INDEPENDENT SCIENTIFIC PANEL REPORT ON UNDERGROUND COAL GASIFICATION PILOT TRIALS

June 2013

Queensland Independent Scientific Panel for Underground Coal Gasification (ISP)

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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.

[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

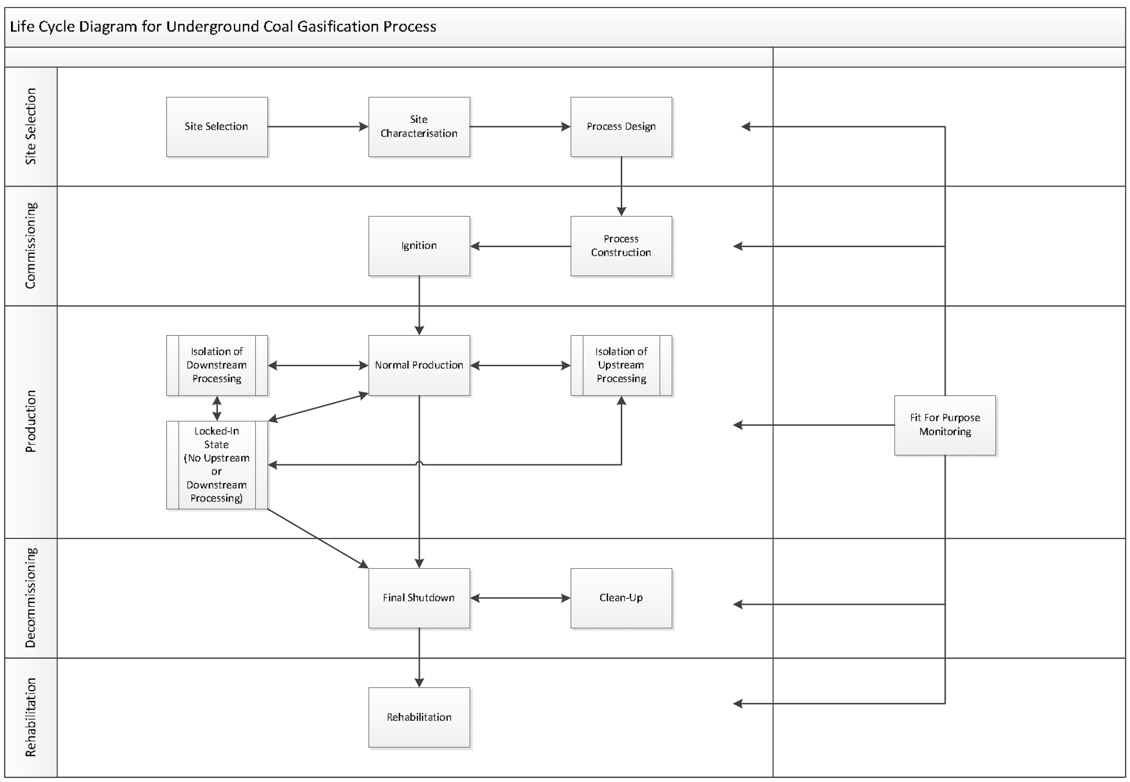

Figure 1 - Schematic of Life Cycle Stages for a UCG Plant

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.
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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.

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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.

[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^{o}C and 700^{o}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 Energy 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

[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.

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