Status:	Flagged

Shannon,
To the best of my knowledge, there are no aquifer exemptions for UIC Class I or III facilities in the Ft. Union Formation in Johnson or Campbell counties.

For Class I facilities, the injection zone would be deeper than the Ft. Union. For Class III (ISR) facilities, the injection zone (aquifer exemptions) would be in the overlying Wasatch Formation.

For UIC Class II O&G facilities, you would need to check with the WOGCC.

Thanks.
Don

Don Fischer, PG #2852
North District Geologic Supervisor
WDEQ: Groundwater Section
2100 West 5th Street
Sheridan, WY 82801
307-675-5640
Don.Fischer@wyo.gov

On Fri, Oct 11, 2013 at 8:56 AM, Kevin Frederick <kevin.frederick@wyo.gov> wrote:
Hi Shannon,

I've asked staff to check into this for you. We'll try to have a response for you next week.

Kevin Frederick, P.G.
Administrator
Water Quality Division
Wyoming Department of Environmental Quality
Herschler Bldg. - 4W
122 W. 25th St.
Cheyenne, WY 82002

(307) - 777- 5985

On Thu, Oct 10, 2013 at 10:51 AM, Shannon Anderson <sanderson@powderriverbasin.org> wrote:

Hi Kevin,

Hoping (for many reasons) you are around and not furloughed.

Have a question that I am hoping you or someone on your staff can answer – are there any current aquifer exemptions in the Fort Union formation in Johnson or Campbell Counties? If so, what projects are they related to (who is the permit holder)? Many thanks, Shannon

Shannon Anderson

Powder River Basin Resource Council

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